UNIVERSIDADE NOVE DE JULHO - UNINOVE
DOCTORAL PROGRAM IN PRODUCTION ENGINEERING

MARCOS VIDO

TECHNO-ECONOMIC FEASIBILITY APPROACH TO ADOPT COLLABORATIVE ROBOTS IN SMALL AND MEDIUM-SIZED ENTERPRISES

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A dissertation submitted to the Doctoral Program in Production Engineering – PPGEP at Universidade Nove de Julho – UNINOVE, as partial fulfillment of requirements to obtain the degree of Doctor in Production Engineering.

Supervisor: Prof. Dr. Wagner Cezar Lucato

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PARECER DA COMISSÃO EXAMINADORA DE DEFESA DE TESE DE

MARCOS VIDO

Título da Tese: Techno-Economic Feasibility approach to adopt collaborative robots in Small and Medium-Sized Enterprises.

A Comissão examinadora, composta pelos professores abaixo, considera o(a) candidato(a) Marcos Vido APROVADO.

São Paulo, 17 de agosto de 2021.

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Dipartimento Meccanica Matematica Management

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To Professor Wagner LUCATO
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Bari, August 17th, 2021

Object: Evaluation of PhD dissertation of candidate Marcos VIDO

The PhD dissertation of candidate Marcos Vido is focused on collaborative robots (cobot) and discusses an innovative approach to evaluate the techno-economic feasibility of adopting them in Brazilian small and medium-sized enterprises (SMEs).

The research carried out by the candidate started with the clarification of the research question, followed by an extensive literature research aimed at identifying main contributions already available on the research theme and related limitations. After that, the model developed by the candidate is detailed, and results of the Delphi method carried out on a panel of experts are adopted to calibrate the model. Furthermore, results of a full-scale case study witness the effectiveness of the model proposed in evaluating the techno-economic feasibility of adopting cobot in a Brazilian SME. In the final part of the dissertation, the candidate offers a critical discussion of the results achieved, underling both potential advantages and limitations.

The dissertation of Marcos Vido is well written and well-structured and consists of seven Sections. In the Introduction Section, research field, research motivations, the research question, and related objectives as well as the methodology adopted to achieve objectives are described in a very clear and detailed way. In the second Section, the candidate illustrates the development of industrial robot and cobot, focusing on the interaction between human and robot/cobot in the work environment. In the same Section, the candidate offers an overview of SMEs, identifying barriers and opportunities in the adoption of cobot. Barriers to adopt cobot in SMEs and cobot feasibility are the themes deepened in this section through an extensive literature review based on PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analysis) methodology. The candidate analyzed more than 1500 papers retrieved from eleven electronic databases (1656: 615 papers on barriers to adopt cobot in SMEs and 1041 papers on cobot feasibility study) and identified 69 relevant papers (53+16). Finally, the candidate discusses in this section techno-economic feasibility models available in scientific literature to adopt cobots. Results obtained from this Section are adopted in the building up of the techno-economic feasibility model proposed in the third Section. The model proposed by the candidate in is introduced in the third Section of the dissertation. In this Section, technical and economic factors influencing the feasibility of cobot adoption in production environment are preliminary investigated starting from the findings obtained through the literature research carried out. Factors are combined in the feasibility model proposed and detailed in this section. Results of a full-scale case study is provided, concerning the feasibility evaluation of the adoption of a UR 10e series cobot in a Brazilian manufacturer of automotive components. In the fourth Section of the dissertation, the candidate provides up-to-date details and findings on the Delphi technique. The technique is applied in order to confirm the suitability of the theoretical model developed and to verify its adequacy. The method was applied in a very rigorous and effective way, and a two-round survey led to a large (> 90%) consensus. Results obtained from the Delphi method have been adopted from the candidate to improve of the theoretical techno-economic model proposed. The research steps followed, the results obtained, and the improvement of the theoretical model proposed are summarized in Section 5 of the dissertation. In Section 6 of the dissertation, the candidate discusses the reliability of the model proposed as well as its design principles on the base of results obtained from the application of the Delphi technique. Conclusions, limitations, and further research opportunities are in Section 7 of the dissertation.

The research carried out by the candidate Marcos Vido is of high quality and is characterized by a good level of scientific maturity and rigor. The research findings detailed in the dissertation of the candidate provide additional knowledge and advances in the state of the art in the research field investigated. The theoretical model proposed is the results of a deep search on the issue faced with, and its final version has been enriched thanks to further research carried out by applying the Delphi technique. The model proposed can be considered as an easy-to-use, friendly, effective tool for industrial practitioners. Although the theoretical model has been conceived for the application on Brazilian manufacturing contexts, it can be considered of general validity.
Based on motivations described above, a very positive judgment is expressed on the work done by the candidate. The candidate deserves to achieve the title of Doctor of Philosophy in Production Engineering.

Prof. Salvatore Digiesi

Prof. Francesco Facchini

This work is dedicated to my wife Marisa, and my daughter Marília for providing me perspective. In memory of my parents. Thank you for giving me more than I deserve. This work would not have been possible without all of you!

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At the UNINOVE, wish to acknowledge all my colleagues within the PPGEP for friendship and inspiration. Since the beginning, we have been on this journey with the same focus. My gratitude to the Rectory of the UNINOVE to support my research, providing all IT resources, the high qualification team of professors, the lectures, and knowledge to propose to me to capture quality information. To the undergraduate students at UNINOVE whom I have had the privilege to work with and have inspired me through their enthusiasm, power, and confidence of their youth.
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“Learning is the only thing the mind never exhausts, never fears, and never regrets.”

Leonardo da Vinci

ABSTRACT

Industry 4.0 is identified by the adoption of cyber-physical systems and the internet applied to the manufacturing environment, encompassing what is called the fourth industrial revolution. Thus, a transformation occurs in factories through technological advances in the areas of cloud computing, human-machine interface, additive manufacturing, augmented reality, autonomous robots, and the internet of things. The literature recognizes such practices as the enabler technologies of industry 4.0. Indeed, there is the possibility of industry 4.0 spreading into the manufacturing sector using collaborative robots, which offer the possibility of a working environment in safe conditions alongside humans, applied in a shared workspace in a production environment. Within this perspective, Small and Medium-sized Enterprises (SMEs) are facing several challenges compared to large organizations to adopt advanced technologies in this new industrial era. Centered on the literature, the aim of this dissertation was to introduce a techno-economic feasibility approach to evaluate the viability of using collaborative robots in a shared workplace, focusing on Brazilian SMEs. Regarding the methodology, this work performed a qualitative approach. A full-scale industrial case study was performed to demonstrate the design of the proposed conceptual model, followed by interviews conducted with experts from the industrial sector through the Delphi method to certify the conceptual model. The results of this work incorporate contributions to both the academic and industrial communities. First, it adds new knowledge to the body of literature as it brings a novel procedure to certify the feasibility of adopting collaborative robots by SMEs, which was a gap identified in the specific literature. Furthermore, this research can be used by practitioners in the industry sector to perform a feasibility approach through an easy-friendly model, seeking to evaluate the reliability of implementing collaborative robot technology.

Keywords: Collaborative robot, Small and Medium-sized Enterprises, Industry 4.0, Technical feasibility; Economic feasibility, Conceptual model

RESUMO

A indústria 4.0 é reconhecida pela adoção de sistemas ciber-físicos e da internet aplicados ao ambiente de manufatura, englobando o que denominamos de quarta revolução industrial. Assim, ocorre uma transformação nas fábricas por meio de avanços tecnológicos nas áreas de computação em nuvem, interface homem-máquina, manufatura aditiva, realidade aumentada, robôs autônomos e internet das coisas. A literatura identifica essas práticas como as tecnologias facilitadoras da indústria 4.0. De fato, existe a possibilidade de a indústria 4.0 se propagar para o setor de manufatura utilizando robôs colaborativos, que oferecem a possibilidade de um ambiente de trabalho em condições seguras ao lado do ser humano, aplicado em um espaço de trabalho compartilhado em um ambiente de produção. Dentro dessa perspectiva, as Pequenas e Médias Empresas (PMEs) estão enfrentando diversos desafios em relação às grandes organizações para adotar tecnologias avançadas nesta nova era industrial. Centrado na literatura, o objetivo desta tese foi apresentar uma abordagem de viabilidade técnico-econômica para avaliar a viabilidade do uso de robôs colaborativos em um ambiente de trabalho compartilhado, com foco em PMEs brasileiras. Quanto à metodologia, este trabalho teve uma abordagem qualitativa. Um estudo de caso industrial em escala real foi realizado para demonstrar o desenho do modelo conceitual proposto, seguido de entrevistas realizadas com especialistas do setor industrial por meio do método Delphi para certificar o modelo conceitual. Os resultados deste trabalho incorporam contribuições para a comunidade acadêmica e industrial. Em primeiro lugar, acrescenta novos conhecimentos ao corpo da literatura, pois traz um novo procedimento para certificar a viabilidade da adoção de robôs colaborativos por PMEs, o que foi uma lacuna identificada na literatura específica. Além disso, esta pesquisa pode ser usada por profissionais do setor da indústria para realizar uma abordagem de viabilidade por meio de um modelo fácil de usar, buscando avaliar a confiabilidade da implementação da tecnologia de robôs colaborativos.

Palavras-chave: Robô colaborativo, Pequenas e Médias Empresas, Indústria 4.0, Viabilidade técnica; Viabilidade econômica, Modelo conceitual

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

CNI	*Conselho Nacional da Indústria*
Co_2	Carbon dioxide
Cobot	Collaborative robot
CPS	Cyber Physical Systems
DPP	Discounted Payback Period
EMA	Editor for manual assembly activities
EU	European Union
HG	Hand guiding operation
HRC	Human-Robot-Collaboration
I 4.0	Industry 4.0
IFR	International Federation of Robotics
IIoT	Industrial Internet of Things
IRR	Internal Rate of Return
IoT	Internet of Things
ISO	International Organization for Standardization
IT	Information Technology
KRNW	knowledge resource nomination worksheet
MARR	Minimum Attractive Rate of Return
NPV	Net Present Value
PFL	Power and force liming
PLC	Programmable Logic Controller
PRISMA	Preferred Reporting Items for Systematic Review and Meta-Analysis
RFID	Radio Frequency Identification
ROI	Return Of Investment
SEBRAE	*Serviço Brasileiro de Apoio às Micro e Pequenas Empresas*
SMEs	Small and Medium-sized Enterprises
SMS	Safety-rated monitored stop
SSM	Speed and separation monitoring
TAM	Technology Acceptance Model
UN	United Nations

TABLE OF CONTENTS

1 INTRODUCTION

The introductory chapter presents the direction of this dissertation. The following sub-sections highlight the scenario where the theme is located and provide the context prevailing the field area connecting it to the research gap of this work. Then the statement of the research problem is made, followed by the research objectives. Further, this chapter describes the research justification and the dissertation outline.

1.1 BACKGROUND

Organizations are continuously facing techno-economic challenges, and new technological concepts are being presented to support modern business development. The new technological concepts enable the development of manufacturing companies, including their performance and competitiveness (ÖZDEMIR; HEKIM, 2018). Such new technologies emerge with modern manufacturing and they are driven by the so-called Industry 4.0 (I 4.0), which refers to the fourth industrial revolution, a term that has been used since 2011 to describe the broad integration of information and communication technologies in an industrial manufacturing environment (QIN; LIU; GROSVENOR, 2016, DRATH; HORCH, 2014).

Nowadays, Industry 4.0 calls for the reorganization of the manufacturing production systems, focusing on flexible collaborative work cells. Under such circumstances, the increasing interest in collaborative robotic cells for assembly or fabrication has led to their inclusion Industry 4.0 enabling technologies (BRUNO; ANTONELLI, 2018). The implementation of Industry 4.0 has been mostly developed in large companies (MASOOD; SONNTAG, 2020), and the adoption of I 4.0 in production could help Small and Medium-sized Enterprises (SMEs) from the industrial sector to increase performance and competitiveness (PECH; VRCHOTA, 2020).

In such a scenario, advanced robotics set the needed standards for assessing a country's technological innovation level and manufacturing maturity stage (WANG; TAO; LIU, 2018). The idea that an industrial robot can take roles, cooperate, and support human workers in a shared workspace are part of an Industry 4.0 paradigm and envisions smart factories in which humans and robots will work ever closer (WEISS et al., 2016). In fact, collaborative robots (cobot) could be an alternative industrial process to support the development of manufacturing companies. The inclusion of the Human-Robot-Collaboration (HRC) in the shop floor introduces an alternative to fill the constraint of automation solutions in SMEs (CENCEN; VERLINDEN; GERAEDTS, 2018). This work contributed to the theory identifying a gap in the use of cobot in SMEs offering an approach that summarizes the literature and allows advanced technology practices in such field of industry. Besides, this dissertation explores a scenario where robots and humans can share the same workspace in a collaborative mode (IBARGUREN et al., 2015, KRÜGER; LIEN; VERL, 2009), which is presented in Chapter 2. It aims to advance the academic literature on the use of collaborative robots in SMEs.

1.2 RESEARCH CONTEXT AND GAP FORMULATION

Despite the progress in research about industrial robots since their introduction in manufacturing in the early 1960s (BALLARD et al., 2012; WALLÉN, 2008), the SMEs are not familiar with robots, because they traditionally consider the industrial robots as complex equipment, with a high initial investment, expensive to install and requiring specialized maintenance (BOGUE, 2016). Those facts are considered as barriers to adopt this solution as a new and innovative practice in SMEs (MOEUF et al., 2018, BOGUE, 2016). Moreover, in the field of advanced robotics, where this research is located, the current methods and approaches to investigate, develop, and explore the use of cobots mentioned in the literature are concentrated mainly in large corporations (MOEUF et al., 2018). Generally, SMEs has only recently started to explore the HRC on the shop floor. In fact, the findings obtained from academic research papers to develop this work indicated a gap in terms of the use of cobot in SMEs (MOEUF et al., 2018, ZANCHETTIN et al., 2015).

A systematic literature search, which is being described in Chapter 2, was performed through an extensive literature evaluation covering several digital academic databases, to identify articles related to the techno-economic feasibility studies to implement collaborative robots in Small and Medium-sized Enterprises. The findings resulting from this pursuit indicate a small number of papers related to the cobot utilization in the SMEs environment (OBERC et al. 2019; FACCIO; BOTTIN; ROSATI, 2019, ACCORSI et al. 2019, MATEUS et al. 2020). Besides, many authors have usually investigated either technical (AKKALADEVI; PLASCH; PICHLER, 2017; FACCIO; BOTTIN; ROSATI, 2019) or economic (MOEUF et al., 2018; ZANCHETTIN et al., 2015) approaches to deploying a cobot in a SMEs manufacturing environment, but not a combination of both. Nevertheless, none of the selected articles refer to developing countries, particularly Brazil. Additionally, it is known that the characteristics of SMEs in Brazil are quite different from those observed in the countries to which the above articles relate (LUCATO et al., 2017). Consequently, the absence of works related to the study of the techno-economic aspects linked to the utilization of cobots in developing countries are a research gap that this dissertation proposes to fulfill.

1.3 PROBLEM STATEMENT AND RESEARCH QUESTION

Therefore, the problem statement to guide this work aims to provide an approach to support SMEs to justify the adoption of collaborative robots in a shared workspace in terms of economic and technical characteristics to fulfill the research gap identified. The basic ideas behind the problem statement of this dissertation are those concepts related to the Human-Robot-Collaboration in a shared workspace (BRUNO; ANTONELLI, 2018; WANG; TAO; LIU, 2018; WEISS et al., 2016; PEREIRA; ROMEIRO, 2017; IBARGUREN et al., 2015; KRÜGER; LIEN; VERL, 2009). In consequence of the issues raised above, this work addresses the following research question:

RQ. *How to develop a techno-economic feasibility approach to implement collaborative robots in Small and Medium-sized Enterprises in Brazil*?

1.4 OBJECTIVES

Hence, the general research objective of this dissertation is to develop a techno-economic feasibility approach to implement collaborative robots in SMEs focusing on Brazil.

To accomplish that, several specific objectives are considered as follows:

a) Technical criteria identification;

b) Economic criteria identification;

c) Conceptual model for techno-economic feasibility;

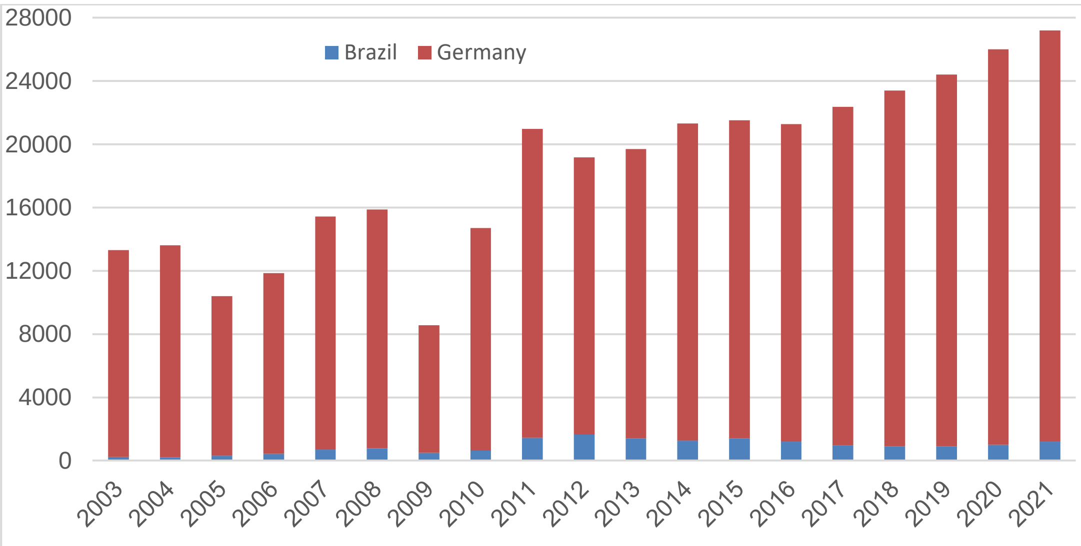
d) Calibration of the conceptual model throughout the Delphi method.

1.5 RESEARCH MOTIVATION AND JUSTIFICATION

First, a factor that motivates and influences this research is related to the number of industrial robots installed in Brazil. According to the International Federation of Robotics - IFR (2019), since 1999 there are approximately 13,700 units of industrial robots installed in Brazil, being the automotive industry responsible for 44% of that total.

According to the report from IFR (2019), the average global density of industrial robots in 2018 was around 99 robots per 10,000 employees. In Germany, the density is around 338 robots per 10,000 employees while in Brazil the robot density is barely 10 robots per 10.000 employees. Furthermore, Brazil occupies the 21st position in the global ranking, with 1,207 robots installed in 2018. From Germany's perspective only, this number was almost 24,000. These figures indicate that there are plenty of opportunities in Brazil for the expansion of robotics, especially in SMEs. Figure 1 shows the evolution of robot sales in the country since 2003, indicating that it can be considered as an emerging market for this technology. Nevertheless, Figure 1 also reveals the comparison between the units of industrial robots sold in Brazil and in Germany, showing an awesome difference between both countries.

Figure 1 – Sales of industrial robot – unit volume comparison



Source: Adapted from IFR (2019).

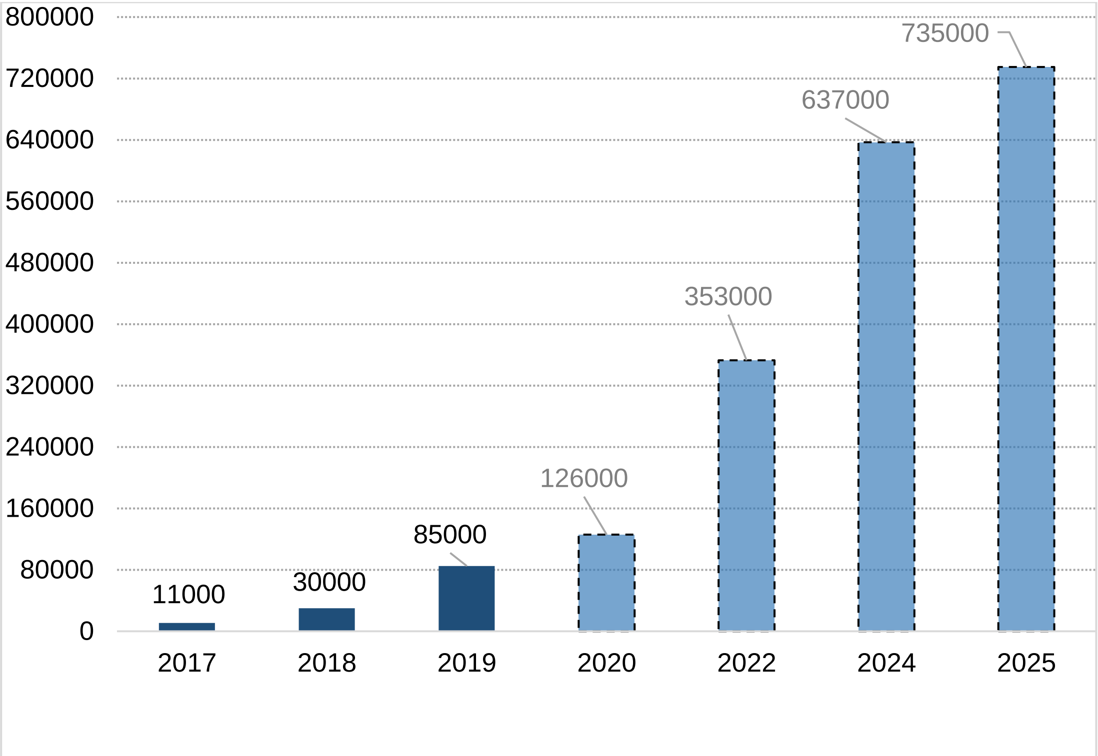
The second motivation to justify this work is focusing on the applicability of the industrial robot, especially considering the challenges to build a collaborative robotic system based on HRC. Likewise, cobots are still not widespread in the manufacturing industry in general due to the lack of examples of their full potential achievement and safety issues for their acceptance of the human co-worker (WEISS et al., 2016; BDIWI; PFEIFER; STERZING, 2017; TSAROUCHI; SOTIRIS; CHRYSSOLOURIS, 2016). Furthermore, advanced robotics involve several technologies, including automation, sensors, computing, and artificial intelligence, being considered as an advanced technology necessary for the industry development into the digital environment (WANG; TAO; LIU, 2018).

Thus, the introduction of cobot technology in manufacturing allows different phases of the production process to share tasks between humans and robots, as well as to save the human workers from repetitive and monotonous tasks, engaging them in high value-added activities (IBARGUREN et al., 2015). The collaborative robots offer advantages over conventional industrial robots (BLOSS, 2016; CERIANI et al., 2015; MICHALOS et al., 2014) as they provide lower installation costs due to the no requirement of safety fences and other protection devices, which are necessary for a typical industrial robotic cell (BOGUE, 2016).

Bogue (2016) argues that other benefits can be identified in the implementation of collaborative robots such as the reduction of physical installation layout, easier robot programming that reduces commissioning time and costs, a quick adaptation to new tasks, and lower capital investment, around € 20.000,00 to € 40.000,00. These features are particularly attractive for Small and Medium-sized Enterprises. In addition, according to Bogue (2016), around 2.3 million small and medium European companies are expected to lead the adoption of collaborative robots in the short term, indicating the importance of this technology for SMEs in Europe. However, there is no similar research in Brazil, which could be also an opportunity to foster the utilization of the cobot by SMEs in the country, by providing a tool to make the techno-economic evaluation of this technology an additional incentive for its adoption.

The projections of IFR (2019) for the collaborative robot sales foresee an important growth in this specific market. The IFR (2019) reported that the demand for collaborative robots would reach around 37% of the total industrial robot market by 2025. Figure 2 shows the forecast demand for collaborative robotics in the coming years, which translates into a 71% average annual growth rate in the next four years. Considering the insignificant number of cobots used in Brazil (VIDO; LUCATO; MARTENS, 2019), these projections imply that for being part of the competitive global market, the country should also increase substantially the adoption of said technology. Thereby, an approach that would demonstrate the techno-economic feasibility to embrace the utilization of cobots in the Brazilian industry could be of significant support in that direction.

Figure 2 – Sales of collaborative robot – unit volume forecast



Source: Adapted from IFR (2019).

The literature search on HRC has shown few publications on the use of collaborative robots when considered their application in Small and Medium-sized Enterprises (MOEUF et al., 2018). Specifically, in Brazil, where these companies seem to have no clear strategy, facing financial barriers and competitive constraints, there is a need to develop more research focusing on the utilization of cobots in SMEs (OLIVEIRA; TAN; GUEDES, 2018, THÜRER et al., 2014). Therefore, they could use those investigations to create production flexibility and increased speed, quality, and agile deliveries (NAIR; KUHN; HUMMEL, 2019).

The third justification of this dissertation is related to the SMEs themselves. They are considered the cornerstone of the economy of most countries around the world, due to their important role in manufacturing, being responsible for most of the employment generation in that sector (THÜRER et al., 2014, CASADO-BELMONTE et al., 2020, ALKHORAIF; RASHID; MCLAUGHLIN, 2019). According to Brazilian Micro and Small Business Support Service (SEBRAE), Brazil embraces more than 6 million Small and Medium-sized Enterprises, from which over 99% are micro and small companies. They are responsible for 52 % of the country's formal employment, representing more than 16 million employees. Work performed by Massod and Sonntag (2020) indicated that the SMEs' challenges are mainly related to how to stay competitive, seeking solutions related to innovation, digital, internationalization, and workforce training to reach a new industrial competitiveness level.

Therefore, the implementation of new technologies in SMEs manufacturing companies is another motivation for this work. The emerging concept of Cyber-Physical-Systems (CPS), which are controlled by the advanced resources such as computer-based algorithms, analytics, connectivity, and business intelligence (HERMANN; PENTEK; OTTO, 2016), should be the next challenge for SMEs, especially in Brazil. In fact, Industry 4.0 (I 4.0) represents an opportunity for integration between these systems and the industrial organizations, besides presenting itself as a new stage in the development of industries (MASOOD; SONNTAG, 2020, QIN; LIU; GROSVENOR, 2016). I 4.0 has been defined as a set of resources that seeks to computerize manufacturing through real-time communication between humans, machines, and the management of the company (DRATH; HORCH, 2014).

In fact, with the advent of Industry 4.0 and it is expected that the adoption of smart factories, all potentially unhealthy and repetitive tasks in an assembly workstations are going to be eliminated from human responsibility and transferred to collaborative robots, which are able to perform such tasks faster and without human supervision (ÖZDEMIR; HEKIM, 2018). That is why cobots are identified as an enabling technology of I 4.0 (BRUNO; ANTONELLI, 2018; WANG, TAO; LIU, 2018; TSAROUCHI; SOTIRIS; CHRYSSOLOURIS, 2016; PEDERSEN et. al., 2016), and provide a viable solution to make the work between humans and robots compatible (VASIC; BILLARD, 2013; KOOTBALLY, 2016).

Another important motivation for this work relates to the restrictions of SMEs to have access to digital technologies. Since the introduction of Industry 4.0, SMEs has remained with a low level of I 4.0 related applications (QIN; LIU; GROSVENOR, 2016, DRATH; HORCH, 2014). This is especially true considering both SMEs manufacturing issues and its management perspectives (MASOOD; SONNTAG, 2020, MODRAK; SOLTYSOVA; POKLEMBA, 2019, THÜRER et al., 2014). An industrial survey related to the SMEs performed by Masood and Sonntag (2020) in the United Kingdom, indicated that there is a gap between Industry 4.0 and SMEs, basically related to financial barriers and financial performance. The survey indicates also the limited technical resources faced by SMEs, including personnel skills to deal and learn about digital technologies and little interest to adopt them. As stated at the beginning of this chapter, understanding, and identifying key techno-economic feasibility approach for the utilization of collaborative robots in SMEs industrial companies, could be a way to support Brazilian SMEs to enhance their insertion in the digital era and foster their competitiveness.

1.6 THEME DELIMITATION

This dissertation focuses on developing a techno-economic feasibility approach to implementing collaborative robots in Small and Medium-sized Enterprises. To perform this research, this sub-section describes its delimitation in scope to better define the research boundaries. The selection of the country where the research was developed is the first delimitation of this work. In fact, the reason to perform the research in Brazil relies on two main motives; a) easy to access to National data; and b) According to the *Conselho Nacional da Indústria* (National Industry Council) – CNI (2018), the manufacturing industry contributes to 12% in the Brazilian GDP, and that sector is responsible for 62% of investments in research and development in the private sector. Furthermore, the industrial segment is responsible for 15% of formal employment and 42% of goods exports. These data indicate that the Brazilian industrial sector is relevant to the country's economy, besides its potential growth for the application of industrial robots in Brazilian manufacturing, which is eager to increase its productivity and competitiveness.

The second delimitation refers to the definition of the robot type. Among several possibilities, this work focuses on collaborative robots only and the related HRC. For the data collection in the field research, this work selected a scenario where the cobot is incorporated into an industrial environment as part of a collaborative workstation design. From the previous discussion, there is a need for novel techniques to improve the use of collaborative robots in SMEs (MASOOD; SONNTAG, 2020; CENCEN; VERLINDEN; GERAEDTS, 2018; MOEUF et al., 2018). Also, in manufacturing, HRC is one of the promising opportunities for the development of industrial robotics applications in the future (CERIANI et al., 2015) since the increase of automation and workstation modernization allow for productivity and efficiency gains in manufacturing facilities.

Moreover, following the specific research context, all research themes related to safety, such as collision avoidance systems, artificial vision systems, motion-capturing systems, safety regarding traditional industrial robot work cell, e.g., safety fences, and warning signals are out of the scope of this work. Besides that, any negative impact on the acceptance and use of the robot by end-users are not the subject of this dissertation.

1.7 METHODS

For the purpose of this work, to conduct the systematic literature search showed in Chapter 2, a set of academic digital databases was selected to identify and evaluate prior scientific works in the field of study (DRESCH; LACERDA; ANTUNES, 2015). In order to gather relevant information and documents, search composition terms referred to the literature gap were selected. This work adopted the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA), (Moher et al., 2009) to conduct different phases of the literature review, allowing a systematic process to conduct the documentation analysis and revision.

To answer the research question, this work adopted a two-round interview with experts, which were performed through the Delphi technique, once it is a toll of exploratory qualitative research (HALLOWELL; GAMBATESE, 2010), and allows reaching consensus among experts from the industrial sector (OKOLI; PAWLOWSKI, 2004). The use of the Delphi technique showed in Chapter 4 has allowed the researcher in acquiring insight from scholars and practitioners to verify statements and observations (SAMPIERI; COLLADO; LUCIO, 2013) to validate the conceptual model proposed in this work and to generate a best practice feasibility model. The procedure for selecting experts applied to this work was generated based on the knowledge resource nomination worksheet (KRNW) to enable potential candidates and organizations prior to the final panel selection (MURPHY; PERERA; HEANEY, 2015). Hence, the KRNW was built based on four focus-group disciplines from the industrial sector, including academics, experts in robotics, and end-users.

1.8 DISSERTATION OUTLINE

The structure of the research comprised seven chapters, including this introduction. Chapter 2 focuses on a systematic literature review related to the knowledge and research efforts that relate to this work. It explores the industrial robot's historical milestones and presents an introduction to the SMEs' characteristics. Further, it introduces the collaborative robot focusing on Human-Robot-Collaboration, and their potential applications. Then issues associated with the implementation of collaborative robots in SMEs are explored in detail. This chapter goes through the state of the art in collaborative robots, the challenges, and feasible automation solutions for SMEs, and describes the models identified in the literature to perform techno-economic feasibility analysis of cobot implementation. Moreover, this Chapter introduces the methods for literature review.

The conceptual model to investigate the research question is explained in Chapter 3. It introduces a novel and innovative model to perform a Techno-economical approach to implement collaborative robots in SMEs in Brazil. Moreover, a full-scale industrial case study was performed to demonstrate the conceptual model.

The methods and data acquisition techniques chosen to answer the research question are presented in Chapter 4. It explores the research field, including data collection and the structure of expert panels and interviews. The field research procedures and testing are outlined in detail.

Chapter 5 shows the findings from the data collected and provides a final version of the proposed conceptual model adjusted to the recommendations resulting from the field.

Chapter 6 discusses the results in the face of the extant literature and the observations of the researcher, the consequence of the entire research process.

Finally, Chapter 7 presents the dissertation conclusions, the research contributions to the theory, practice, and society, the work limitations, and suggests a future research agenda to expand what was found and established herein.

2 LITERATURE REVIEW

This chapter provides a review of the related work, including applications and research that have supported the implementation of collaborative robots in the manufacturing sector. It describes previous works and different approaches presented by other researchers on which the dissertation’s theme is located. First, this chapter has an introductory section dedicated to the historical milestones of industrial robots and the literature related to the state-of-the-art in collaborative robots. It also includes a subsection focused on the benefits, challenges, and safety issues of the Human-Robot-Collaboration. The main characteristics of SMEs are described in this chapter. Finally, a specific sub-section provides a complete overview of the extant literature dealing with cobot feasibility evaluations.

2.1 BUILDING UP THE INDUSTRIAL ROBOT ERA

The aim of this section is to highlight the development of the industrial robot with a short introduction to its history, highlighting what the academy investigated regarding its development and applications in the manufacturing sector.

2.1.1 Deployment of industrial automation

Ever since the first industrial revolution started in the 18th century, industrial automation has been a major force when organizations tried to rationalize the production process to replace manual work in manufacturing factories (WALLÉN, 2008). The introduction of machines in the production lines was one of the most important events of the second industrial revolution (FERNANDEZ et al., 2012). According to Jovane, Koren and Boer (2003), the automation of industrial factories could be characterized as a key driver of manufacturing and it has been present in industries since the beginning of the second industrial revolution era. Moreover, Fernandez et al. (2012) point out that the implementation of industrial automation on the shop floor has resulted in an increase in productivity, allowing the industry to meet society's growing demands in the early days of capitalism.

Pushed by the industrial automation growth described above, the industrial robot emerged in the early 1950s, as a perspective for automation solutions in a production environment (GASPARETTO; SCALERA, 2019). It was driven as a solution for the demand that occurred due to the growth of industrial automation in the manufacturing sector. Besides the increasing demand for automation, the development of the industrial robot was possibly also through the emerging of the digital computer, which occurred in the 1950s, at the same time the first industrial robot was developed (FERNANDEZ et al., 2012). The advent of the integrated circuit, which has its development early in the 1970s, has contributed to the industrial robot development, as well.

2.1.2 The UNIMATE robot

Due to concerns about human tasks in the production environment, an American inventor called George Charles Devol Jr. created the world's first industrial robot, named UNIMATE (FERNANDEZ et al., 2012, GRAU et al., 2017). It focused on the hazardous tasks performed by humans in production lines, especially where humans were often forced to operate in no ergonomic, cramped, dirty conditions, and surrounded by toxic chemicals and defective or unsafe machinery (BALLARD et al., 2012).

The UNIMATE, which represents the early stage of current industrial robot technology, was the first robot used in manufacturing. In fact, they were introduced in the American market in 1961, using the automotive industry as a gateway (BARD, 1986). The utilization of the UNIMATE transformed the manufacturing environment, especially in the automotive industry in the USA (BALLARD et al., 2012, GRAU et al., 2017), when General Motors, introduced the UNIMATE in its New Jersey plant to operate die-casting machines, which were not adequate for humans, releasing them from risky and harmful tasks. (GARCIA et al., 2007).

Table 1 shows the most relevant industrial robot’s technological milestones since the UNIMATE was introduced in 1961. This phase is recognized as “The first industrial robot age”. The increase in competition and the design of the lightweight robots and their integration with computer and Programmable Logic Controller (PLC) are defined as “The second industrial robot age”. Finally, the milestones highlight “The third industrial robot age” which comprises of the advent of the heavy-duty robot payload and the introduction of advanced robotics or collaborative robots on the assembly line as an alternative for hybrid systems (GRAU et al., 2017).

Table 1 – The industrial robot technological milestones

Year	The first industrial robot age
1954	George Devol's patent filed and granted in 1961
1961	UNIMATE robot is installed at GM plant in the USA
1967	The first VERSATRAN robot was imported to Japan (UNIMATE competitor)
1967	The first industrial robot in Europe, a UNIMATE robot, is installed at Metallverken, Uppsland Väsby - Sweden
1969	Kawasaki develops the Kawasaki - Unimate 2000, the first industrial robot produced in Japan, under license from UNIMATION corporation
	The second industrial robot age
1969	Development of Stanford's arm - the first lightweight, all-electric multi programmable robotic arm with six degrees of freedom, designed by Victor Scheiman from Stanford University
1973	About 3,000 industrial robots are in use around the world, improving the way workplaces operates every day.
1974	Robots are applied to load and unload, spot welding and paint spraying applications
1975	ASEA over in Europe developed the ASEA IRB in 1975 that is the first fully electric driven robot.
1978	Unimation presents the PUMA robot arm (Programmable Universal Machine for Assembly), design to duplicate the functions of the human worker
1979	Yamanashi University designs the Selective Articulated Robot Arm (SCARA) for assembly jobs in industrial factories
1981	Kawasaki develops its own electric robots (P Series)
1981	Westinghouse acquires Unimation
1982	Fanuc (Japan) and General Motors (USA) build a joint venture to manufacture and sell robots in North America
1886	Kawasaki terminates its long-term relationship with Unimation and develops and produces its own line of electric robots
1988	ASEA robots become known as ABB robots
1989	Stäubli group purchases UNIMATION from Westinghouse
	The third industrial robot age
1994	Yaskawa Motoman - Japan, introduces the robot control system. Editable from an ordinary desktop PC, the MRC made it possible to control up to 21 axes
1998	Robots are increasingly used for laser cutting, precision wire cutting, plastic injection mold, quality control
1998	Motoman introduces the XRC controller allowed the control of up to 27 axes and the synchronized control
1998	ABB - Sweden, launches the FlexPicker, the world's fastest picking robot
1998	OTC DAIHEN introduces the Almega AX series, a line of arc welding and handling robots
2003	KUKA is the first robot manufacturer to bring people and robots into close contact: in the Robocoaster, the robot whirls passengers around
2003	Developed in cooperation with the Institute of Robotics and Mechatronics in Germany, the outer structure of the KUKA lightweight robot is built in Aluminum

Table 1 (Continued)

2005	Universal Robot launched in Odense – Denmark the UR robot. Such robot will eventually be known as the pioneer of the cobot or collaborative robot in the market
2007	KUKA - Germany, launched the first long-range robot and heavy-duty robot with a payload of 1,000 kg
2008	FANUC - Japan, launched a new heavy-duty robot, M-2000iA, with a payload of almost 1,200kg
2012	Amazon purchased the robotics company Kiva Systems, using autonomous mobile robots to automate the material handling in its warehouses
2016	AUDI, BMW, Daimler increasing use of a very lightweight robot and collaborative workstation
2020	Virtual reality, virtual commissioning, vision systems are supporting new industrial robot applications in the manufacturing sector

Source: Adapted from Grau et al. (2017).

2.1.3 Industrial robot definitions

Obviously, one of the first definitions of the term industrial robot was given by George Devol in 1954, proposing that “a robot could be a more or less general-purpose machine that has universal application to a vast diversity of applications where cyclic digital control is desired” (BALLARD et al., 2012). Since then, the literature gathers several definitions regarding industrial robots. The work conducted by Bard (1986) explored the advances in robotics that occurred in the 1970s to define the term industrial robot as “a multipurpose machine composed of three interdependent components; manipulators, a power supply, and a controller.” Still, according to Bard (1986), the manipulator consists of linkages and joints that provide motion along different axes and usually have three degrees of freedom. A hydraulic system comprising an electrical pump, filter, reservoir, and heat exchanger is the most popular power supply for the robot. A robotic manipulator, or robot arm, is a serial chain of rigid limbs designed to perform tasks with its gripper. Work performed by Li et al. (2020) represents the latest update in robotics and defines the industrial robot as “a type of Mechatronic product containing multiple field components such as machinery, electronics, control unit, and computer.”

According to the Robotic Industries Association – RIA (2020), “*the industrial robot is a programmable, mechanical device used in place of a person to perform dangerous or repetitive tasks with a high degree of accuracy*.” The International Federation of Robotics - IFR (2019), refers to the International Organization for Standardization (ISO 8373:2012) to define the term industrial robot, which describes it, “*as an automatically controlled, reprogrammable, multipurpose manipulator* *programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications*".

Another robotics association, the British Automation & Robot Association (BARA, 2020) widens the definition: "*designed to both manipulate and transport parts, tools, or specialized manufacturing implements through variable programmed motions for the performance of specific manufacturing task*s". Furthermore, the industrial robot is characterized by a complex structure, long lead times, and high manufacturing costs.

2.1.4 Industrial robot: application areas

The basic idea George Devol wrote in his U.S. Patent 2,988,237 was to adopt robots to first deal with dangerous and monotonous tasks, being devices that could perform repetitive tasks with more precision and repeatability than human workers could do. The industrial robot can also perform tasks at a lower cost, and finally, they can be allocated to other production tasks if required (BALLARD et al., 2012). The later incorporation of industrial robots into other types of production processes besides manufacturing, added new requirements for more flexibility and intelligence in industrial robots (GARCIA et al., 2007), since they became designed to handle objects and interact with their environment, mainly during tasks such as polishing, milling, assembling, pick and place, welding, painting (KIM et al., 2013). In an industrial scenario, robots are used to reduce costs, increase productivity, improve product quality, and eliminate no ergonomic and harmful tasks for humans (WALLÉN, 2008).

In recent years, the academic research in industrial robots has focused on solving a variety of tasks requiring sophisticated motion in complex environments. Brogardh (2007) focuses on examples of development areas that get attention in multi-robot control, safe control, force control, 3D vision, remote robot supervision, and wireless communication. Garcia et al. (2007) explored the influence of the automotive industry in the development and specification of industrial robots to cover their technical product requirements. The authors mentioned studies in the kinematic calibration, which is a necessary process due to the inaccuracy of kinematic models based on manufacturing parameters, and in motion planning, wherein sub-goals are calculated to control the completion of the robot's task. Ha (2008) developed a calibration method for an industrial robot using a laser sensor to measure the distance between the robot tool and the measurement surface. In that method, the sensor is incorporated into the robot gripper. This method can calibrate the robot without calibrating the transformation from the world coordinate system to the robot base coordinate system.

Following the current issues and trends related to industrial sustainability, several works have been presented in the domain of industrial robots as well. Pellicciari, Berselli and Leali (2013) proposed a method for reducing the total energy consumption of sorting and picking robots. Brossog, Bornschlegl and Franke (2015) argued that the reduced energy consumption of an industrial robot would automatically reduce operating costs and carbon dioxide (CO_2) emissions, focusing on green production systems. The authors proposed a method of energy reduction based on theoretical, experimental, or modeling and simulation approaches. According to Gadaleta, Pellicciari and Berselli (2019), energy consumption strongly affects the financial payback period of industrial robots, as well as the related manufacturing process sustainability. The authors have proposed the optimization of energy efficiency of a robotic cell by means of digital manufacturing tools, such as the Internet of Things (IoT), Industrial Internet of Things (IIoT) to explore and analyze process data (GRAU et al., 2017).

In summary, the main motivation of increasing investment in automation of assembly systems is concentrated on improving its utilization (workload and capacity), save space on the shop floor (compact cell solutions), and improve the return on investment. Those represent challenges presently faced by manufacturing companies (LJASENKO et al., 2019).

2.2 REVIEW ON HUMAN-ROBOT-COLLABORATION (HRC)

This section provides an overview of collaborative robots, the state-of-the-art, and their potential applications.

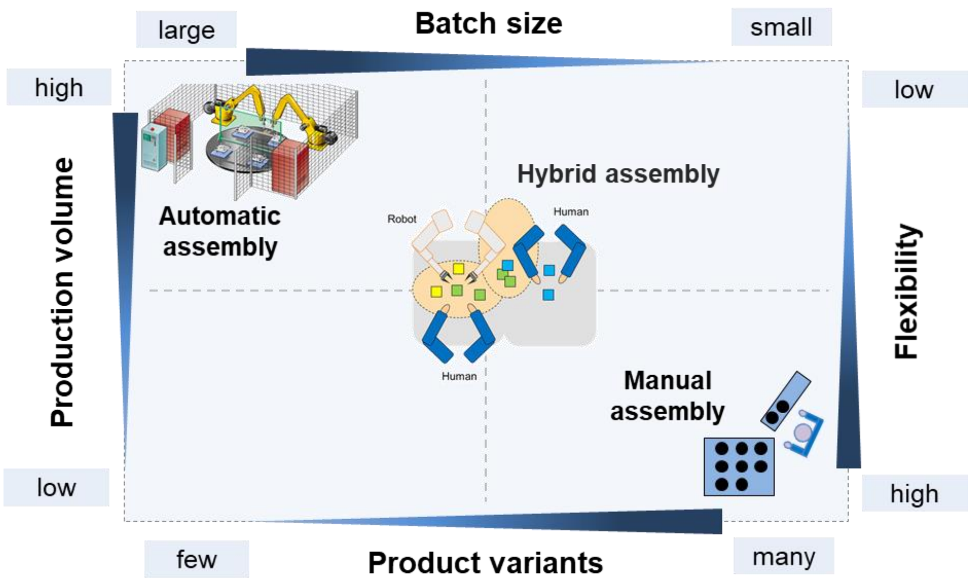
2.2.1 Hybrid assembly systems

In terms of assembly systems applied to production automation solutions, Krüger, Lien and Verl (2009) classified the hybrid assembly cells as workspace and time-sharing. Normally, the number of types of assembly processes described in the literature is classified as manual, semi-automatic or hybrid, and fully automatic systems

(GROOVER, 2017; LOTTER, 2012). Within this classification of assembly process types, Groover (2017), Lotter (2012), and Takata and Hirano (2011) indicate that an automatic system is the right decision for a large production volume, but it should be combined with a smaller number of product variants. Normally this type of process is indicated to handle complex parts (TAKATA; HIRANO, 2011), with the disadvantage of being not flexible to add different products in the line (CHEN et al., 2013). In the manual assembly process, Lotter (2012) argues that such a solution achieves around 30% to 50% of the total production time and represents a high-cost contribution. The hybrid system, on the other hand, has been generating a competitive advantage in the industry for more than two decades (LIEN; RASCH, 2001).

The hybrid system is one of the most relevant production solutions (CHEN et al., 2013), as the current manufacturing process requires shorter production cycle times combined with different product requirements, including customization (WANG et al., 2017). The hybrid system is the ideal solution when medium/low volumes and a wide set of different models are required to use production lines designed to reach flexibility and efficiency in a single system (PAOLI; OLIVEIRA NETO; LUCATO, 2013; ROSATI et al., 2013). The literature also indicates that the decision-making to select the production process type is related to the batch sizes, flexibility in production, and the number of product variants (HEILALA; VOHO, 2001; BRUNO; ANTONELLI, 2018; ROSATI et al., 2013), as shown Figure 3.

Figure 3 – Process assembly framework



Source: Adapted from Heilala and Voho (2001).

According to the framework shown in Figure 3, batch production relies on the manufacturing of different product variants (or models) in batch mode. Once a particular model in a batch is produced, setups are changed to deal with the next models. When high production volume operation is required, automatic production line solutions are recommended. Even when a single product is manufactured with no variation, the automatic assembly line is fully recommended. The hybrid systems (or flexible manufacturing) using cobots as a solution is recommended to produce a variety of products and the capacity to produce the required batch size, improving ergonomic conditions of humans during assembly tasks (SALUNKHE et al., 2019).

2.2.2 The shift to collaborative robot

The industrial robot is a useful equipment to be included in a manufacturing line dedicated to a large production volume, where parts and process flow are automatically handled away from human interference to prevent any contact and hazard, especially those applications in Small and Medium-sized Enterprises (ZANCHETTIN et al., 2015). Technological characteristics such as precision, repeatability, and accuracy are key robot characteristics, as it performs tasks with consistent and repetitive cycle times, including no-ergonomic jobs and dangerous tasks for human operators in unhealthy environments (GROOVER, 2017; WANG et al., 2017; DJURIC; URBANIC; RICKLI, 2016; BROWN; BESSANT, 2003). Appendix 4 details the benefits of cobot and industrial robots.

On the other hand, the industrial robot is limited by its lack of agility, as it is not very flexible to be adapted to other products in the production line (KOOTBALLY, 2016). Besides, the automated line requires more floor space than more conventional approaches (MÜLLER; VETTE; GEENEN, 2017). According to Peshkin et al. (2001), the collaborative robot is defined as a robot designed to physically interact with humans in a shared workspace and fill the gap between a manual and an automatic workstation. Work performed by Krüger, Lien and Verl (2009), indicated that a cobot is a piece of mechanical equipment for application in an assembly line in different types of operations, such as mechanical assembly, screwing, packaging, handling tasks, automotive assembly, electronic part assembly (HENTOUT el at, 2019). The cobot provides Human-Robot Collaboration with possible physical contact. In comparison with a traditional industrial robot, the hybrid automation solution (LOTTER, 2012) with a cobot brings to the shop floor changeability, quality, low cost in use including no need for safety fences and or any special safety devices (ANDRISANO et al., 2012).

New technologies such as special control algorithms, human-machine interface, and integrated sensors to avoid collisions and elevate the safety level are embedded in the current design of those cobots, to provide a quickly reprogramming, flexibility, and human safety. The cobots associate the strength and resistance capacity of the industrial robots with human cognition and decision-making sensing (DJURIC; URBANIC; RICKLI, 2016). The cobot can also provide to the operators the reduction of their ergonomic concerns, which usually arise due to the material handling activities, and at the same time, it improves safety, quality, and productivity (CHERUBINI et al., 2016). Its ultimate objective is to enable collaborative work between humans and robots since cobots are developed to improve the flexibility of industrial processes while reducing operator fatigue (CHERUBINI et al., 2016; BLOSS, 2016; PEDROCCHI et al., 2013).

The cobots are able also to handle low-weight products. However, approximately 45% of the products involve product loads above 15 kg (BOGUE, 2016). The author states that collaborative robots can offer lower installation costs due to the no requirement of safety devices. It can save space in workstations and could allow a quick adaptation to new tasks. Nevertheless, even with sensor technology embedded in the collaborative robots to allow collaborative work, the human is still the fundamental component in the collaborative operations (GROOVER, 2017).

2.2.3 The Rules of Human-Robot collaboration (HRC)

A Collaborative human-robot collaboration (HRC) is a particular kind of operation and it is designed to plan the tasks to be distributed between humans and robots in a collaborative mode in a shared workspace (GERVASI; MASTROGIACONNO; FRANCESCHINI, 2020). Following the authors, the main target of the HRC is to provide direct interaction between a human and an industrial robot in a shared workspace and combine the skills of both together. The HRC in industrial applications seeks to combine the flexibility and adaptability of a human being with speed, accuracy, controllability, even predictability of a robot and transform the workstation in a dynamic environment. The collaborative workspace includes the cobot, end-effector, the part to be handled automatically, and the human co-worker, which is able to perform different tasks simultaneously in direct cooperation, at the same time, and in the same space (SCHOLER; VETTE; RAINER, 2015). The cobot is dedicated to carrying out parts automatically without human intervention (KRÜGER; LIEN; VERL, 2009), and should be controlled adaptively based on the real situation (WANG et al., 2017).

Based on conventional manual work conditions in a manufacturing environment, human and robot tasks could be optimized when the workstation design provides a routine where the human does only what he or she is able to adequately perform and the robot does only the tasks allowed for it, helping each other. In this scenario, there are a cyber-physical system (MARVEL; FALCO; MARSTIO, 2014; SCHOLER; VETTE; RAINER, 2015), to support engineers during the design phase to bring the workstation from its concept to the shop floor reality, collecting data and achieve a reliable robot system safety level (ROBLA-GÓMEZ et al., 2017).

In the past years, the literature presented methods for interaction between humans and robots. According to the work performed by Wang et al. (2019), "*the Human-Robot-Collaboration in a manufacturing context aims to realize an environment where humans can work side by side with robots in close proximity, and share the same workspace and resources*." The shared workspace, including the human and robot task division, is a requirement during the design phase of the collaborative workstation to identify the conditions in which the interaction will be performed, including the process, material flow, space between equipment, parts to be assembled, in-process workpiece flow, batches, logistic planning, material handling, and inventory allocation area (MARVEL; FALCO; MARSTIO, 2014). Many authors summarize in the literature the classification of human-robot collaboration, as follows:

a) **Human-Robot Coexistence**: the robot is not allowed to perform any task if the human operator enters the robot's work zone. This means that all assembly tasks and functions are performed at different times and spaces. The robot work zone is fenced and locked (WANG et al., 2019; MÜLLER; VETTE; GEENEN, 2017; ANDRISANO et al., 2012);

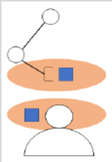
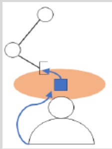
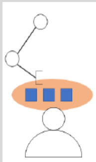
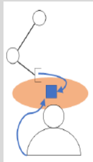
b) **Human-Robot Interaction**: the robot and the human co-worker share the same workspace but there is no direct contact between them. Assembly tasks should be performed systematically and in a planned assembly sequence. No fences or safety devices are required in the workstations (WANG et al., 2019; MICHALOS et al., 2014);

c) **Human-Robot Cooperation** The robot and human co-worker share the same workspace. Physical contact with the human co-worker can occur. Both can work simultaneously, and all assembly tasks and functions are performed in the same workspace, but on separate tasks (WANG et al., 2019; MÜLLER; VETTE; GEENEN, 2017; MICHALOS et al., 2014);

d) **HRC**: The robot and human co-worker share the same workspace and perform the same operation tasks. A collaborative workstation layout configuration is generated, including the equipment, shop floor utilities, product characteristics, and the proposition of an optimal task allocation between human and robot to perform the assembly operations (WANG et al., 2019; SCHOLER; VETTE; RAINER, 2015). The right workload distribution has been taken into consideration, especially those related to the main skills and strengths of both, humans and robots (BRUNO; ANTONELLI, 2018; MALIK; BILBERG, 2019). All assembly tasks and functions are performed at the same workspace, and at the same time (GERVASI; MASTROGIACONNO; FRANCESCHINI, 2020; WANG et al., 2019; MÜLLER; VETTE; GEENEN, 2017; MICHALOS et al., 2014) focusing to mitigate the physical and mental stresses, including an ergonomic evaluation of movements and tasks, to avoid hazards for the human co-worker (GERVASI; MASTROGIACONNO; FRANCESCHINI, 2020).

A risk assessment should be developed to identify the limiting criteria of forces and robot speed in case of a collision (CHEMWENO; PINTELON; DECRE, 2020; GUIOCHET; MACHIN; WAESELYNCK, 2017). The classification of human-robot collaboration is shown in Table 2.

Table 2 – Classification of human-robot collaboration

Subject	**Coexistence** 	**Interaction** 	**Cooperation** 	**Collaboration** 
Workspace	Without overlapping	Sharing the same workspace on collaborative mode	Partially overlapping workspace	Shared common workspace on collaborative mode
Physical interaction	Not planned	Not planned	Cognitive interaction level	Direct interaction
Work tasks	Without overlapping	Share the same workspace at the different time	Share the same workspace at the same time	Share the same workspace at the same time
Task performance	Both works independently of each other	Can work on the same task, but not at the same time	Work in separate tasks	Work on the same task as the robot at the same time
Simultaneous Assembly process	Without overlapping	Sharing the same workspace for task assembly	Partially overlapping workspace for task assembly	Shared common workspace for task assembly
Sequential process	Work separately and independently	Complete the task step by step in sequential order	Direct contact is not typical between cobot and human	To share their different capabilities, competencies and resources
Human skills	Dexterity	Perception / dexterity	Perception / dexterity	Perception / dexterity
Robot skills	Strength, accuracy, repeatability safety devices that can detect the presence of a human operator in the robot's workspace	Cobot to implement with safety- first behavior	Cobot design embedded with force/ vision / presence sensors Strength, accuracy, repeatability	Cobot design embedded with force/ vision / presence sensors Strength, accuracy, repeatability

Source: Adapted from Müller, Vette and Geenen (2017).

Groover (2017) argued that in the collaboration between humans and robots, it is necessary to have the best qualities of both in the workspace, including precision for performing the assembly tasks, cognition for coordinating the workstation, and agility for handling products. Table 3 shown the distribution of the specific skills and characteristics of the human operator and the collaborative robot to combine the best attributes and achieve enhanced efficiency in the process.

Table 3 – Specific characteristics of human and robot to perform assembly tasks

Collaborative robot	Human operator
Very repetitive Easier handling movements Elementary visual verification in a daily routine task	High cognitive skills and reasoning Complex movements and dexterity Very complicated visual verification in a routine task
Fatigue-proof, Reliability Reliable straight forward decision making	Problems with no ergonomic assembly tasks Elaborate decision making, distribution of tasks
Mainly standardized tasks	Flexible adaptability to product variants

Source: adapted from Groover (2017).

Within the issue regarding the shared workspace, Groover (2017) clarified that human operators have certain attributes that give them advantages over the collaborative robot in certain situations and certain types of routine tasks in a collaborative assembly workstation. To achieve the maximum potential for physical collaboration between both, the division of tasks must be planned (SCHOLER; VETTE; RAINER, 2015). According to Tsarouchi, Makris and Chryssolouris (2016), a collaborative operation adds value, as it keeps the production costs at a favorable level and combines the main skills of humans and robots. The collaborative operation improves the production quality indicators, reduced rework, and increased flexibility, efficiency, and ergonomics levels. Besides, a collaborative operation could keep the cycle times and the necessary space very close to the previous manual workstation (TSAROUCHI; MAKRIS; CHRYSSOLOURIS, 2016; SCHOLER; VETTE; RAINER, 2015). Table 4 shows a comparison of the qualities between both in a shared workspace.

Table 4 – Quality and attributes of human and robot to perform assembly tasks

Human operator	Collaborative robot
Feel unexpected stimulus	Execute repetitive tasks consistently
Develop new solutions for problems	Store big quantities of data
Deal with abstract problems	Retrieve memory data reliably
Adapt to changes	Execute multiple tasks simultaneously
Generalize based on observations	Apply intense force and power
Learn with experience	Execute simple calculations fast
Take tough decisions based on incomplete data	Perform routine decisions quickly

Source: adapted from Groover (2017).

In addition to the aspects related to the advanced robotics technology, environmental sustainability related to the safety of human operators in manufacturing gains attention (SCHOLER; VETTE; RAINER, 2015; MARVEL, 2013), because of the need for cooperation between humans and robots in Industry 4.0 applications. Therefore, the safety condition of the human is the main concern in the collaboration between humans and robots in a shared workspace (BDIWI; PFEIFER; STERZING, 2017; CERIANI et al., 2015; PEDROCCHI et al., 2013).

The International Organization for Standardization (ISO - 2020) provides definitions of collaborative work to enable the expansion of applications of collaborative robots in manufacturing. To develop an approach to assess the collaboration between humans and industrial robots, ISO published, earlier in 2016, the ISO/TS 15066 (ISO, 2016) to complement the ISO 10218 (International Safety Standards - parts 1 and 2). Such specifications introduced safety standards to meet the requirements of a collaborative operation (CHEMWENO; PINTELON; DECRE, 2020; GUIOCHET; MACHIN; WAESELYNCK, 2017).

2.2.4 Collaborative workstation layout

In contrast with the traditional manual workstation environment, a collaborative workstation allows the Human-Robot-Collaboration with possible physical contact (HENTOUT et al., 2019; PESHKIN et al., 2001). The proposal of such a concept is to ensure safe, and relieve workers of physical fatigue and enhance their capabilities for cognitive and complex tasks (VILLANI et al., 2018). Figure 4 indicates a shared workspace scenario and demonstrates a cooperative and collaborative mode between human and robot during an assembly task.

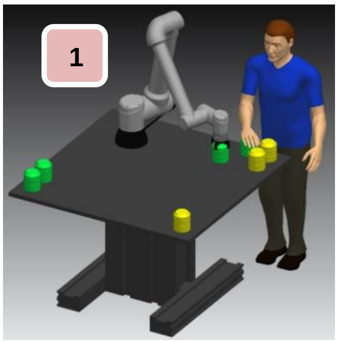
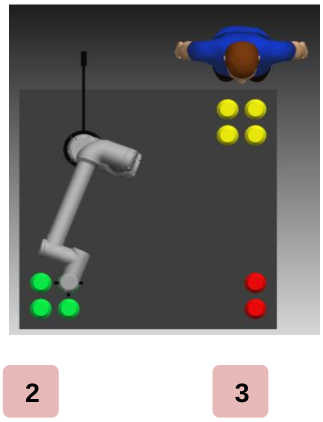
Based on the collaborative workstation shown in Figure 4, in order to start the interaction in the workstation, the human operator entered the collaborative assembly workspace safely. Then, in position #1, when the operator starts working on his assembly task (yellow part) the robot arm brings the other component (green part) called part acquisition (from position #2 or #3) and waits for the operator to request the part. Here the cobot stands in a cooperative mode (WANG et al., 2019; MÜLLER; VETTE; GEENEN, 2017; ANDRISANO et al., 2012; KRÜGER; LIEN; VERL, 2009). Since position #1 is the collaboration area (WANG et al., 2019), the robot is ready for part request and approaches the operator with speed restrictions in a collaborative mode as soon as the operator request the part (SCHOLER; VETTE; RAINER, 2015; MÜLLER; VETTE; GEENEN, 2017).

During the operation assembly tasks, as the physical contact could be possible during the collaborative mode, the human-robot interaction and communication in position #1 are based on human gesture, state recognition control, force control, and advanced sensors. Such concepts are designed to enable the cobot to stop its movement when in proximity to humans, therefore, tracking the human co-worker movements during the collaboration process (WANG et al., 2019; MÜLLER; VETTE; GEENEN, 2017; MICHALOS et al., 2014). A conservative speed limitation related to tool velocity should be less than 250 mm/s, following ISO 10218 (MAGRINI et al., 2020; ZANCHETTIN et al., 2015). Additionally, a vision system embedded in the robot platform, for example, could be an additional safety solution to help the robot to deliver the green part requested by a gesture made by the operator to hand over the part to position #1. Based on the ISO/TS 15066, in the collaborative workspace, contact between and humans and cobot is allowed, but it could not result in pain or injury for the human (CHEMWENO; PINTELON; DECRE, 2020; GUIOCHET; MACHIN; WAESELYNCK, 2017; HULL; MINARCIN, 2016).

When the handover is complete the cobot starts the cooperative mode, where the human and robot are located close to each other, but with no overlapping (WANG et al., 2019; ANDRISANO et al., 2012). Then, the cobot arm moves away from the collaborative workspace into position #2 or #3 to pick up the next part and goes to the position where it will be ready for another part request. In the coexistence mode, the cobot is allowed to run at a high speed to increase the output of the process doing the repetitive or non-ergonomic tasks and frees the operator to finish the assembly and perform other cognitive tasks planed in the production process (MÜLLER; VETTE; GEENEN, 2017).

From the literature, it is possible to identify that the technical specification ISO/TS 15066 aims to apply restrictions and reduce contact during a human-robot interaction in a collaborative operation (CHEMWENO; PINTELON; DECRE, 2020; BDIWI; PFEIFER; STERZING, 2017). In addition, the proposed shared workspace scenario shown in Figure 4 allows the application of the collaboration modes in accordance with the guidelines of the international standards. Besides, this type of cyber-physical system combines a human and a lightweight industrial robot system based on the requirements to assure the application of the four types of collaborative operations.

Figure 4 – Design layout of a collaborative workstation

<table>
<tr>
<td>Position #1:
</td>
<td>Position #1: shared workspace and collaborative tasks
Human and robot work simultaneously and hand in hand
Physical contact between human and robot is possible
▪ Operator executes the cognitive tasks (when skills are required) and decision-making process;
▪ Human enable to predict what movements cobot will take
▪ Cobot executes the repetitive tasks;
▪ Cobot operates at a safely reduced speed or collaborative mode, and in a safe monitored position to reduce impact forces;
▪ Cobot must sense and keep a safe distance from the operator.
Position #1: green & yellow parts assembled</td>
<td rowspan="2">Collaborative operation type - ISO/TS 15066
Risk assessment – EM ISO 12100</td>
</tr>
<tr>
<td>Position #2 and or, #3:
</td>
<td>Position #2; #3: non collaborative workspace
The worker is not present in the shared workspace. Space for load and unload parts
▪ There is no overlap between the operator and the Cobot;
▪ No human physical contact while the robot is moving to handle part in the load station;
▪ Cobot run at a high speed to do a no collaborative task (precision and endurance);
▪ Load parts (position #2) / unload parts (position #3);
▪ No human action is required;
▪ Cobot performance as a typical industrial robot.
Position #2: green part individual
Position #3: red part individual</td>
</tr>
</table>

Source: adapted from Zanchettin et al. (2015) and Robla-Gómez et al. (2017).

The design of the collaborative workstation shown in Figure 4, indicates the HRC considered as a base for the conceptual model described in Chapter 3 for the field research. It is worthy to mention that the conceptual model of this dissertation did not consider workstations such as in machine tending, where only the robot single alone is used as a solution, working as a traditional industrial robot, and thus not working in an HRC mode.

2.3 OVERVIEW ON SMALL AND MEDIUM-SIZED ENTERPRISES

As described before, the implementation of cobot in SME manufacturing companies is one main motivation of this research. This section introduces the main aspects and features related to the SME and introduces international definitions of this kind of company based on the European Union (EU) as a guide to conduct the field research of this work. In addition, this section provides an overview related to the barriers and challenges faced by SME to adopt I 4.0 technologies from an international perspective.

2.3.1 European context of SME

Under international perspective, the Small and Medium-sized Enterprise classification can be categorized following the European Union – EU (the European Union 2003/361), where the SMEs are defined based on either staff headcount, or turnover as shown in the Table 5.

Table 5 – European Union recommendations to define SME

Company category	Staff headcount	Annual turnover
Medium-sized	< 250	≤ € 50 million
Small	< 50	≤ € 10 million
Micro	< 10	≤ € 2 million

Source: European Commission Recommendation of 6 May 2003 concerning the definition of micro, small, and medium-sized enterprises (2003/361/EC), Official Journal of the European Union, L 124/36, 20 May 2003.

Although the EU recommends the classification of an SME based on headcount or on its turnover, for the purposes of this work and to make its field research feasible, only the staff headcount variable will be considered. In fact, the data related to the annual revenue of an organization are often treated confidentially and difficult to obtain, the reason why it was not used in this work as a proxy to classify the SMEs.

As mentioned in Chapter 1, SMEs are the cornerstone of the economy of most countries around the world (CASADO-BELMONTE et al., 2020). As a reference, European economies, including Italy, Croatia, Estonia, and Spain, are basically constituted from SMEs (RAUCH; SPENA; MATT, 2019). In such a scenario, the introduction of Cyber-Physical-Systems through new technologies will be the next challenge for them, once the application of such technologies remains at a low level in that king of companies (QIN; LIU; GROSVENOR, 2016).

Since there is presently a gap between I 4.0 and its utilization in SMEs (MASOOD; SONNTAG, 2020), researchers continue to investigate that relationship. For instance, work performed by Moeuf et al. (2020) conducted a set of business cases with twelve SMEs experts applying the Delphi Method to gather information about risks, opportunities, and critical success factors to implement I 4.0 enablers. Research findings indicated a lack of expertise and a short-term strategy in SMEs. Such results also suggested that robots are not considered as key elements in improving performance. Moreover, the lack of financial resources, quality management systems, no transparency of production process (WUEST; THOBEN, 2011), information technology structure, operational capabilities, single business model and training (DYERSON; SPINELLI; HARINDRANATH, 2016; MÜLLER; VOIGT, 2017) are features faced by SMEs in the global market.

Another barrier collected from the systematic literature review relates to the implications faced by SMEs to automate their manufacturing processes. This is because their business model does not envision the needed flexibility to attend to current mass customization market demands. Therefore, in this business scenario, the SMEs are forced to work with a wide range of products, combined with low batches and high flexibility (LIENENLÜKE et al., 2018, MOEUF et al., 2020), enabling the production of unitary and customized products in larger volumes (CENCEN; VERLINDEN; GERAEDTS, 2018).

The search in the academic literature highlights several challenges SMEs should deal with. Critical success factors come from increased information management culture and knowledge management (WUEST; THOBEN, 2011), personnel resources, financial resources (MÜLLER; VOIGST, 2017), innovation strategy and culture (TERZIOVSKI, 2010), lack of leadership, fact-based decision-making, networking (KUMAR; KHURSHID; WADDELL, 2014), standardization, degree of Information Technology (IT) and digitization (DYERSON; SPINELLI; HARINDRANATH, 2016, MÜLLER; VOIGST, 2017). Table 6 summarizes the main barriers and characteristics in a SMEs environment.

Table 6 – Barriers and characteristics in SMEs

Barriers	SMEs characteristics
Financing resource to invest in technology	Low
Normalization, international standards	Low degree of formalization
Training and skills	Lack of Human resource management
Management strategy	Restricted to the leader
Structural organization	Less complex
Carrier development	High turnover
Leadership	Bureaucratic
Organization flexibility	Low, is driven by the leader

Source: Adapted from Dyerson, Spinelli and Harindranath (2016) and Müller and Voigt (2017).

2.3.2 Brazilian context of SMEs

According to the Brazilian governmental organization to support SMEs called SEBRAE (Brazilian Micro and Small Business Support Service), Brazil totals around 6 million companies and organizations with the relevant fact that 99% of the total are comprised of SMEs. Around 52% of formal jobs in the private sector (around 16 million) are concentrated in SMEs (SEBRAE, 2018). Brazil also encompasses one of the most important automotive production centers in the world, including 22 different carmakers producing passenger cars, trucks, and buses for the local market and exports (VANALLE et al., 2017). The participation of SMEs in Brazil is mostly concentrated in the services sector with a participation of 41%, followed by commerce with 37% participation and Industry with 12% participation (SEBRAE, 2018).

The literature related to the Brazilian SMEs has shown a relevant number of documents in the spectrum of Manufacturing. Meanwhile the specific literature on Brazilian SMEs has addressed initiatives, practices, and issues predominantly in the lean manufacturing and sustainability areas of study. With respect to lean initiatives and practices, a study performed by Godinho Filho, Ganga and Gunasekaran (2016) investigated the degree of lean manufacturing practices implemented in Brazilian SMEs. Oliveira, Tan and Guedes (2018) have highlighted the SMEs importance in the Brazilian economy, and the authors have proposed a study of lean and green practices for the development of new products in SMEs. Stankalla, Koval and Chromjakova

(2018) investigated the critical success factors of Lean Six Sigma and Six Sigma implementation in manufacturing SMEs in Brazil conducting a literature review.

In terms of sustainability sought by SMEs, the work performed by Oliveira Neto et al. (2017) explored the limitations in the implementation of cleaner production in Brazilian SMEs using a literature review to propose a framework to them. Silva and Figueiredo (2020) conducted a case study in a rubber product enterprise to explore the practice of sustainability in supply chain management and the sustainable development goals based on the triple bottom line perspective. De Jesus Pacheco et al. (2018) focused on a list in of sixteen primary determinant factors for the successful adoption of eco-innovation in Brazilian SMEs in proposing a framework of eco-innovation them. Schmidt et al. (2018) identified practices of company sustainability, environment, supplier, customers, and community relationships.

Kaminski, de Oliveira, and Lopes (2008) performed a case study with 32 metal-mechanic enterprises to evaluate product development methodologies used in SMEs. De Oliveira and Kaminski (2012) proposed a model to support small and medium industrial enterprises on new product development and technological innovation, including product differentiation and launching strategy. Work performed by Thürer et al. (2014) proposed a survey to check the competitive priorities and competitive capabilities of SMEs in the manufacturing field. Table 7 shows an overview of the literature focusing on Brazilian SMEs.

Table 7 – Literature on Brazilian SMEs

Authors	Research method	Finds
Silva and Figueiredo (2020)	A five-stage process for case research in a five-stage process in a medium-sized family-owned company that manufactures rubber products used in the health and educational fields	Sustainability occurs, both internally and along the supply chain, through five different practices: cooperating, understanding, deeming, improving, and changing the logic. The practice of sustainability must be constant and based on shared values and principles. Managers need to recognize the elements supporting the learning process to promote sustainability.
Oliveira, Tan and Guedes (2018)	Systemic review in order to identify 16 lean and green enablers for the development of new products. A structured interview consisting of 96 questions were applied in SME as well	16 lean and green enablers for product development: 1-continuous improvement, 2-cross-project knowledge transfer, 3-definition of value and value stream, 4- eco-design tools and green dynamic capabilities, 5-knowledge and learning, 6-life cycle assessment, 7-materials selection, 8-process standardization, 9-product variety management, 10-rapid prototyping, simulating and testing, 11-responsibility-based planning control, 12-set-based engineering, 13-simultaneous engineering, 14-specialist career path and workload leveling, 15-strong project manager, 16-supplier integration
Stankalla, Koval and Chromjakova (2018)	The study compares critical success factors for the implementation of lean Manufacturing in manufacturing SMEs. The review was based on seven articles from six countries (the United Kingdom, India, Italy, Kenya, the Netherlands, and Malaysia)	Business management and the link of Six Sigma to business strategy are the top priority critical success factors, for SME and large organizations as well. SME managers to develop a feasible communication plan and link Six Sigma to customers. The top management commitment is necessary for any lean project development.
De Jesus Pacheco et al. (2018)	Qualitative exploratory research, including a systematic literature review related to eco-innovation in SMEs. A set of interviews using an open questionnaire to Brazilian experts on eco-innovation was performed	The finds indicate difficulties of the diffusion of sustainable innovations in Brazilian SMEs, and most of the literature focuses on large organizations. The study contributes with new knowledge on the factors that influence the translation of eco-innovations within SMEs
Schmidt et al. (2018)	Case studies in 16 SME from the manufacturing sector with interviews with the companies' managers	Results show differences in environmental commitment in favor of companies with higher revenues. Even all the companies are aware of the importance of sustainability, there is a need to focusing on actions regard to corporate social responsibility
Oliveira Neto et al. (2017)	Literature review in order to propose a framework to overcome barriers to implementing cleaner production by SMEs A set of four case studies in metallurgical companies was conducted	Changes in the SME systems are required to adopt Cleaner Production principles. The proposed framework has allowed the identification of possible economic saves that SMEs can obtain as the result of technical cleaner production applications.

Table 7 (Continued)

Godinho Filho, Ganga and Gunasekaran (2016)	An exploratory survey of small and medium-sized manufacturing enterprises was conducted in seven states in Brazil. Partial least squares structural equation modeling (PLS-SEM) was used to estimate the lean practice	Just some lean Manufacturing practices are being implemented in SMEs in Brazil There is a lack of technical knowledge about lean principles and tools
Thürer et al. (2014)	Survey with 46 enterprises	Competitive priorities appear to be shaped more by the business environment than by capabilities, and competitive capabilities appear to be shaped more by priorities than by the business environment.
De Oliveira and Kaminski (2012)	A single case study	A guideline to be used for SMEs to launch their products on time. The guideline serves as a tool for directives and management decisions
Kaminski, de Oliveira and Lopes (2008)	Case studies with 32 metal-mechanic enterprises	The results point to a degree of maturity in SMEs, which allows product development to be conducted in cooperation networks. The importance of the involvement of customers and suppliers in long-term solid relationships can be perceived, where the interaction can generate innovative Project solutions and the strengthening of the productive chain where the SME is inserted

Source: Author.

Several global models that address the techno-economic feasibility study related to cobots was identified in the specific literature (ACCORSI et al., 2019). Therefore, the lack of academic papers related to the implementation of new technologies in SMEs, mainly any approach to justify the adoption of collaborative robots remains a gap in the specific literature for the Brazilian environment. However, according to the finds showed in Table 7, some components should play a role in developing this research. Overall, this work is looking for the characteristics and attributes of Brazilian SMEs that are considered relevant to design the conceptual model described in Chapter 3, to develop the techno-economic measurements of the mentioned model. Therefore, the main characteristics of Brazilian SMEs to take into consideration as an assumption to design the techno-economic feasibility study of the conceptual model is summarized as follows:

a. Competitive capabilities: to evaluate the internal and external organizational environment, including competitiveness in terms of cost, delivery time, and flexibility to attend to the market demand.

b. Management commitment: which is responsible to develop the organization’s strategic plan in the long-term perspective and assures the level of satisfaction of customers and employees through leadership.

c. Launch products on time and product variety management; building production flexible processes, focusing on attending the customer needs and customization to attract the market.

d. Diffusion of sustainable innovation: to support the mission, vision, and goals stated by the top management in order to address company values to the stakeholders.

e. Knowledge and learning: an asset to align the organization’s expectations to a conscious development attempt to the future.

f. Access the human and robot knowledge; use of human knowledge and the robot dexterity to build a hybrid manufacturing process base on HRC.

g. The interdependence of the computational systems: with a focus on the cyber-physical system to connect the digital and real word in terms of I 4.0 enablers.

2.4 THE KNOWLEDGE GAP ON THE USE OF THE COBOT IN SME

This section introduces an understanding of the research gap allocation, seeking to gather useful and relevant theoretical information related to the following research question addressed in this dissertation:

RQ. How to develop a techno-economic feasibility approach to implement collaborative robots in Small and Medium-sized Enterprises in Brazil?

In order to find out the nature of the use of collaborative robots in such kind of industry, the literature investigation had a focus on identifying potential gaps in SME, or, understand what happens in terms of the use of collaborative robots in these companies. Therefore, this search aims to identify the following aspects:

1. Use of the industrial robot in small and medium-sized companies (worldwide);
2. Use of collaborative robot in Small and Medium-sized Enterprises (worldwide);
3. Reasons or barriers for not using collaborative robots in Small and Medium-sized Enterprises (worldwide).

As pointed out above, this research step is necessary to understand the fundamentals related to the use of collaborative robots in SMEs to release the perspective of this dissertation. The main phases of the search protocol were adapted from work performed by Cobo et. al. (2011) and define the search criteria for the databases, keywords, and publication period, preliminary data collection, the criteria for inclusion & exclusion of all documents related to the theme, and the document evaluation. Therefore, the document selection criteria were based on the following search protocol aspects:

a. Explicit discussion of industrial robot projects implemented in SMEs;
b. Qualitative or quantitative studies in the context of the use of the collaborative robot in SMEs;

c. Articles which the key terms matching with the title and, or abstract, or keywords.
d. Academic journal articles;
e. Old references occurred in the search, starting from 1995;
f. English language;
g. Databases.

Delimitations: all documents non-refereed as scientific documents (journal articles), such as conferences, books, and magazines were excluded from the initial search in the scientific database (FAHIMNIA; SARKIS; DAVARZANI, 2015). Besides that, the “collaborative robot” and “Small and Medium-sized Enterprises” research terms or their synonyms that were published in other languages were excluded from this search. Terms such as “fourth industrial revolution,” “advanced manufacturing”, “smart factory” and “smart manufacturing” were also not included in the search composition terms. The selection includes all documents related to the Research area of Engineering. The final date of retrieval of the search has been concluded on 23/05/2021.

2.4.1 An overview of the selected literature

Based on the above protocol, a systematic literature search on digital databases was conducted to identify and evaluate prior scientific works (DRESCH; LACERDA; ANTUNES, 2015, TRANFIELD; DENYER; SMART, 2003), to investigate the related finds to the research question. The literature search in academic databases was limited to the key terms to avoid a huge volume of data (EISENHARDT; GRAEBNER, 2007). Besides that, the mentioned key terms to identify the literature gap is indicated in Table 8:

Table 8 **–** Search composition terms referred to the literature gap

A1	"collaborative robot" OR “cobot” AND "small-and-medium-sized enterprises"
A2	"collaborative robot" OR “cobot” AND "SME"
A3	"collaborative robot" OR “cobot” AND "barriers"
A4	"collaborative robot" OR “cobot” AND “implementation”

Source: Author.

This search has offered the basic knowledge in the area of use of the collaborative robot in SMEs and was combined to address in the content of a paper to get the related features (LIAO et al., 2017). Therefore, the “collaborative robot” key term (VILLANI et al., 2018) and “Small and Medium-sized Enterprises” key term (MOEUF et al., 2018; MOEUF et al., 2020; RAUCH; SPENA; MATT, 2019) have been used to identify the stage of the use of the collaborative robot in SME worldwide. The search has been conducted based on preliminary information collect through Scopus, which is the largest database with multidisciplinary scientific literature analysis tools (AGHAEI CHADEGANI et al. 2013). It is used for searching the literature and has an indicator of more information opportunities and accuracy statistically (GUZ; RUSHCHITSKY, 2009).

The Web of Science and Science Direct electronic databases were selected as well, due to their relevance to the theme and research field (ROSA et al., 2020; PESSÔA; BECKER, 2020; LIAO et al., 2017). Those three academic search databases have returned the most documents. The search has covered also documents collected from other relevant databases (FREWER et al., 2013), as Emerald Insight, Springer, ProQuest, Taylor & Francis, Wiley, IEEE Xplore. The EI Compendex and EBSCOhost databases were also covered in the search, but they have returned the fewest results. The Table 9 shown the documentation collection results, which have been acquired from those eleven academics’ database searches.

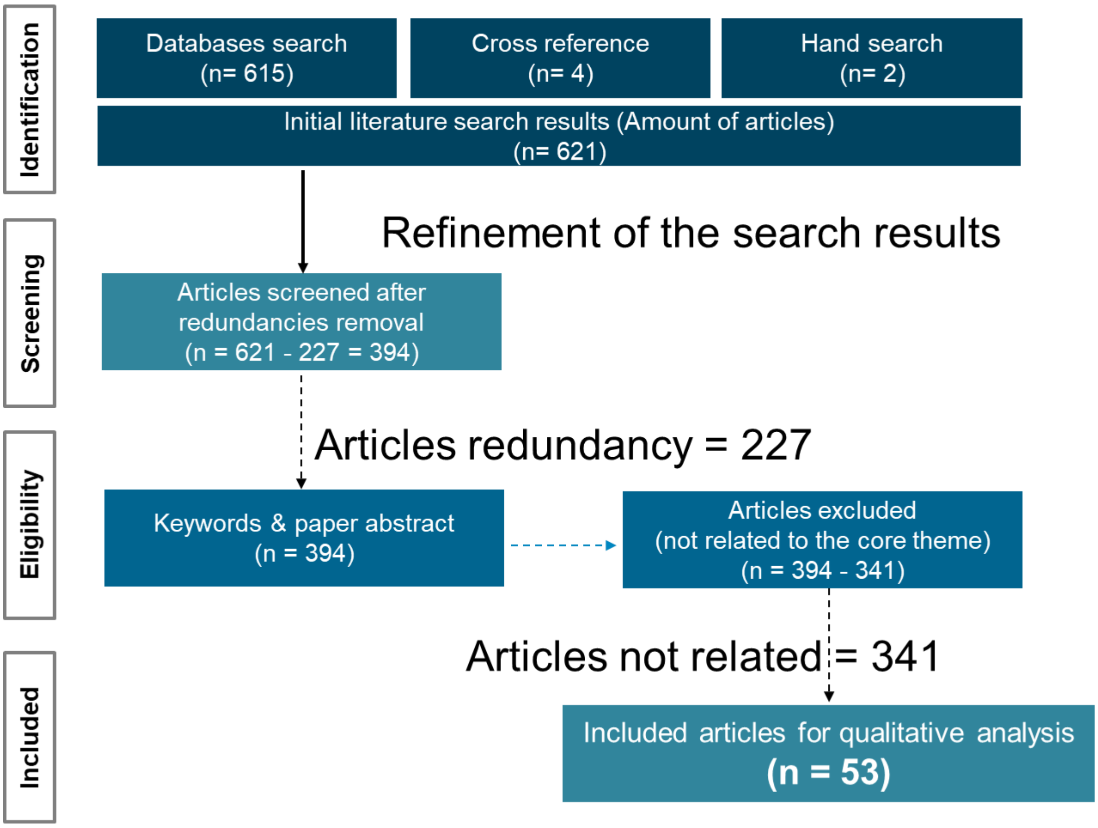
Table 9 – Document search in literature regarding adoption of cobot

key terms selection	Documents	Engineering	Conference	Articles	Journals	English
"collaborative robot" OR “cobot” AND "small-and-medium-sized enterprises"	437	180	36	73	73	72
"collaborative robot" OR “cobot” AND "SME"	463	187	43	87	88	86
"collaborative robot" OR “cobot” AND "barriers"	342	316	100	107	97	94
"collaborative robot" OR “cobot” AND “implementation”	1.008	767	198	382	377	363
Total	**2.250**	**1.450**	**377**	**649**	**635**	**615**

Source: Author.

The next step of the search was responsible for the analysis of the 615 documents found in the literature search as shown in Table 9. In order to gather relevant information from such documents. The concept flowchart shown in Figure 5 was adapted from the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) proposed by Moher et al. (2009) to conduct different phases of the literature review in a systematic process model was selected to conduct the analysis of the documents.

Figure 5 – PRISMA flowchart to analyses the literature search



Source: adapted from Moher et al. (2009).

As previously stated, the research builds upon the work across the implementation of collaborative robots in small and medium-sized industries, presenting the required literature as a basis of this dissertation. While explaining how the literature search was conducted and aligned with the PRISMA flow chart (MOHER et al., 2009), an amount of 53 academic articles was selected to answer the research question.

As stated in Chapter 1, there are a few academic papers related to the use of cobot in a SME manufacturing environment (MOEUF et al., 2018). In the set of industrial automation, the industrial robot as equipment, has been implemented in the past decades in different manufacturing sectors, mostly in the automotive sector (IFR, 2019), which requires a high degree of precision and repeatability in its production lines (BALLARD et al., 2012). Hence, the research in the industrial robot domain is predominantly focused on large corporations, with production comprising low flexibility and high production volume (GARCIA et al., 2007) focused on fully automatic lines. The wide utilization of industrial robots in the industrial sector has not been noticed yet and represents a relevant barrier for their deployment in other fields other than automotive, especially for SMEs, which are involved in a limited range of robotic applications in their daily production operations (MOEUF et al., 2018; ZHANG et al., 2020).

The main results obtained from the systematic literature review indicated efforts from academic researchers to investigate issues related to the Industry 4.0 enabling technologies used in a SME environment. However, Moeuf et al. (2018) highlight that technologies with an impact on business transformations such as Cyber-Physical-Systems, big data, and collaborative robots are still not in the domain of SMEs field. This is particularly true for collaborative robot applications, because no papers were found reporting cases in SMEs. The literature search to perform this work indicated that in the field of advanced robotics and despite the important growth of the collaborative robot papers in the academy (HENTOUT et al., 2019, VILLANI et al., 2018), the SMEs have only recently started to explore Human-Robot-Collaboration (HRC). In fact, the findings collected from academic papers indicate a gap in terms of the use of cobot in specific companies, especially in SMEs (MOEUF et al., 2018, ZANCHETTIN et al., 2015).

For instance, work performed by Mittal et al. (2018) investigated the maturity level of SMEs to adopt industry 4.0 technologies, more specifically the cobots. According to the authors, a lack of resources, risks in investing in wrong solutions, the lack of technical knowledge in emerging technologies are the major problems faced by SMEs. The search performed according to the parameters described in section 4.1 allowed the selection of 53 academic papers related to barriers faced by SMEs' to adopt the cobots. An overview of those articles and findings investigated by the researcher while the literature review was performed are summarized in Table 10.

Table 10 – Barriers to adopt cobot in SMEs

	Authors	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
01	Lienenlüke et al. (2018)	x	x	x	x	x	x	x		x							
02	Nair, Kuhn and Hummel (2019)	x		x	x						x	x	x				
03	Bernhardt et al. (2007)			x							x						
04	Bogataj et al. (2019)	x												x			
05	Moeuf et al. (2020)			x											x		
06	Moeuf et al. (2018)												x			x	x
07	Rojas et al. (2019)							x								x	
08	Cencen, Verlinden and Geraedts (2018)								x								
09	Olender and Banas (2019)			x				x	x								
10	Zhang, H. et al. (2020)			x					x								
11	Rauch, Spena and Matt (2019)																x
12	Gherardini, Renzi and Leali (2017)				x												
13	Wang et al. (2016)															x	
14	Song, T. et al. (2014)															x	
15	HUANG, B. et al. (2019)															x	
16	Wang et al. (2018)		x	x													
17	Su et al. (2008)			x													
18	Bloss, Richard (2016)		x		x		x										
19	Mateus et al. (2020)	x															
20	Akkaladevi et al. (2017)			x					x								
21	Dobra and Dhir (2020)							x	x							x	
22	Aaltonen and Salmi (2019)							x									
23	Oberc et al. (2019)			x							x						
24	Oliff et al. (2018)	x	x							x							
25	Aaltonen, Salmi and Marstio (2018)							x	x								
26	Accorsi et al. (2019)	x					x									x	
27	Kildal et al. (2018)								x								
28	Hentout et al. (2019)	x		x					x				x				
29	Schlette et al. (2020)	x								x							
30	Faccio, Bottin and Rosati (2019)											x					x
31	Erasmus et al. (2020)												x			x	
32	Messina and Marvel (2019)										x						
33	Peshkin and Colgate (1999)								x								
34	Wilkesmann and Wilkesmann (2018)															x	

Table 10 (Continued)

35	Bogue, Robert (2016)			x													x
36	Lindblom and Alenljung (2020)								x								
37	Garbellano and Da Veiga (2019)			x												x	
38	Fager, Calzavara and Sgarbossa (2020)							x			x						
39	Olivares-Alarcos et al. (2019)									x							
40	Bruno and Antonelli (2018)	x															
41	Nemec et al. (2018)	x															
42	Ajoudani (2018)								x								
43	Sadik and Urban (2017)												x				
44	Khalid et al. (2016)								x								
45	Scholer, Vette and Rainer (2015)	x						x									
46	Arduengo and Sentis (2020)	x															
47	Pérez et al. (2020)							x	x							x	
48	Cohen et al. (2019)			x												x	
49	Huang et al. (2016)															x	
50	Zhang et al. (2016)															x	
51	Guo, Liang (2016)															x	
52	Li, Song and Huang (2016)															x	
53	Alizadeh and Soltanisehat (2020)			x													
	Total citations	**12**	**4**	**15**	**4**	**1**	**3**	**9**	**13**	**4**	**5**	**2**	**5**	**1**	**1**	**16**	**4**

Source: Author's elaboration of data from literature review of section 2.4.

(A) degree of automation; (B) investment risk; (C) employee deficits / no experts / lack of expertise; (D) wide range of products; (E) High investment in tooling; (F) Efficiency; (G) Safety; (H) HRC rules; (I) Usability; (J) Batch size; (K) Speed; (L); Flexibility (M); Craft work age; (N) lack of leadership; (O) Industry 4.0 issues; (P) costs.

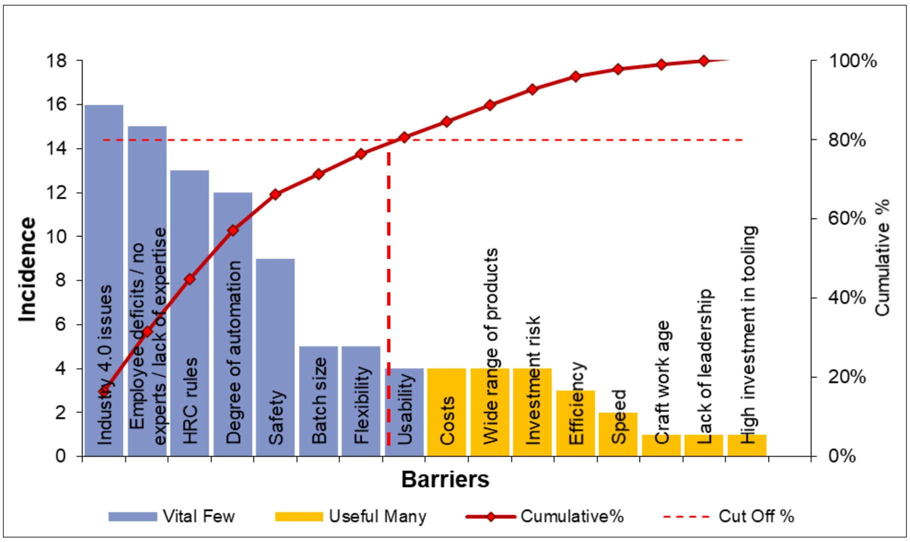
As can be seen in Table 10, the most important barrier to adopt cobot in SMEs is related to the knowledge of Cyber-Physical-Systems associated with Industry 4.0 in SMEs (MASOOD; SONNTAG, 2020, QIN; LIU; GROSVENOR, 2016). In fact, the behavioral decisions of leadership combined with employee knowledge shortages, or lack of employee expertise contribute to generating a barrier to adopting cobot in SMEs. For this dissertation, the Pareto principle associated to the ABC classification (GROSFELD-NIR; RONEN; KOZLOVSKY, 2004) was chosen as the classification method to select the most relevant barriers found in the literature to adopt cobot by SMEs. The Pareto analysis, which was developed by the Italian economist called

Vilfredo Pareto is defined as one of the most used classification methods to identify relevant activities and recognized relevant priorities for the management decision (CEBI; KAHRAMAN, 2012). The principle of such method is the 80 - 20 rule, where the amount of 20% percent of the population possesses 80% of the wealth (SANDERS, 1987), or perhaps, 80% of the activities is caused by 20% of the factors (KRAJEWSKI; RITZMAN, 2002).

The Pareto classification criteria distinguish a few activities having high importance of many activities having no importance (JACOBS; CHASE; AQUILANO, 2005). It has been used as a managerial tool to determine the called curve ABC, or the “A” class, “B” class, and “C” class according to the item’s relevance, cost-effective, storage sequence or usage, for example (BALLOU; SRIVASTAVA, 2007, GROSFELD-NIR; RONEN; KOZLOVSKY, 2004). For instance, work performed by Pacchini et al. (2019) to investigate the degree of readiness for the implementation of Industry 4.0 employed the same approach used here as a classification technique to select the most relevant I 4.0 enabling technologies to allow the I 4.0 implementation in the manufacturing industry.

Lande, Shrivastava and Seth (2016) proposed a Pareto analysis method to identify and classify the critical success factors of Lean Six Sigma implementation in SMEs with a focus on quality and productivity improvement. According to the Pareto analysis shown in Figure 6, the first eight issues listed in the diagram cover an amount of 81,2% of the total incidence of barriers gathered in the literature to adopt cobot in SMEs.

Figure 6 – Barriers to adopt cobot in SMEs



Source: Authors’ elaboration based on data in Table 10.

As shown in Figure 6, the lack of expertise and a short-term strategy mindset are major barriers faced by SMEs to deploy new production processes to attend the customization and customer demands (MOEUF et al., 2020). Consequentially, the lack of infrastructure in information technology and the low level of financial resources to invest in the production processes appear as relevant barriers to adopt the enabler technologies of Industry 4.0, including the adoption of advanced robotics (MULLER; VOIGT, 2017). Once the robots are not considered as key elements in improving performance in this type of company (MOEUF et al., 2020). As mentioned above, the lack of expert support function to optimize the tasks to be distributed between humans and robots and design the possible four types of collaborative robot operation based on the ISO/TS 15066 (CHEMWENO; PINTELON; DECRE, 2020) impacts the HRC deployment on the shop floor.

The degree of automation related to the industrial robot applications and the safety requirements applied to a collaborative workstation (BDIWI; PFEIFER; STERZING, 2017) are enablers that justify the development of techno-economic feasibility analysis to adopt the use of cobot by SMEs. Batch size relies on the manufacturing of different product variants, and cobot is recommended as a solution to produce a variety of products (SALUNKHE et al., 2019). Flexibility and usability are related to the batch size and the number of product variants of the product (HEILALA; VOHO, 2001), and cobots are developed to improve the flexibility of industrial processes (CHERUBINI et al., 2016).

2.5 REVIEW ON FEASIBILITY STUDIES

This section introduces an understanding of the research gap allocation, seeking to gather useful and relevant theoretical information related to the research question addressed in Chapter 1. The search seeks for documents that define and indicate models proposed in the literature, including those, which approaches how to perform a technical or economic feasibility analysis to select cobot as a solution for implementation in an SME. The road map of the model proposed in this dissertation to answer the research question will be built based on the findings of the literature based on the methodology proposed in this section, including the findings in section 2.4, as well. In order to find out the most interesting and appropriate solution for Brazil, to merge in the model to be proposed in this dissertation, the search in the literature has a focus on a feasible model to allow the use of cobot in SME, trying to identify the following contents:

1. Development of a model to allow the economic use of cobot in SME;
2. Development of a model to allow the technical use of cobot in SME;

This research step is necessary to understand the economic and technical issues related to the use of collaborative robots in SMEs to release the perspective of this dissertation. As described in section 2.4, the main phases of the search protocol were adapted from Cobo et. al. (2011). The final date of retrieval of the search has been concluded on 17/07/2021.

2.5.1 An overview of the selected literature

Based on the protocol described in section 2.4, the literature search in academic publications was extended to the set of key terms indicated in Table 11, in order to identify the related literature:

Table 11 – Search in academic literature regarding to the feasibility

B1	"collaborative robot" OR “cobot” AND "feasibility"
B2	"collaborative robot" OR “cobot” AND "viability"
B3	"collaborative robot" OR “cobot” AND "technical feasibility"
B4	"collaborative robot" OR “cobot” AND "economic viability"
B5	"collaborative robot" OR “cobot” AND "performance"
B6	"collaborative robot" OR “cobot” AND "efficiency"

Source: Author.

This search has offered the basic knowledge in the area of use of the collaborative robot in SMEs. Therefore, the “collaborative robot” key terms (VILLANI et al. 2018), “feasibility”, and “viability” key terms have been used to identify the stage of the use of collaborative robots in SMEs, on a worldwide level. The Table 12 shown the documentation collection results, which have been acquired from those eleven academics database search.

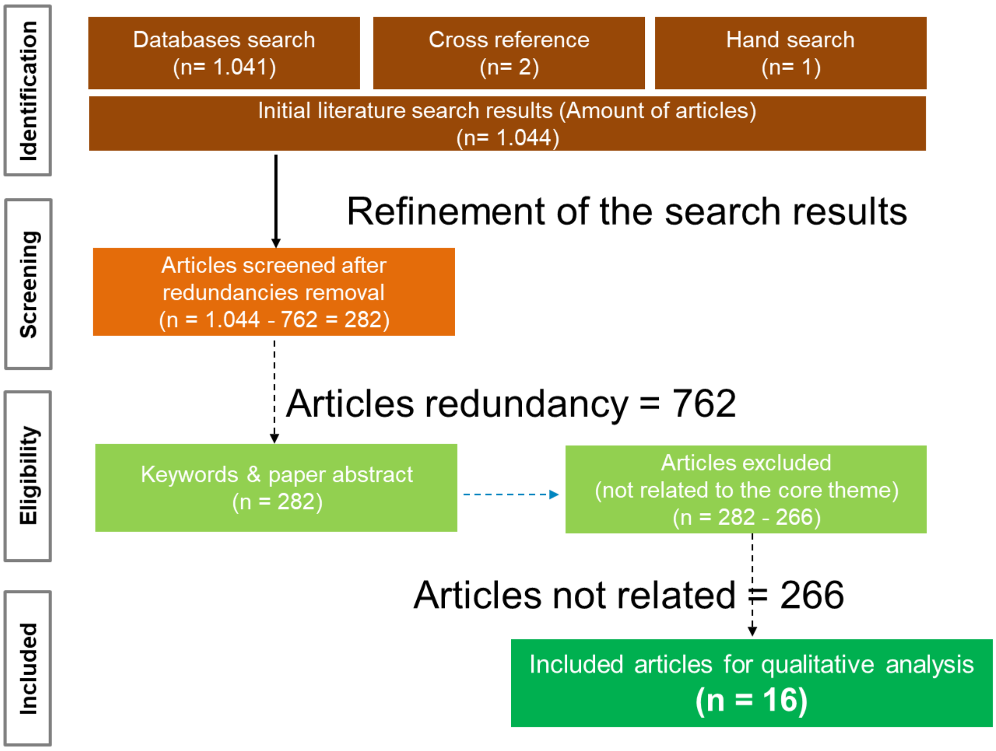
Table 12 – Search in academic literature regarding cobot feasibility

key terms selection	Documents	Engineering	Conference	Articles	Journals	English
"collaborative robot" OR "cobot" AND "feasibility"	341	256	92	126	124	122
"collaborative robot" OR "cobot" AND "viability"	44	30	7	13	12	13
"collaborative robot" OR "cobot" AND "technical feasibility"	18	11	6	5	5	5
"collaborative robot" OR "cobot" AND "economic viability"	7	6	2	5	5	5
"collaborative robot" OR "cobot" AND "performance"	1.815	1.342	339	597	585	572
"collaborative robot" OR "cobot" AND "efficiency"	1.081	820	187	331	330	324
Total	**3.306**	**2.465**	**633**	**1.077**	**1.061**	**1.041**

Source: Author.

The next step of the search was responsible for the analysis of the 1.041 documents found in the literature search as shown in Table 12. In order to gather relevant information from the search, the concept flowchart shown in Figure 7 was adapted from the PRISMA (MOHER et al., 2009) to conduct the analysis of the documents.

Figure 7 – PRISMA flowchart to analyses the literature search



Source: adapted from Moher et al. (2009).

As previously stated, the research builds upon the work across the implementation of collaborative robots in small and medium-sized industries, presenting the required literature as a basis of this dissertation. While explaining how the literature search was conducted and aligned with the PRISMA flow chart (MOHER et al., 2009), an amount of 16 academic articles was selected to answer the research question.

To understand the principles of application of cobot in SMEs, this work focuses on the feasibility study characteristics as an important step prior to implementing a new technology solution in a manufacturing environment. Accordingly, the Cambridge Business English Dictionary (2011) defines the meaning of the feasibility study as:

a. General approach: an examination of a situation to decide if a suggested method, plan, or piece of work is possible or reasonable.

b. Business approach: an investigation carried out by a company or other organization that examines whether a planned business activity or project is likely to be successful.

Therefore, the concept of feasibility study provides an important starting point for the techno-economic assessment to properly evaluate new technology, including its design and construction phases. The feasibility study of a new industrial solution is performed prior to the design and manufacturing stage to create viable scenarios to support the decision-making by management and avoid the wrong decisions for the investors (MARZOUK; AMER; EL-SAID, 2013). To justify the assessment of a new manufacturing system, the feasibility study consists of a series of analyses, which can be carried out in different areas of the project. Economic and social benefits, versatility, profitability, legal requirements, the return on investment, and scheduling of the project implementation are areas to consider in a feasibility assessment (MUKHERJEE; ROY, 2017). Overall, the feasibility study contents provide data to develop a robust and successful financial project and implement new concepts related to products or services (SHEN et al., 2010; GEORGAKELLOS; MACRIS, 2009).

Requirements for techno-economic feasibility study have been selected to develop the conceptual model described in Chapter 3 to identify whether the economic viability and technological accessibility while using a cobot in an SMEs. As mentioned before, the feasibility study is a measurement of a manufacturing system or equipment, which is centered on selected techno-economic variables with key characteristics to evaluate the viability of the implementation of a new assembly station or a new manufacturing automation system (LENZ et al, 2020; ZHANKAZIEV et al., 2018). In such perspective, the techno-economic feasibility study is related to economic and technical evaluations, where the technical study is concentrated on proposing new technologies to enable a new production process. The economic study seeks to identify the investment costs and benefits generated through the proposed new technology and its viability (OYESOLA, MPOFU; MATHE, 2019; BAUSE et al., 2014; SHEN et al., 2010; GEORGAKELLOS; MACRIS, 2009).

2.5.2 Characteristics of feasibility study on cobots

The literature also highlights the feasibility study emphasizing the use of cobots through examples of decision criteria and assessment on the use of cobots in the manufacturing industry. This brings new challenges in terms of the production process development, especially those related to cost-efficiency in developing a safety process during HRC and improvement in ergonomics. Such benefits could optimize the workstation design through the production efficiency expected from the human operator and the industrial robot during the HRC to enable the use of cobots in a SME industrial environment (GUALTIERI et al., 2020).

The precision and repeatability of the robots, incorporated by the support of digital technologies, such as machine vision combine with human experience can result in a novel manufacturing approach with potential techno-economic benefits in comparison with the traditional manual assembly lines (PÉREZ, et al., 2020). According to Gualtieri et al. (2020), the HRC concept focuses on improving human work conditions to target the production performance of the collaborative workstation in comparison with a manual assembly station minimizing the hazards and task times while optimizing the manual and the cognitive work.

Pérez et al. (2020) carried out a techno-economic feasibility assessment proposing a new methodology for a process cell design and operation, enhanced implementation, and real-time monitoring operation. The model was based on creating a digital twin of the manufacturing process combined with a virtual reality interface before the physical collaborative work cell's implementation phase. In this setting, the authors pointed out a selection of feasibility issues to be raised before an industrial manufacturing assembly process is automated:

a) What are the costs in terms of money, time, safety, etc., of the current manual process?
b) Is the use of robots technically feasible for the tasks?
c) Will the robot work isolated or collaboratively with humans?
d) What are the costs of the new automated or semi-automated process? Which costs are reduced, and which ones are increased?
e) Is the new process cost-effective?
f) Does propose automation reduce risks and enhance safety?

Work performed by Baskaran et al (2019) discussed a simulation with the support of the Siemens Tecnomatix process simulation software in a carmaker's assembly line to mimic the optimal technical feasibility process in terms of time and ergonomic impacts on physical human performance during the collaborative assembly tasks. The feasibility study was developed based on digital twin technology. A work based on a case study related to an automotive car battery assembly line from Malik and Bren (2021) classified the fast integration and production reconfiguration as technical feasibility when using the digital twin to design and optimize the HRC constraints in the mentioned workstation.

Work conducted by Lopez-Hawa et al. (2019) provided a useful basis for developing a measuring workstation with a moderate accuracy of industrial parts in an automotive scenario, applying the use of a UR-5 cobot and Keyence vision systems as the measurement alternative. The technical feasibility was reached with easier programming and station operation. According to the authors, the compact layout area and the space-saving to allocate safety devices in comparison with a traditional industrial robotic cell is a technical advantage as well. The work performed by Lopez-Hawa et al. (2019) presented the replacement of a traditional measuring system for a collaborative system indicating an economic feasibility benefit in the initial station investment (US$ 35,000.00 from the collaborative system against a US$100,000.00 investment for then traditional metrology equipment).

Huang et al. (2019) developed a case study in the remanufacturing field, proposing a collaborative robotic disassembling cell, applying a KUKA LBR iiwa 14 R800 cobot, for press-fitted components (the rotor sub-assembly process, the flange, and the pump casing) from an automotive water pump. The results demonstrated the technical feasibility through the reduced setup efforts and shifting resources demands, which are assessed by the level of flexibility and adaptability of the collaborative cell. The strength, precision, and repeatability of robots and human knowledge and dexterity are highlight, according to the technical feasibility results. The authors stated that the economic feasibility can be assessed through small batches (different products with the same basic disassembly operations) and reduction of capital investment required for collaborative robots. The reduction of safety fences and safety devices are classified as economic feasibility achieved in the case study.

Actually, also in the remanufacturing field, work conducted by Li et al. (2020) proposed the use of KUKA LBR iiwa cobot to perform autonomous unfastening of screws for dismantling of an automotive end-of-life turbocharger. The techno-economic feasibility indicated reduction of manual labor, increased productivity, and safety, which were traditionally limited by manual disassembly processes. Wojtynek, Steil and Wrede (2019) introduced a novel feasibility study named Plug-and-Produce concept, where participants from Bielefeld University have performed a flexible work cell setup and robot programming in a smart assembly line (consisting of modular production systems equipped with KUKA collaborative robots in a laboratory environment). The results indicated that the collaborative human-robot interaction scheme made easier for humans to perform during the setup of the collaborative work cell from a technical feasibility perspective.

The general purpose of cobot in a collaborative workstation is to replace manual tasks to relieve workers from physical fatigue, excessive workload, and non-value-added operations (VILLANI et al., 2018). Essentially, the implantation of the cobot in manufacturing represents the reduction of manual labor through investment in automation to quickly respond by reducing manufacturing costs expected when adopting cobot as s solution to replace human labor. As discussed previously, the viability study focuses on increasing profits with a premise to investigate the cost reduction generated by the decrease of manual labor as a result of cobot adoption to obtain the desired return-on-investment planned before implementing a collaborative workstation. Based on the findings in the literature, the features related to the techno-economic feasibility study to use cobot in a production environment are summarized as follows:

a. Economic feasibility analysis prior to starting the cobot acquisition: compare the initial investment outlay to acquire the cobot, its installation costs and the collaborative workstation disbursement with the increase in revenue or in cost-savings generated over time to investigate if the planned investment is economically feasible in comparison with a manual workstation during the economic life of the investment. (PÉREZ, et al., 2020, LI et al., 2020, LOPEZ-HAWA et al., 2019). The economic feasibility analysis typically addresses the issue of investments needed to implement new types of equipment in production lines.
b. Technical feasibility analysis prior to starting the cobot acquisition: is a technical assessment of the proposed investment when automating a manual workstation. The technical analysis investigates the details on how the new collaborative workstation will perform, including benefits for the human co-worker in terms of fatigue, which occurs with the high workload during manual assembly tasks.

Normally, during the technical feasibility stage analysis, a simulation of the optimal technical feasibility process is investigated to the improvement of ergonomics in humans during the collaborative assembly tasks. The technical feasibility study assesses the benefits for the human co-worker during HRC. An evaluation of the performance of the collaborative workstation in terms of production to allow batch size flexibility, the time required for setups and robot programming to adopt a new product in the workstation precede the release of investments needed to implement the cobot.

2.6 MODELS IN THE LITERATURE TO ALLOW THE COBOT FEASIBILITY

This section provides the features gathered in the literature to design the principles of the conceptual techno-economic feasibility model described in Chapter 3, encompassing several approaches along the spectrum of collaborative robots applied as an automation solution for SMEs.

As mentioned before, this work aims to investigate the existing feasibility models of the field where the research question is located to support the construction of the proposed conceptual model. Therefore, this work focuses on previous proposals gathered throughout the literature that can contribute to enhancing the techno-economic assessment of using cobots in different industry fields with a range of applications (HENTOUT et al., 2019). For the purpose of this research, the search procedures applied to investigate feasibility models mentioned in the literature follow the approach design method described in section 2.4, combined with the return and analysis of the documents. The findings gathered from the literature indicated that researchers investigated both, techno or economic feasibility approaches based on frameworks and models related to the adoption of the use of robots.

For instance, Oberc et al. (2019) proposed a training model focusing on any manual assembly station with the potential to be replaced by an HRC workplace. One simulation software editor to design manual assembly activities, which is applied in industry, academia, and education, was selected by the authors as a guide to design the training model. A quick check tool through a questionnaire was used to support the researchers to simplify the movements and tasks presenting in the workplace. Besides that, such a questionnaire is used to deal with HRC demands, worker training, financing, and the economic feasibility of an HRC in a workstation. The proposed training model was tested in Germany and comprises four stages:

a. Access to the theory (knowledge, understanding, and input on HRC rules);

b. Skills (application of HRC methods);
c. Practices (implementation and optimization of the workstation);
d. Design of new workplaces with support of simulation software editor (analysis and feedback of HRC scenarios, lessons learned).

Such a model allows engineers to plan the workload tasks between humans and robots and provide simulation and capability of the collaborative workstation. The aim of such a model is to cover issues related to the economic aspects and methods to analyze HRC. However, it was not proposed for utilization under SME environment.

Work performed by Faccio, Bottin and Rosati (2019) investigated how collaborative assembly systems could achieve better performance than manual workstations. A mathematical model to investigate the real feasibility to implement an HRC in a workstation was proposed by the authors. Hence, the key requirement of the proposed model is to check the improvement of the production costs. A case study of an HRC focusing on an assembly workstation for a screwing operation, including the use of a universal robot UR model with an electric screwdriver embedded was analyzed. The main parameters selected to build the mathematical model were as follows:

a. Manual assembly time;
b. Manual manipulation time;
c. Price of a collaborative robot;
d. Price of a traditional working cell fully equipped with security sensors;
e. Hourly cost of the human operator.

Nevertheless, this model does not perform an easy to use comparison between the required investment and the related savings obtained, which does not make it suitable for SME utilization.

Accorsi et al. (2019) proposed a method comprise of a set of process, ergonomic and economic performance parameters to identify the design and assessment of HRC layout configuration to replace manual chores and no-added value tasks in a workstation. A case study in a catering food facility to pack finished meals was performed to explore an application of cobot proposing a method for decision-makers before the replacement of manual work. The focus of such a method is to indicate the techno-economic feasibility for decision-making before the replacement of any manual tasks in the workstation. The performance parameters applied in the proposed method were based on the human worker, process assembly, ergonomic issues, and investment analysis, as described below

a. Personnel: refers to the number of operators employed on the task;
b. Process parameters: applied to the system set-up and visual inspection;
c. Ergonomic parameters: planning of load and unload parts. Time spent for loading parts and the number of parts by the operator in the entire work shift;
d. Economic parameters: initial investment on equipment, variable cash flow, and the payback time, which could be affected by the production batch size and the number of lots processed per shift.

Despite being a model with a robust feasibility analysis, it is dedicated to the food catering industry, besides its complexity to be used by SME.

Mateus et al. (2020) proposed an algorithm embedded by-product information on CAD models (SolidWorks) for the identification of assembly sequence tasks to avoid conflicts between human and cobot planned tasks. The result seeking for optimization of workforce resources, collaborative workstation layout, and safety standards for HRC. The generation of the proposed algorithm is based on the following inputs:

a. Liaison matrix: generate collision matrices;
b. Identify sub-assembly: a set of sub-assembly parts based on the product design;
c. Generate sub-assembly matrices and final assembly matrices.

It does not perform an economic feasibility analysis.

Bogner et al. (2018) proposed a novel integer linear programming (ILP) to cover several aspects of collaborative workspace and to optimize the distribution of tasks between the human operators and cobots in a HRC workstation. The test of the model was performed in Matlab R2016b and run on a standard PC. Economic considerations were not provided.

Work performed by Faccio et al. (2019) developed an algorithm to simulate the workstation design and identify how the sequence of product assembly affects HRC during assembly tasks, including a measurement of the time difference between the start and finish of component assembly tasks. According to the authors, such a model provides SMEs with a useful tool to enable HRC. The proposed algorithm was built assuming the main model definitions as described below:

a. Input variables and parameters: number of parts to be assembled, side of the square workspace (mm), manual assembly time (h/100 parts), manual unit pick a time (h/100 parts), cobot assembly time (h/100 parts); the speed of human operator movement (mm/sec);
b. Output variables: total assembly time (h), total manual assembly time (h), total robot assembly time (h), cycle time (h), manual task scheduling, robot task scheduling.

As can be seen no economic evaluation was included as part of this model.

Faccio et al. (2020) proposed a model based on simulation of human behaviors in an HRC workstation to simulate the product assembly process based on product characteristics (number of parts to be assembled) which could affect the assembly tasks in a collaborative workstation. The goal of such model is to measure the time difference between the start and finish of an assembly task, focusing on optimize the cycle time of the work process. The model proposed to evaluate the influence of product characteristics in a collaborative workstation comprised of the following input variables:

a. Product characteristics: Number of parts to be assembled, workspace design, patterns and arrangements of assembly tasks;
b. Process characteristics: Task location into picking and placing (human and UR 10 cobot), assembly process (fastening), and task features to allow the HRC.

No economic feasibility was included.

Akkaladevi, Plasch and Pichler (2017) introduced the novel learning framework named XRob. The proposal was to reduce the time of robot task programming by no experts, enabling the HRC in an intuitive way, even in a complex environment. The XRob software includes the following features:

a. The Perception system software: gathering data from the current stage of the workspace environment;
b. The planning and execution system: calculation of collision movement zone;
c. The Application Development: Software in modules to follow the cobot movements.

Likewise, no economic feasibility evaluation was considered.

Work performed by Lienenlüke et al. (2018) from Aachen University, in Germany, was motivated by a low level of automation in machine tools due to the wide range of products. The study proposed an engineering requirement framework to optimize the manufacturing process planning order to allow a flexible and easy handing part (load and unload) in machine tools (machine tending with cobot) in SMEs located in Germany. A mobile robot platform including the cobot and gipping system was proposed. The main aspects of the conceptual design of flexible automation investigated by the authors were related to the machine & workpiece flexibility, efficiency, and the usage of the operator knowledge in the machining process. The mobile robot platform works as temporary automation of tending machines and planning tasks with flexibility. The method includes a software solution to enable the engineer to control all requirements for loading, assembly, and handling tasks and a simulator to support the human operator to plan the assembly sequence.

Cencen, Verlinden and Geraedts (2018) developed research about the use of collaborative robot in SMEs and proposed a human–robot-collaboration methodology named “Coproduction design methodology” in a HRC design process (HRCDP). The target of the proposed HRCDM was to support production engineers to plan and design manufacturing systems solutions based on the Human-Robot-Collaboration in SMEs, focusing on the issues related to the batch production sizes during production assembly tasks. According to the authors, an efficient and effective HRC workstation design allows an increase in the product quality, because, in most SMEs, the operator has multiple functions, covering multiple tasks in different machines and processes.

As can be seen from the content above, the results of the literature search did not indicate any document proposing a friendly technical and economic feasibility analysis that would be adequate for SMEs. In addition, none of the obtained papers dealt with models considering the SME environment in Brazil. Table 13 shows an overview of the findings in the literature regarding relevant models and their main characteristics.

Table 13 – Techno-economic feasibility models to adopt cobots

Authors	Proposed model	Feasibility approach	Field of application
Oberc et al. (2019)	Simulation software editor Quick check tool based on a questionnaire	Economic Methods to investigate HRC	General industry Academia Education
Faccio, Bottin and Rosati, 2019	Mathematical model	Feasibility to implement a HRC improvement of the production costs	General industry
Accorsi et al., 2019	Method for decision making before the replacement manual tasks	Design and assessment of HRC layout configuration (process and ergonomics)	Catering food industry
Mateus et al., 2020	Algorithm embedded by-product information on CAD models (SolidWorks)	Identification of assembly sequence tasks	General industry
Bogner et al., 2018	Integer linear programming	Optimize the distribution of tasks between the humans and cobots	General industry
Faccio et al., 2019	Algorithm to simulate the workstation design	Identify how the sequence of product assembly affects HRC during assembly tasks	SME
Faccio et al., 2020	Simulation of human behaviors in an HRC workstation	simulate the product assembly process based on product characteristics	General industry
Akkaladevi, Plasch and Pichler, 2017	Learning framework named	Reduce the robot programming time by no experts	General industry
Lienenlüke et al., 2018	Engineering requirement framework	Optimize the manufacturing process planning control all requirements for loading, assembly, and handling tasks	Machine tending with cobot in SME
Cencen, Verlinden and Geraedts, 2018	Coproduction design methodology" in a HRC design process	Support production engineers to plan and design manufacturing systems solutions based on HRC	use of collaborative robot in SMEs

Source: Author.

According to the findings obtained from Table 13, none of the characteristics covered in each model referred in the literature to develop a techno-economic feasibility study to adopt cobot is applied to developing countries, especially under the Brazilian manufacturing SMEs. Consequently, as emphasized in section 1.2, it can be concluded that there is a gap in the literature, and such a gap was covered in this dissertation.

3 TECHNICO-ECONOMIC FEASIBILITY MODEL TO ADOPT COBOT

In this part of the dissertation, it will be proposed a conceptual model to develop the economic and technical feasibility analyses to be used by SMEs when evaluating the convenience of adopting cobots as part of their traditional manufacturing systems. As such, the development of this section will be divided into two parts, the technical feasibility analysis followed by the economic evaluation aspects.

3.1 TECHNICAL FEASIBILITY ANALYSIS

The literature that follows provides management with the technical aspects in the context of the company strategy to justify and release the investment in technology development. As mentioned in Chapter 2, technical feasibility investigates the availability of the proposed cobot technology, more specifically in the Brazilian market, and describes how such technology will benefit the competitiveness and how it will work in the production environment. To make investment decisions in response to a decrease of financial risks, such analysis identifies how long the automation solution will take to be implemented, when the level of automation functionality will be reached, and which problem needs to be solved under the assembly process perspective. A harmonized automation with minor modifications on the shop floor is a clear target of the technical evaluation aspects to avoid any staff resistance.

3.1.1 Technical variables for the technical feasibility analysis

In the context of automation based on industrial robots, they perform tasks at constant quality and an unlimited number of cycles. However, there are relevant differences between traditional industrial robots and cobots in terms of deployment, safety, shop floor structure, besides the fact that the traditional industrial robot programming is a task for experts. The investigation in terms of practical perspective of the organization is a major target of a technical feasibility analysis, once technological advances in robotics might directly lead to the reduction of production infrastructure investments to receive the automation solution. This allows the organization to increase its competitiveness against other players in the market.

As presented in the literature review in Chapter 2, cobot provides safe applications when working besides humans without relevant investments in protective guarding. It is designed to be easy to program, easy to re-deploy, and flexible in setup. Therefore, to evaluate the technical aspects of a feasibility study and how feasible it is to automate manual tasks based on a collaborative mode, the subsequent variables should be identified prior to perform the technical analysis of cobot adoption:

a) **Availability of cobot technology in the local market:** Technological advances in robotics have now enabled an operational feasibility environment with small changes, quality of output, ease of use, including what sort of technical assistance support services vendor provides for the local market (BOGUE, 2016). The origin of the equipment, whether local or imported, the potential cobot supplier, savings on maintenance, warranty terms, availability of spare parts, and technical support are the usual questions to define the type of equipment the company is looking for;

b) **Technical expertise or skill shortage -** The technology could be available at the local market, but a lack of skills required to properly deal with such technology could happen (MATEUS et al., 2020). The labor need, skilled or unskilled, hiring new operators or training the current staff, whether training or building a new team, will affect the project implementation schedule of the collaborative workstation (ACCORSI et al., 2019). In fact, if the production staff lacks the necessary qualification to perform no cognitive tasks, they should be allocated to the cobot;

c) **Building and facilities –** Normally the costs of building and facilities improvements in the shop floor, including water, air, and power supply installation should be adapted to the robot that will be used in the production line (FACCIO; BOTTIN; ROSATI, 2019);

d) **Site foundations and floor –** Normally, extra costs are being expended with the floor reinforcement to increase its load-bearing capacity to receive the industrial robot and other production pieces of equipment. The floor should consist of a slab of reinforced concrete and impermeable to groundwater. This is not applied to the cobot solution, once its design is based on lightweight materials (BLOSS, 2016).

e) **Shop floor Layout –** The workstation layout determines the way in which materials, people and information flow through the process operation (MARVEL, 2013). Usually, the layout concept depends on the product volume and it is planned to avoid costs with many parts in inventory and during the work progress (LJASENKO et al., 2019). The layout of a collaborative workstation shall consider inherent safely, flexibility for new product family arrangements, and should make optimal use of the total floor space available (ROBLA-GÓMEZ et al., 2017, ANDRISANO et al., 2012, KRÜGER; LIEN; VERL, 2009). It should also be considered that the product characteristics have a direct impact in the workstation layout and in the complexity of production process flow. Impacts in manufacturing facility costs to receive the layout could also occur;

f) **Product, process variants and customization -** To assess the tasks planned to be shared with cobot based on the variety of products and the associated different requirements for assembly (SALUNKHE et al., 2019). The analysis includes the potential of producing a wide mix with low volumes in a "batch" mode. In general, batch size suggests that the company is being asked by its customers to add production capacity on the shop floor in terms of quantity and quality to reach customization and production flexibility to attend the customer demand (HEILALA; VOHO, 2001; BRUNO; ANTONELLI, 2018; ROSATI et al., 2013). Nevertheless, the process should be reliable with short setup time costs, focusing on a quick product-launching phase, a faster delivery time. Therefore, the manufacturing process and product variant conditions might be able to capture the customer needs on time (CHEN et al., 2013).

3.1.2 Proposed guideline to evaluate technical feasibility analysis

Next, this work evaluates scenarios affecting the production process to predict the technical feasibility evaluation. A previous simulation study of assembly tasks is a tool available for engineers, during process planning, to simulate a wide range of applications in the field of traditional industrial robots applied in larger systems. The simulation can support the implementation of the collaborative robot investigating previously the automation of manual tasks in a collaborative mode, seeking for those related to non-value-adding processes, physical strain, or monotonous work, releasing the human co-worker to concentrate on cognitive tasks. In the case of the use of cobots, the simulation is proposed to assure that the cobot can reach a cycle time in each collaborative assembly task situation, besides simulates a proposed assembly sequence in a collaborative workstation.

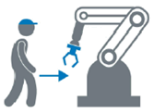
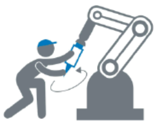
Such simulation supports the technical feasibility analysis identifying potential problems during task allocation between cobot and human co-worker, checking the availability of space even offer sufficient freedom of cobot arm movement. Workers and engineers with basic robot programming knowledge can easily configure the cobot motion sequences during the process planning development. The cobot programming activities are used to investigate the angle of the cobot arm, the directions that the arm has to move, cobot arm's speed of movement to finalize the assembly task, and reach the planned cycle time are activities to certify the technical feasibility analysis. Inaccuracies in the cobot end-effector movement, which can be dangerous for the human-coworker are relevant during cobot programming to assure safety for the human co-worker.

As mentioned in the specific literature, non-experts can program cobots. For instance, a linear movement for easier assembly tasks comprising of two points, as a load and unload parts, can be quickly and easily programmed. For tasks that require more movements, the cobot is oriented based on the CAD part model where a program is uploaded into the software. Even with the support of a simulation tool, is possible to encounter applications that are not so technically feasible to implement.

Besides the positive impact of the simulation to investigate the collaborative assembly process, special standards must be met to ensure the safety of human-robot collaboration during assembly tasks. An addition, support the technical feasibility evaluation to estimate whether the use of cobots is financially worthwhile for the respective collaborative workstation. From an international perspective, the International Organization for Standardization (ISO) provides definitions of collaborative work to enable the expansion of applications of collaborative robots in manufacturing. To develop an approach to assess the collaboration between humans and industrial robots, ISO published, earlier in 2016, the ISO/TS 15066 (ISO, 2016) to complement the ISO 10218 (International Safety Standards - parts 1 and 2). Such specifications introduced safety standards to meet the requirements of a collaborative operation (CHEMWENO; PINTELON; DECRE, 2020; GUIOCHET; MACHIN; WAESELYNCK, 2017).

Figure 8 shows collaborative operation scenarios based on ISO/TS 15066, which includes four techniques for collaborative operation: safety-rated monitored stop (SMS), hand guiding operation (HG), speed and separation monitoring (SSM), power and force liming (PFL) (CHEMWENO; PINTELON; DECRE, 2020).

Figure 8 – Collaborative operation scenarios based on ISO/TS 15066

Collaboration mode ISO / TS15066	**Collaboration aspects**	**Authors**
Safety-rated Monitored Stop 	When the worker moves in the collaborative workspace, the robot stops and stays in another zone to avoid any contact. Moves, but not both at the same time	Djuric, Urbanic and Rickli (2016); Hull and Minarcin (2016); Bdiwi, Pfeifer and Sterzing (2017); Chemweno, Pintelon and Decre (2020); Magrini et al. (2020)
Hand-guided 	The worker can teach the robot by guiding it during the operation. The robot controlled by the operator. Both can move at the same time	Djuric, Urbanic and Rickli (2016); Hull and Minarcin (2016); Bdiwi, Pfeifer and Sterzing (2017); Chemweno, Pintelon and Decre (2020); Magrini et al. (2020)
Speed & Separation Monitoring 	Speed and separation based on safety zones. The laser sensor distance allocated in the robot detects when the worker runs close to the robot and the robot slows down and stops movements. Both can move at the same time, but the robot will slow upon approach	Djuric, Urbanic and Rickli (2016); Hull and Minarcin (2016); Marvel (2013); Chemweno, Pintelon and Decre (2020); Magrini et al. (2020); Ceriani et al. (2015)
Power and Force Limited 	The robot cannot apply enough force to injure and reacts when contact occurs. Risk assessment required. Both can move at the same time	Djuric, Urbanic and Rickli (2016); Hull and Minarcin (2016); Bdiwi, Pfeifer and Sterzing (2017); Chemweno, Pintelon and Decre (2020); Magrini et al. (2020)

Source: Adapted from Chemweno, Pintelon and Decre (2020).

3.1.3 Inherent safety design features

In terms of industrial collaborative workstation design, safety is a priority factor (CHEMWENO; PINTELON; DECRE, 2020; DJURIC; URBANIC; RICKLI, 2016). To enhance the safety of humans and mitigate risks when working alongside robots a proper design of the safe work cell concept should be implemented in the workplace to integrate the robot system and human cognition, including interfaces and safe strategies (MICHALOS et al., 2014). The target of a safety concept is to prevent the occurrence of any injury, hazard, or danger to humans when working with industrial collaborative robots.

The safety in a shared workspace allows the collaboration between humans and robots tasks being done at the same time and at the same place, with force, speed, and movement control (DJURIC; URBANIC; RICKLI, 2016). Thus, this work proposes a workstation safety design based on the literature, including the guiding standards, the robot system design, the robot technology, and the planning of the safety scenario, including passive safeguards, active safeguards (control-related), and risk-oriented approach, as follows:

a. **Guiding standards**: should be applied to assure the safety of the workspace and should be guided by the international safety standard ISO 10218 (DJURIC; URBANIC; RICKLI, 2016), comprising also a risk assessment evaluation as per ISO 12100. By doing this, it will be possible to enhance and improve the operational safety conditions during cooperation and collaboration with a cobot (CHERUBINI et al., 2016; GUIOCHET; MACHIN; WAESELYNCK, 2017).

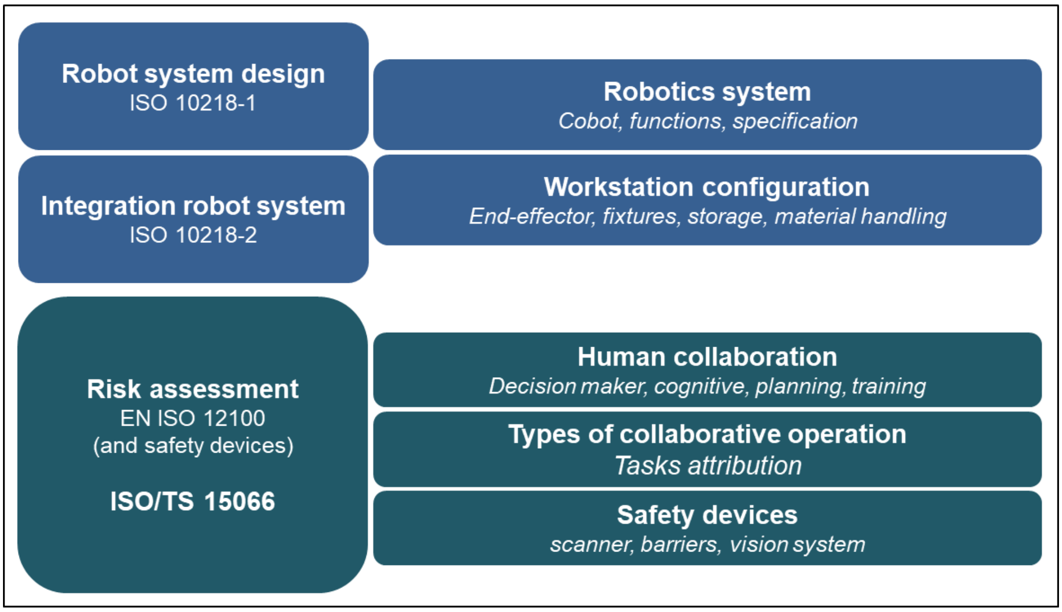
b. **Robot system design**: encompassing the industrial robot specification (payload, speed, and accuracy required), an end-effector selection, the parts to be handled by the robot, and additionally any safety equipment required by the risk assessment analysis, such as light barriers, sensors, and vision camera to support the robot to perform its task (KHALID et al., 2016; KHALID et al., 2018; MÜLLER; VETTE; GEENEN, 2017);

c. **Robot technology:** an industrial collaborative robot can be used in a collaborative operation (PESHKIN et al., 2001) to perform repetitive tasks or those where no special skills are required (IBARGUREN et al., 2015; CHERUBINI et al., 2016) and designed with a lightweight material technology (MAGRINI et al., 2020);

d. **Collaborative safety scenario**: in order to have an industrial collaborative environment, the ISO/TS 15066 criteria should be applied following the four different types of collaborative operation (MAGRINI et al., 2020). Force and torque limiting functions, deceleration, and robot stopping functions (BLOSS, 2016), determining the optimal position for locating the interface between humans and robots during task performance, thereby effective for the collision avoidance (VILLANI et al., 2018; DJURIC; URBANIC; RICKLI, 2016).

Figure 9 shows the framework requirements proposed in this work for the use of the collaborative robot to perform the technical feasibility study, including the robot standards, robotic system design, robot technology, and the technical specification ISO/TS 15066.

Figure 9 – Safety configuration framework of a collaborative workstation



Source: Author, adapted from Marvel, Falco and Marstio (2014).

The application of safety standards shown in Figure 9 requires an interpretation of the safety conditions of operators, which must be associated with the sensing resources available. In the case of collaborative operation, risk assessment methodologies should be applied (GOPINATH; JOHANSEN, 2016).

3.1.4 Collaborative workstation layout

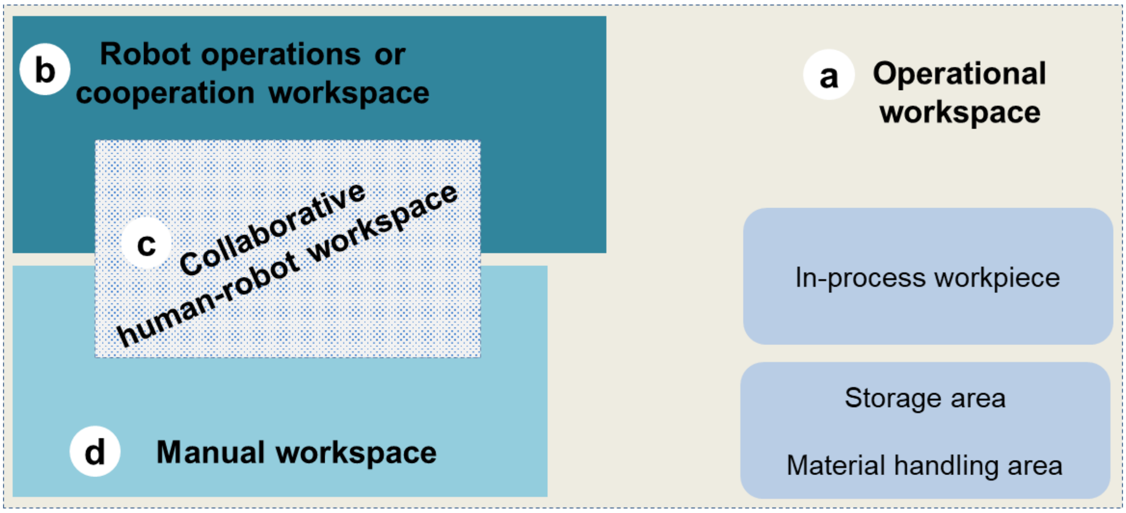
A collaborative workstation layout configuration is designed to generate the workstation, including equipment, shop floor utilities, product characteristics, and the proposition of an optimal task allocation between human and robot to perform the assembly operations (WANG et al., 2019; SCHOLER; VETTE; RAINER, 2015). It includes the right workload distribution, especially those related to the main skills and strengths of both human and robot (BRUNO; ANTONELLI, 2018; MALIK; BILBERG, 2019). In the Collaborative workstation layout, the cobot with the required safety device could be an agent, which can carry out different parts in weight and size to support the human co-worker in continuous, repetitive, and non-ergonomic assembly tasks (MARVEL; FALCO; MARSTIO, 2014). The operational layout concept indicated in Figure 10 planned to encompass the entire operational workspace. It comprises three groups of operational layouts planned when humans and robots share a workstation: human operations, robot operations, and collaborative human-robot operations (MICHALOS et al., 2018).

a. **Operational workspace**: focuses on process and material flow, space between equipment, parts to be assembled, in-process workpiece flow, batches, logistic planning, material handling, and inventory allocation area (MARVEL; FALCO; MARSTIO, 2014). The operational layout includes space to add the robot and safety equipment required to perform the collaborative operation with its human co-worker.
b. **Robot operations or cooperation assembly workspace**: where humans and robots perform tasks at different times, but in the same workspace. Cobot is dedicated to carrying out parts automatically without human intervention. The workstation design should consider that there is no overlap between human and robot movements in a non-collaborative task. In this area, the robot can run at a high speed, used for repetitive tasks, providing a high level of capability and performance (KRÜGER; LIEN; VERL, 2009);
c. **Collaborative human-robot workspace**: or the collaborative assembly workspace is a particular kind of operation and is designed to plan the parts to be handled and distributed between human and robot tasks in a collaborative mode. In the collaborative assembly workspace, the robotic system, which includes the cobot, end-effector and the part to be handled automatically and the human co-worker, is able to perform different tasks simultaneously in direct cooperation, at the same time and in the same space (SCHOLER; VETTE; RAINER, 2015). The human workload, more specifically, the efforts of the human co-worker to finalize the assembly tasks on the planned time related to the

collaborative workstation should be planned in order to mitigate the physical and mental stresses, including an ergonomic evaluation of movements and tasks, to avoid hazards for the human co-worker as well (GERVASI; MASTROGIACONNO; FRANCESCHINI, 2020). A risk assessment should be performed to identify the limiting criteria of forces and robot speed in case of a collision (CHEMWENO; PINTELON; DECRE, 2020; GUIOCHET; MACHIN; WAESELYNCK, 2017);

d. **Human operations or manual workspace**: it is planned to release the worker to complete the assembly tasks (GUIOCHET; MACHIN; WAESELYNCK, 2017). The cognitive tasks including the level of production, maintenance planning, material flow control, decision-making, quality control. Adjustments in the collaborative workstation among others are carried out by workers. Here it is included metrics to evaluate the speed-monitoring separation in shared workspaces (MARVEL, 2013).

Figure 10 – Operational layout concept



Source: Author, adapted from Marvel (2013).

Figure 10 describes to what degree the layout would benefit the production process flow, the level of deployment, and its flexibility for the trade dynamics due to the market-changing scenarios. The operational layout exploits how well the operational layout would work, and how well received this layout solution would be from both, management, workers, and it is a key reason why the organization is able to release the technical feasibility analysis.

3.1.5 Conceptual guideline to perform the technical feasibility analysis

To conclude this chapter, and to provide engineers with essential data-driven information to carry out a technical feasibility analysis, the proposed guideline indicates in its first section a set of primary elements subject to mandatory requirements to be included in manufacturing systems that incorporate collaborative robots. The purpose of such mandatory requirements, which is indicated in the first section of the proposed guideline, approaches the deployment of a collaborative workstation referred to in the literature, covering the primary technical aspects related to the cobot use (ZANCHETTIN et al., 2015; ROBLA-GÓMEZ et al., 2017). The mandatory requirements are criteria to cover technical issues during the collaborative workstation design phase (VILLANI et al., 2018). Such requirements are mandatory to introduce cobot in a production environment, independent of the field or size of the company (MOEUF et al., 2020; WUEST; THOBEN, 2011). To put this into this work perspective, both, large company or SMEs, needs to follow the mandatory requirements before the cobot adoption.

The second section of the proposed guideline is related to a set of desirable requirements that enhance the performance of the feasibility study and could be used as a support during the design phase of the project. Such desirable requirements are normally comprised of a set of software tools to investigate the proposed automation solution, conducting a process simulation, a cycle time check, or a virtual reality of the station to identify any interface between the equipment and the process, for instance (OBERC et al., 2019). Such technological tools require an investment in engineering structure, including computer systems, a simulation database, and a server system Infrastructure developed by the Information Technology (IT) department, software license's management, and training for the production engineers.

Although the technological tools support engineers to investigate in detail the technical feasibility of a proposed production process, the required investments to build such kind of structure are available normally in large corporations, and with a worldwide footprint (GARCIA et al., 2007). Such a company profile provides, for example, the possibility to share investigations about a new technology among other subsidiaries to make decisions before releasing a technical feasibility study. In fact, the large organizations have the possibility to share the costs of the software licenses, besides, combine their engineering staff experience and culture with other branches. Those possibilities gathered by a large organization are a natural economic and technical barrier which is faced by SMEs to manage investment costs in technological tools (MÜLLER; VOIGST, 2017), but they are considered not a mandatory requirement as criteria do adopt cobot in the shop floor. The desirable requirements define additional actions that the company should take to release the use of cobot. Therefore, the company may implement those actions in the future.

Nevertheless, to adopt the use of the cobot in SMEs, this work proposes a proposed guideline comprising of a set of requirements gathered in the literature, which are useful to develop a technical feasibility analysis. The guideline is up to date with the literature and it reflects the state of the art to implement cobots in a production environment. The main purpose of the guideline is to support engineers during design and planning phases to investigate the technical aspects of cobot adoption before submitting the project to the management approval. The proposed guideline to perform a technical feasibility study to adopt cobot is shown in Table 14.

Table 14 – Proposed research guideline for technical feasibility analysis

Mandatory Requirements	**Reference**	**Yes**	**No**
ISO / TS 15066 technical specifications to introduce safety standards	Guiochet, Machin and Waeselynck (2017)		
Robot design and system integration according to ISO 10218 (International Safety Standards - parts 1 and 2)	Djuric, Urbanic and Rickli (2016)		
HRC rules: collaborative workstation design according to the types of collaborative operation	Chemweno, Pintelon and Decre (2020)		
Compliant risk assessment: evaluate potential contact between portions of the robot system and a human operator	Guiochet, Machin and Waeselynck (2017)		
Robot system design and safety requirements	Khalid et al. (2018)		
Robot design with a lightweight material technology	Magrini et al. (2020)		
Safety configuration of a collaborative workstation	Marvel, Falco and Marstio (2014)		
Design and usability of collaborative workstation and operational layouts	Zanchettin et al. (2015); Robla-Gómez et al. (2017).		
Public policy towards cobot technology for each country	Bloss (2016)		

Desirable Requirements	**Reference**	**Yes**	**No**	**Actions Required**
Design phase criteria - map the manual process to be automated and translate this manual task into a robotic task	Müller, Vette and Geenen (2017)			

Table 14 (continued)

Integration phase criteria - it is possible to automate a whole application with a short setup time	Heilala and Voho, 2001; Lotter (2012)			
Operation phase criteria - supports remote connection and performance software	Djuric, Urbanic and Rickli (2016); Groover (2017)			
Batch production (specified groups or amounts of products)	Heilala and Voho (2001)			
Degree of automation, flexibility (attributes between human and robot)	Groover (2017), Lotter (2012)			
Availability of Industry 4.0 enabler to increase performance and competitiveness	Pech and Vrchota (2020)			
Lack of expertise: robot programming expert	Wang et al. (2017)			
Markings, signs and written warnings additional to the risk assessment	Wang et al. (2019); Hull and Minarcin (2016)			
Warnings and safety work concepts (lamps, etc.)	Michalos et al. (2014); Cherubini et al. (2016)			
Training for the Production engineers	Marvel (2013)			
In-house software robotics expertise	Barguren et al. (2015); Cherubini et al. (2016)			

Source: Author.

Following the design of the conceptual feasibility model, the research guideline to perform a feasibility study can be carried out to perform the technical section of the conceptual feasibility model.

3.2 ECONOMIC FEASIBILITY ANALYSIS

As presented in the literature review, the economic feasibility analysis should compare the initial investment expenditures to acquire the cobot and the installation costs of the collaborative workstation with the increase in revenues or cost-savings generated over time with the use of the proposed equipment. Therefore, the first step to perform the aforementioned analysis is to identify the economic variables to enable the desired evaluation, followed by a proposed technique to make the comparison between investment and related earnings / cost savings.

3.2.1 Economic variables for the economic feasibility analysis

Based on what has been presented so far, the first step to perform an economic feasibility analysis is the definition of the economic variables to be considered. Based on Sullivan et al. (2018), they are:

a. **Initial investment to acquire the cobot** – One of the first data to be obtained is the total investment required to acquire the adequate cobot. Here, besides the cobot cost itself, it should be considered that all other expenditures required to have operational and running. Some examples are: cobot installation costs, peripheral costs, labor training to program and operate the collaborative robot, emergency spare parts needed etc.

b. **Initial investment to install the collaborative workstation** – As explained before, the cobot will operate alongside its human counterpart to accomplish the manufacturing operations assigned to this workstation. Also, some examples of such engineering costs expenditures are robot end-effector and suction cups to be assembled in robot arm and safety assessment (vision systems or force sensing to identify human position and to handling product, which depend on the risk assessment);

c. **Other startup costs** – In many cases there may be some other costs incurred before the workstation where the cobot is installed becomes operational. As part of this kind of expenditures it could be mentioned: layout rearrangements to accommodate the new collaborative workstation, adjustments required in the material storage, handling facilities, robot protection for hygienic environments;

d. **Cost savings resulting from the cobot utilization** – In many cases, the utilization of cobots in the manufacturing process aims to reduce the labor content or improve the safety level of an operation. To allow an adequate evaluation of the economic feasibility of a cobot application, these cost savings and hazardous factors should be translated into monetary values. The labor reductions could be determined by comparing the total labor costs employed in the workstation before the cobot utilization with an estimation of the same after its adoption. The difference should be adjusted for the subsequent annual volumes and forecast for at least five years ahead. In relation to the hazardous conditions with the cobot use, estimated costs savings with reduction of investment in safety fences, scanners and light barriers in the workstation are expected compared to the deployment of a traditional industrial robot. Such engineering cost savings are results from the risk assessment evaluation to clearly identify the safety concerns related to humans during collaborative assembly tasks, especially when the cobot is moving parts with sharp edges or using a cutting tool in robot's arm. Other estimated cost savings could be reached by reduction of scrap and rework, which normally occurred in a typical manual operation where humans are performing repetitive tasks.

e. **Additional revenues generated by the new collaborative workstation** – There are cases where the utilization of cobot by a SME will eliminate an existing production bottleneck, allowing this manufacturing line to increase product output. In this case, the additional volume will generate additional contribution margin[1], which will directly improve the company profits. These additional profits could be related solely to the cobot utilization. The annual additional profits should be adjusted for the subsequent annual volumes and forecast for at least five years ahead.

f. **Power consumption of cobot -** Robot trajectory, joints positions and velocity of the robot arm are factors, which affect the power consumption of industrial robotics cells. A mentioned in Chapter 2, simulation tolls supporting engineers in optimize robot movements to save to save energy consumption (BROSSOG; BORNSCHLEGL; FRANKE, 2015). According to the technical specifications of UR10 cobot series, the power consumption of that model is approximately 350 watts, when applied in a typical robot program.

3.2.2 Economic feasibility evaluation

According to Sullivan et al. (2018), the economic feasibility evaluation of a given project comprises three steps: a) building up an Income Statement for a period of at

[1] Contribution margin is the excess of net sales over the variable costs of a product. It is the amount of money available to cover fixed costs and generate profits (Shim and Siegel, 2009). If the fixed costs remain practically constant with the cobot utilization (they will be increased only by cobot etc. depreciation), the additional contribution margin obtained will percolate directly to profits.

least five years (longer periods could be used upon company conveniences), where the annual revenues and / or cost reductions are considered alongside with the project specific annual operating costs and expenses, producing as a final product the annual additional profits generated by the investment (see Table 15); b) building up a Cash Flow for the same period as the one considered for the Income Statement, where the initial investment (assumed to be spent in year “0”) is shown with the profit generation for the future periods, plus some additional adjustments as it will be described later on (see Table 16); and c) the calculation of decision-making indicators that will allow the project incumbent to decide if the proposed investment is feasible.

Is part of the model proposed by this work, a suggested Income Statement form that, besides meeting the requirements recommended by Sullivan et al. (2018), be easily understood and friendly fulfilled by SME practitioners. Therefore, the spreadsheet shown in Table 15 is recommended.

Table 15 – Suggested Income Statement

(Values in €)	Year					
Total Cost Savings due to Cobot Utilization (a)	**0**	**1**	**2**	**3**	**4**	**5**
Additional Contribution Margin due to Cobot Utilization (a)	-					
Total Additional Income	-					
Operational Costs and Expenses due to Cobot Utilization	-	**0**	**0**	**0**	**0**	**0**
- Depreciation	-					
- Cobot Maintenance	-					
-	-					
-	-					
-	-					
Total Operational Costs and Expenses	-	**0**	**0**	**0**	**0**	**0**
Additional Gross Profit due to Cobot Utilization	-	0	0	0	0	0
- Income Tax	-	0	0	0	0	0
Additional Net Profit due to Cobot Utilization	-	0	0	0	0	0

(a) Detail values in separate support sheets.

Source: Prepared by the author.

Using the same approach applied for the Income Statement (technical requirements as proposed by Sullivan et al. (2018) and easiness to fulfil), the Cash Flow form can be proposed as another spreadsheet show in Table 16. As usual in Engineering Economy studies, there is a convention where the incoming values in the cash flow are represented by positive figures while outflows are considered as negative amounts.

Table 16 – Suggested Cash Flow

(Values in €)	Year 0	1	2	3	4	5
Initial investment to acquire the cobot (a)						
Initial investment to install the collaborative workstation (a)						
Other startup costs (a)						
Total Investment	0					
Additional Net Profit due to cobot utilization						
- Depreciation						
- Other Incomes (a)						
Other Expenses (a)						
Net Cash Flow	0	0	0	0	0	0

(a) Detail values in separate support sheets.
Source: Prepared by the author.

The principles of Engineering Economy teach that to decide if a given investment is viable, there are three most frequently used indicators to do that: a) Net Present Value (NPV); b) Internal Rate of Return (IRR) and c) Discounted Payback Period (DPP) (SAMANEZ, 2009).

However, before describing how to calculate each one of them, it is necessary to access the concept of Minimum Attractive Rate of Return (MARR). Sullivan et al. (2018) define the MARR as the minimum return rate the fund provider for an investment expects to receive due to the benefits resulting from it. Samanez (2009) suggests two ways for an investor / company define the MARR: a) If the company has its own capital to invest, the MARR should be the interest rate that such capital would be receiving if applied in the financial market plus a project risk related premium (the higher the project risk, the higher the premium); and b) If the company does not have its own capital to invest and goes to the financial market to obtain it, the MARR should be the cost to obtain said capital also adjusted for a project risk related premium.

Even though these are well established concepts for those working in the financial area of companies, this consideration could not be valid when pondering SMEs, especially considering the “S” part of them. In fact, Lucato (2013) indicates that many small sized companies are run by the proprietor itself or by him or her supported by family members. The degree of professionalization and the utilization of sophisticated financial concepts in this kind of company is extremely low.

Therefore, the MARR concept could not be presented as defined above because it would be considered too complex, what goes against the fundamental principles of the model developed herein (easy to understand and friendly to use). To overcome this issue, the present development will indirectly define the MARR by asking the person who oversees the feasibility study the following question: *"What is the* <u>*minimum*</u> *return rate (in % per year) would you like this investment to bring back to your company?* The answer will be the MARR to be considered in the economic feasibility analysis.

Another question relates to the minimum payback period accepted by a company to consider an investment viable. Likewise, many considerations could be made about it, but for practical reasons and as explained earlier, its determination could be practically done by answering the following question: "*What is the* <u>*maximum*</u> *period (in months) would you like this investment to return back to your company?* The response will be the minimum payback period to be considered in the economic feasibility analysis.

Back to the decision-making indicator calculation, it should be assumed that for the great majority of investment projects, the typical cash flow would look like the one shown I Table 17, where:

I – Initial investment (shown as negative value because it represents an outflow)

i – Minimum Attractive rate of Return

p – Maximum accepted payback period

R1 to R5 – Returns obtained by the initial investment from year 1 to year 5 (shown as positive values because they represent inflows)

Table 17 – Typical Net Cash flow for investment projects

(Values in €)		**Year 0**	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Net Cash Flow		-I	R1	R2	R3	R4	R5
What is the minimum return rate would you like this investment to bring back to your company (% per year)	i						
What is the maximum period would you like this investment to return back to your company (in months)	p						

Source: prepared by the author.

Based on this net cash flow representation, its Net Present Value (NPV) can be calculated by the following formula (Samanez, 2009):

$$NPV = -I + \frac{R1}{(1+i)} + \frac{R2}{(1+i)^2} + \frac{R3}{(1+i)^3} + \frac{R4}{(1+i)^4} + \frac{R5\ (^2)}{(1+i)^5} \qquad (1)$$

As can be seen from this calculation, the factors $\frac{Rn}{(1+i)^n}$ bring each one of the respective returns to date zero, by discounting them at the MARR rate. Therefore, if the sum of all returns in date zero will be higher than the initial investment, this means that the proposed investment is viable and consequently the NPV will be positive. Otherwise, if the sum of returns in date zero will not be enough to surpass the initial investment, this makes the proposed project not viable and the NPV is negative.

Another possibility is to evaluate an investment feasibility by calculating its Internal Rate of Return (IRR). According to Sullivan et al. (2018), the IRR is the interest rate that makes the NPV of a given cash flow null. Therefore, to calculate the IRR the following formula should be used:

$$0 = -I + \frac{R1}{(1+IRR)} + \frac{R2}{(1+IRR)^2} + \frac{R3}{(1+IRR)^3} + \frac{R4}{(1+IRR)^4} + \frac{R5\ (^3)}{(1+IRR)^5} \qquad (2)$$

This calculation when performed manually involves not quite simple linear interpolation. However, modern calculation resources like Excel® or equivalent spreadsheets or financial calculators available for download in cell phones, make the IRR determination a straightforward task.

Finally, it is possible to evaluate the investment feasibility by calculating its Discounted Payback Period (DPP). Sullivan et al. (2018) indicate a formula to calculate approximately the DPP (N_p expressed in months) of a cash flow as follows:

$$N_p = \frac{I}{\frac{R1}{(1+i)} + \frac{R2}{(1+i)^2} + \frac{R3}{(1+i)^3} + \frac{R4}{(1+i)^4} + \frac{R5\ (^4)}{(1+i)^5}} \times 5 \times 12 \qquad (3)$$

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(2) If the economic analysis performed involves more than 5 years of returns, the formula will be the same, just adding as many $\frac{Rn}{(1+i)^n}$ factors as required.

(3) If the economic analysis performed involves more than 5 years of returns, the formula will be the same, just adding as many $\frac{Rn}{(1+i)^n}$ factors as required.

(4) If the economic analysis performed involves more than 5 years of returns, the formula will be the same, just adding as many $\frac{Rn}{(1+i)^n}$ factors as required plus adjusting the number of years of returns considered.

The decision-making criteria to be applied here are: a) If $N_p \leq p$, the investment is considered viable; and b) If $N_p > p$, it is assumed not viable according to the established expectations form the company.

Analyzing these three possibilities, it seems that for a SME practitioner or manager, the concepts of IRR e DPP it is more easily understood, reason why this dissertation will assume these two concepts as those to be considered in the economic feasibility model as the viability decision-making indexes. In fact, understanding the meaning of a positive or negative NPV involves the comprehension of how its calculation is made, which, as said before, is not a simple thing for small business owners and/or managers. For this specific reason, this development will not consider NPV as a possible decision indicator.

To complete the economic analysis of the proposed model, it is relevant to mention that to fulfil the forms shown above and process the respective calculations, an Excel® or another equivalent spreadsheet should be prepared in advance. As part of this work, the Appendix 1 shows said worksheet in which values are integrated and all required formulas added. All a SME practitioner or manager must do is to fulfil the yellow cells and the results of ROI and DPP will be automatically calculated and immediately displayed.

Even though all the explanations on how to perform the economic feasibility of a cobot adoption have been duly provided throughout the previous text, it would be quite beneficial for the understanding of a reader the consideration of a practical example where the proposed technique is applied. For that reason, a case study was analyzed, and its description follows.

3.3 FULL INDUSTRIAL CASE STUDY

The development of the exploratory case study proposed by this work focuses on demonstrating the utilization of the proposed feasibility analysis of cobot in a collaborative workstation solution in terms of economic assessment, once the case study is adequate to confirm a theory (VOSS; TSIKRIKTSIS; FROHLICH, 2002). Primarily, the selected case should fall in the boundary of what one wants to study (EISENHARDT, 1989). For this work, a single case was selected to conduct the research described in this sub-section. A qualitative semi-structured interview (YIN, 2017) has been chosen to perform the proposed economic and technical evaluations.

The main company selection criterion to conduct this exploratory case study required an industrial manufacturing environment, where cobot was being considered to be installed in a particular workstation in the production process. The selected company, from now on designated “Alpha”, is an automotive parts supplier established in São Paulo State, Brazil. It has been in operation for more than 30 years, providing automotive parts focusing on a small number of car assemblers. Alpha has around 96 employees and it is classified as an SME following the European Union – EU classification, as shown in Table 5 in Chapter 2.

Related to its production strategy, Alpha has focus on mechanical engineering and manufacturing knowledge. Its manufacturing footprint comprises of a shop floor with diverse production processes, including typical manual assembly stations, measuring equipment for quality control, besides traditional machine tools and machining centers for milling, drilling, cutting, and welding. Some other manufacturing processes include punching, shearing, and bending sheet metal, all performed in the press shop area. In fact, Alpha seeks solutions through easier manufacturing answers that rely on labor-intensive manual production processes (e.g. assembling parts, pins, nuts, studs, and bolts).

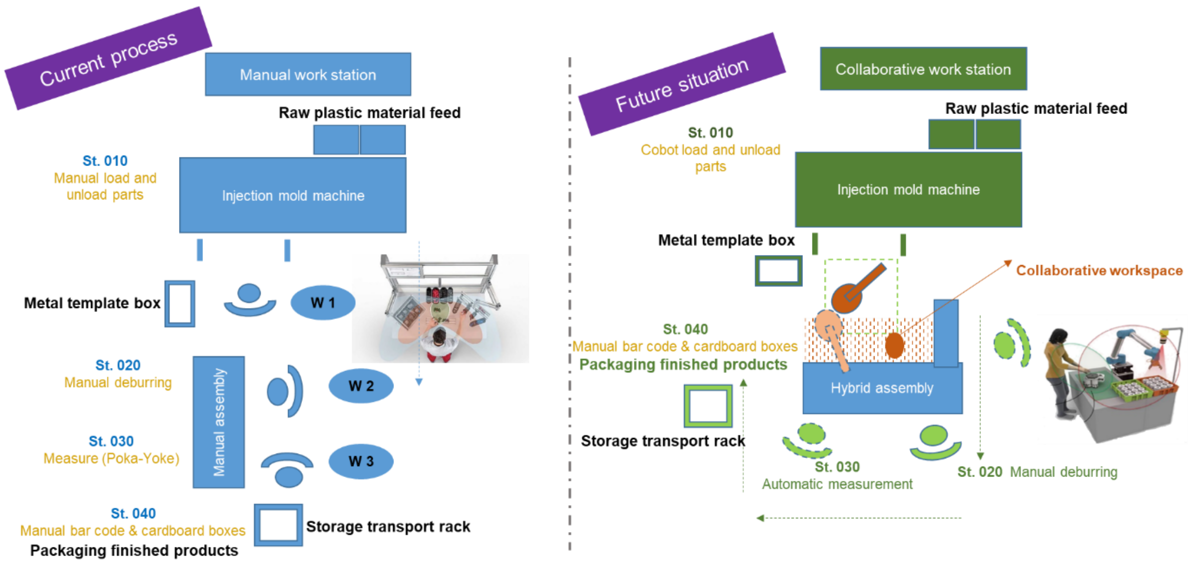
The company is presently facing some manufacturing challenges, especially those related to products with complex design and a low-volume production rate. Alpha has chosen to rely on customer’s recommendations by increasing its level of automation process to reduce scraps and the delivery time. Moreover, Alpha is looking for opportunities to modularize its production process. Lean strategies have been in place for quite some time to improve the production information flow, reducing at the same time all kinds of wastes. Based on this scenario, the company is considering adopting collaborative robots in some workstations as a way to reduce costs and improve process reliability and quality.

3.3.1 Production process

Alpha manufactures sealing fasteners for the carmakers, which involves assembling and handling of components, which became a bottleneck on the production floor. Since Alpha is seeking to scale its production and automation capabilities, the management looked for a cost-effective and robust automated solution to fit its production needs. Since winter 2020, Alpha is planning to adopt one collaborative workstation in one of its production assembly lines. The preliminary design assumptions of such project are based on the current local availability market solutions and intend to follow and update the previous manual assembly tasks process (load and unload parts into the CNC machine, followed by manual assembly tasks to finish the assembly process). As a general idea, a collaborative robot *UR 10e series,* with tasks up to 10 kg from Universal Robots is the first option selected.

Besides the assumptions criteria described above, the main proposition of such investment in cobot automation solution is concentrated in building a collaborative workstation to further evaluate the industrial feasibility of the proposed system to respond to the flexibility needed to attend the market demands. This work emphasizes that the collaborative workstation solution considered by this work is a current internal development and treated as confidential. Nevertheless, the company has authorized the researcher to include in this work a generic planned layout, adding basic information about the process to perform the economic analysis study as proposed here in. Therefore, this work provides the layout shown in Figure 11, which has been built based on preliminary studies developed by Alpha.

Figure 11: Case study - process layout



Source: Author based on company information’s.

This layout can be briefly described as follows:

a) **Present manual workstation (blue color in the layout):**

Station 010 injection molding machine: manual load of metal template into *the* injection-molding tool of the machine. Manual unload parts after the injection cycle is complete. Note: the raw plastic material fed into the machine is handled by the logistics, and such labor is not accounted in this process;

Station 020 hand deburring: in a workbench adapted to perform manual tasks one operator will perform deburring to remove burrs, sharp or unfinished edges and assembly the spiral spring components;

Station 030 finish: another operator measures the product size with a gauge, makes a product visual inspection, and engraves machine operation into finished parts.

Station 040 packing: then the same operator performing operation 30, packs finished products, adds bar code documentation, and load the cardboard boxes, manually stacking finished cardboards into the storage transport rack.

b) Future collaborative workstation (green color in the layout):

Station 010 injection molding machine: the new collaborative robot will perform the load of metal template into the injection-molding tool of the machine and handle the unload parts after the injection cycle is finished.

Station 030 finish: then the cobot will place the molded part into an automated device where the measurement of the product size and engraving machine operation into finished part is automatically performed.

Station 020 hand deburring: one operator removes the part from the automatic device and in a workbench adapted to perform manual tasks will perform deburring to remove burrs, sharp or unfinished edges and assembly the spiral spring components;

Station 040 packing: then the same operator performing operation 20, packs finished products, adds bar code documentation, and load the cardboard boxes, manually stacking finished cardboards into the storage transport rack.

3.3.2 Demonstration of the technical feasibility model

The guideline presented in this chapter was applied at Alpha Company as part of the techno-economic feasibility approach proposed by this work. To do that, a face-to-face meeting was organized by the researcher to explain the goals of the guideline to members of the engineering team designated to design the new collaborative workstation at Alpha company. The engineering manager and one process engineer were nominated to attend such a meeting. In the first phase of the meeting, the researcher highlighted the distinctive characteristics of this work and pointed out relevant information to carry out the technical feasibility study based on the information gathered from the literature.

In the second phase of the meeting, the researcher emphasized that the guideline could be used in conjunction with the design of the proposed collaborative workstation solution as a guideline, and provide eligibility criteria to perform any technical feasibility study. Finally, to ensure that all items listed in the research guideline were covered, the researcher provided an overview of each item to ensure that all engineering members were aware of the content of the guideline.

The researcher's assessment was a detailed revision of the research guideline to ensure that each item was covered, and the engineers made sure that their knowledge and ideas were taken into consideration to develop each element of the new project. Before concluding the meeting, the researcher highlighted that each item of the technical guideline aimed to help the process engineers to prioritize their efforts during the design phase of the new collaborative workstation. Table 18 shown the results of the application of the conceptual model.

Table 18 – Field guideline to release technical feasibility of cobot adoption

Mandatory Requirements	Yes	No
ISO / TS 15066 technical specifications to introduce safety standards	X	
Robot design and system integration according to ISO 10218 (International Safety Standards - parts 1 and 2)	X	
HRC rules: collaborative workstation design according to the types of collaborative operation	X	
Compliant risk assessment: evaluate potential contact between portions of the robot system and a human operator	X	
Robot system design and safety requirements	X	
Robot design with a lightweight material technology	X	
Safety configuration of a collaborative workstation	X	
Design and usability of collaborative workstation and operational layouts	X	
Public policy towards cobot technology for each country	X	

Desirable Requirements	Yes	No	Actions Required
Design phase criteria - map the manual process to be automated and translate this manual task into a robotic task	X		
Integration phase criteria - it is possible to automate a whole application with a short setup time	X		
Operation phase criteria - supports remote connection and performance software		X	Investment in process simulate tool is under investigation to make advance simulations related to the workstation performance.
Batch production (specified groups or amounts of products)	X		
Degree of automation, flexibility (attributes between human and robot)		X	Engineering staff will review the ISO/TS 15066 premises indicated in the mandatory requirements
Availability of Industry 4.0 enabler to increase performance and competitiveness		X	Issue related to the IT department. Efforts in production control software and TQM tools are under development
Lack of expertise: robot programming expert		X	Specific robot programming training related to the new cell will be provide by the system integrator
Markings, signs and written warnings additional to the risk assessment	X		
Warnings and safety work concepts (lamps, etc.)	X		
Training for the Production engineers	X		
In-house software robotics expertise	X		

Source: Author.

As foreseen in Table 18, related to the first section of the technical research guideline, all the mandatory requirements were discussed with the engineering team and a consensus was reached to cover all those mandatory requirements during the design phase of the new collaborative workstation. Related to the second section of the research guideline, focusing on the desirable requirements, some requirements were not present, but the necessary actions in terms of a "*to do list*" were created to provide before the release of the cobot installation. The Alpha management elected the engineering manager to track the evaluation of such a to do list.

After the revision of the technical research guideline, it is foreseen that the technical feasibility study to adopt cobot is reached, once all the mandatory requirements will be covered during the new layout cell design. In terms of the desirable requirements, for those, which are not included, actions were defined by Alpha to implement them before the implementation of the cell on the shop floor.

3.3.3 Demonstration of the economic feasibility model

Table 19 illustrates the project cost, indicating the major items of capital cost, the utilities required for installation and overhead costs that will go into operating the proposed project based on the proposed collaborative workstation shown in Figure 11. Whereas the lack of documentation and information during interviews affects the feasibility calculation, some cost reference, such as the labor costs, were gathered in the market to assess the impact of the cobot's technology adopted in a collaborative workstation. In terms of commissioning costs, it was assumed that the robot programming will be performed by end-user (in-company) after the robot programming training was provided by Universal robots.

Table 19: Commissioning costs to install the collaborative workstation

Subject	**Qt.**	**Supplier**	**Investment cost (in EURO)**
UR 10 cobot	01	Universal Robots	€ 29.850,00
Robot end-effector	01	Schunk / Robotiq	€ 6.152,00
Sensors	01	Sick	€ 1.335,00
Robot programming	35 h	In-company (end-user)	€ 980,00
Training on cobot	20 h	Universal Robots	€ 900,00
Cobot acquisition cost			**€ 39.217,00**
Collaborative workbench	01	Steel fabrication under design	€ 13.320,00
Engineering design costs	250 h	System integrator	€ 8.127.50
Documentation	40 h	System integrator	€ 1.449,60
Installation costs	220 h	System integrator	€ 6.366,80
Risk assessment, ISO/TS 15066	40 h	In-company	€ 1.449,60
Training on process assembly	35 h	In-company	€ 1.012,90
Production support (01 week/02 shift)	40 h	System integrator	€ 1.680,00
Collaborative workstation cost			**€ 33.406,40**
Grand total to install de collaborative workstation			**€ 72.623,40**

Source: Adapted from Alpha Company.

The variables to calculate the production costs are estimated based on the batches sizes to be produced. Alpha has a plan to have a production schedule based on one cobot, which is planned to be installed in the collaborative workstation. Shortly after the cobot system is installed, Alpha will adjust the collaborative workstation to operate in 02 shifts per day, 05 days a week to comply with the production plan. The number of workers estimated per shift and labor costs are variables for production costs considered to perform the economic feasibility study. Table 20 illustrates the variables for production costs before and after the collaborative workstation implementation on the shop floor. The table indicates the results and gains, which were obtained with adoption of the cobot.

Table 20 - Variables for production costs

Variables	**Before cobot adoption (manual station)**	**After cobot installation**	**Savings**
Employees per shift	3	1	# 2
Employees per day	6	2	# 4
Operator monthly wage	€ 920,00	€ 920,00	-
Total monthly cost	€ 5.520,00	€ 1.840,00	€ 3.680,00
Annual labour cost	€ 66.240,00	€ 22.080,00	€ 44.160,00
% cost reduction			**67,0%**

Source: Adapted from Alpha Company.

For the purpose of this work, the criteria to measure the energy consumption (kWh/month) is calculated based on the following variables and equation 4:

I. EC - Energy cost in € / year

II. pc - UR 10 power consumption in Watt = 350 W

III. wh_2 - Working hours / day in two shifts = 17,6 hours

IV. wd - Working days / year = 240 days

V. ce - Cost of energy consumption in São Paulo State = € 2,37/ Kwh

$$EC = \frac{pc \times wh_2 \times wd \times ce}{1{,}000} = \frac{350 \times 17{,}6 \times 240 \times 2{,}37}{1{,}000} = € \ 3{,}508.24/\ year \quad (4)$$

Once the information gathered in Tables 19 and 20 are complete, the next step is to fulfil the spreadsheet shown in Appendix 1. The economic feasibility indicators are automatically calculated as soon as it is complete. Table 21 shows the economic feasibility calculation as per previous information.

Table 21 – Economic feasibility analysis performed for Alpha company

INCOME STATEMENT						
	Year					
(Values in EURO)	**0**	**1**	**2**	**3**	**4**	**5**
Total cost savings due to cobot utilization	-	44.160	44.160	44.160	44.160	44.160
Additional contribution margin due to cobot utilization	-					
Total additional income	-	**44.160**	**44.160**	**44.160**	**44.160**	**44.160**
Operational costs and expenses due to cobot Utilization						
- Depreciation	-	7.262	7.550	7.550	7.550	7.550
- Cobot Maintenance	-	1.833	1.833	1.833	1.833	1.833
- Cobot energy Consumption	-	3.508	3.508	3.508	3.508	3.508
- Technical adjustments required	-					
-	-					
Total operational costs and expenses	-	**12.604**	**12.892**	**12.892**	**12.892**	**12.892**
Additional gross profit due to cobot utilization	-	31.556	31.268	31.268	31.268	31.268
- Income tax	28,5%	8.993	8.912	8.912	8.912	8.912
Additional net profit due to cobot utilization		**22.563**	**22.357**	**22.357**	**22.357**	**22.357**

CASH FLOW						
	Year					
(Values in EURO)	**0**	**1**	**2**	**3**	**4**	**5**
Initial investment to acquire the cobot	-39.217					
Initial investment to install the collaborative workstation	-33.406					
Other startup costs						
Total Investment	**-72.623**					
Additional net profit due to cobot utilization		22.563	22.357	22.357	22.357	22.357
- Depreciation		7.262	7.550	7.550	7.550	7.550
- Other Incomes (a)						
- Other Expenses (a)						
Net cash flow	**-72.623**	**29.825**	**29.907**	**29.907**	**29.907**	**29.907**

What is the minimum return rate would you like this investment to bring back to your company (% per year)	12%	IRR (% per year)	30%
What is the maximum period would you like this investment to return back to your company (in months)	48	Payback period (months)	40

Source: Author.

As can be seen, according to the company approval criteria defined for this kind of investment (12% MARR and 48-month discounted payback period), the acquisition and installation of the proposed cobot would be considered viable from the standpoint of economic feasibility.

4 METHODS

The proposal of this chapter is to present the methodological approach of this research, addressing it to the interrelated research question and the related research objectives, both introduced in Chapter 1. Nevertheless, it is important to emphasize that the methodology applied in searching the key terms in the selected databases to carry out the systematic review of the literature is described in sections 2.4 and 2.5 of Chapter 2.

4.1 DELPHI METHOD

This section introduces the field research activities and describes the tools applied in this dissertation seeking to conduct the collection of raw data in the field of study and to enhance the comparison results with the theory. This section introduces a brief overview of the Delphi technique, which is selected as the research method. The following sub-sections describe a road map to perform the Delphi method proposed in this dissertation to verify the adequacy of the theoretical techno-economic model proposed in Chapter 3.

4.1.1 Delphi method overview

This is exploratory qualitative research. In addition, qualitative research is used when the researcher seeks to understand the contexts or environments in which research participants address a problem (CRESWELL, 2014). In qualitative research, the information gathering from the literature allows the researcher to verify statements and observations about the research theme (SAMPIERI; COLLADO; LUCIO, 2013). According to Yin (2015), qualitative research focuses on capture real conditions and assumes the participant’s perspective of the who are part of these conditions. As described above, this is exploratory research. Related to the nature of this work, following Sampieri, Collado and Lucio (2013, p. 101) *“exploratory studies serve to make us familiar with relatively unknown phenomena, obtain information on the possibility of carrying out a more complete research related to a context particular”*.

For the purpose of this dissertation, the Delphi technique was selected as the method to develop the field research to confirm the suitability of the theoretical model developed in Chapter 3. The first selection criteria were the fact that this method is a widely used research approach (OKOLI; PAWLOWSKI, 2004). Second, the selection of the Delphi method allows this dissertation to obtain quality information from experts in different fields involved in this work. Likewise, the Delphi technique allows the researcher to perform the study in a feasible schedule and at an acceptable cost (MURRY; HAMMONS, 1995).

Another selection criterion was the possibility to access participants from different geographical locations, avoiding face-to-face meetings (TUROFF; LINSTONE, 2002), which is a relevant factor in the face of the present Covid-19 pandemic. Furthermore, the Delphi study is classified in the academic literature as a suitable and flexible research technique used over five decades (LUND, 2020) receiving special attention from academics as a scholarly research method to support graduate students from the doctoral programs in answering their research questions (SKULMOSKI; HARTMAN; KRAHN, 2007).

In addition, the Delphi method has been used in several fields such as science, economy, and technology (LOO, 2002). More specifically, in industrial research, prior investigations relied on the utilization of such a method. For instance, work performed by Beckerle et al. (2018) applied the Delphi method with robotic hand design experts to propose a new robotic hand concept. In this occasion, the Delphi study was performed in 03 rounds with the contribution of professional experts with backgrounds in robotics. In addition, Karuppiah et al. (2020) proposed a Delphi method to investigate barriers to restrict the implementation of green manufacturing practices in SME located in developing countries. Finally, in terms of sustainable development, work performed by Hsu, Chang and Luo (2017) investigated through the Delphi technique how to improve the manufacturing sustainability in SMEs.

4.1.2 Characteristics of Delphi method

As described above, the Delphi method is exploratory qualitative research with an interactive technique used in the academy (HALLOWELL; GAMBATESE, 2010), suited to capture qualitative data (SKULMOSKI; HARTMAN; KRAHN, 2007). According to Skulmoski, Hartman and Krahn (2007), the Delphi technique is widely used in academic graduate, masters, or Ph.D. levels. It differs from traditional surveys because the respondents should be experts in the field of study (HALLOWELL; GAMBATESE, 2010).

The panel of experts is the main characteristic that enhances the use of the Delphi method in academic research, and it is perceived as an attribute to good quality survey feedback, getting consensus among academics and practitioners about a research issue (OKOLI; PAWLOWSKI, 2004). Table 22 summarizes the main features in qualitative research performed by Okoli and Pawlowski (2004) and lists the typical events associated while applying the Delphi technique in comparison with a traditional survey methodology to perform research.

Table 22- Comparison of traditional survey with Delphi method

Evaluation criteria	Traditional survey	Delphi method
Main procedure	Questionnaire protocol adding on its relevant issues addressed the field of research	Questionnaires is applied to Delphi method in several rounds
Population	Researchers decide on the population to attend the survey	Researchers select a group of experts who are qualified to answer the research questions
Survey administration	Researchers select a random sample of the population to administer the survey	The researchers administer the survey and analyze the responses.
Survey analysis	The researchers analyze the usable responses to investigate the research questions	There are loops based on the expert's responses until reach a common degree of consensus among all experts
Representativeness	Researchers randomly select a sample that is representative using statistical sampling techniques	Delphi method is a panel of experts gathered to arrive at an answer to a difficult question
Survey size	Intend to generalize results to a larger population	The literature recommends 10-20 experts on a Delphi panel
Construct validity	is assured by survey design and by pretesting	Can employ a construct validation by asking experts to validate the researcher’s interpretation of the variables
Anonymity	Respondents are almost always anonymous	Respondents are always anonymous to each other, but never anonymous to the researcher
Quality of data	Depends on the form and depth of the questions and efforts in follow-up	An increase in the quality of data because of the multiple iterations and responses revision.

Source: Adapted from Okoli and Pawlowski (2004).

In comparison with a traditional survey methodology shown in Table 22, the Delphi technique requires the most effective use of a group of experts to perform and validate a study through multiple interactions to get a consensus of all experts among several survey rounds. While the traditional survey seeks to summarize the results of the study based on a large population.

Throughout the years, the Delphi method has broadened advantages and limitations as well. Some researchers emphasize the attributes of the Delphi while developing research. According to Avella (2016) and Loo (2002), the Delphi method is a time-tested method used across virtually all disciplines, bringing robustness to ensure a valid study proposed in this dissertation. Such a method is strong for getting consensus among academics and practitioners about a research issue and forecasting an idea about the phenomenon investigated in the research questions (OKOLI; PAWLOWSKI, 2004). An important advantage of the Delphi method is related to its flexibility to perform the survey, once such method could be adapted to a particular situation and does not require the presence of all experts at the same time or same physical location to attend the questionnaire rounds (SKULMOSKI; HARTMAN; KRAHN, 2007).

Nevertheless, the literature indicates that the Delphi method mitigates limitations as well. From the mediator’s perspective, the researcher could be inducted bias and error in the criteria for selection of experts (AVELLA, 2016; LOO, 2002). Depend on the experience level of the mediator a set of poorly developed questions could appear (LUND, 2020; LOO, 2002), and a problematic collation of responses by the researcher could affect the quality of the study (AVELLA, 2016). According to the literature, the Delphi method could bring issues from the expert's perspective, especially the lack of the participant's knowledge about the technique (OKOLI; PAWLOWSKI, 2004). Another issue of the Delphi method gathered in the literature is the potential attrition between participants during the several iterations imposed by the successive questionnaire rounds (YOUSUF, 2007). Following Skulmoski, Hartman and Krahn (2007) the experts in a field of study are often busy and may not be able to attend all questionnaires rounds to get group consensus.

Based on the Delphi assumptions, underlying its strengths and limitations, perhaps, the results of the Delphi study shall validate, by triangulation with another methodology approach (SKULMOSKI; HARTMAN; KRAHN, 2007). The main advantages and limitations gathered in the literature to use the Delphi method as a tool in academic researchers shown in Table 23.

Table 23- Advantages and limitations of Delphi method

Advantages	Limitations
To obtain a genuine consensus of experts as per experts do not know or have never met each other; Expert consensus can be achieved without favoritism, influence, and pressure from any other party	The reliability of the data is highly dependent on the experts involved If researchers fail to choose good experts, the credibility of the findings will be affected. The accuracy of forecasting is constrained by the quality of the views given by the experts A small number of experts are not able to solve all the pertinent aspects of the issue.
Fast to apply and effective Time and cost make typical group meetings infeasible	As the data collection are repeated on the same sample, boredom may set in, affecting the quality of responses No time availability from expert side to participate full time
Can be used to make future expectations Can be used effectively and to get a lot of opinions on complex issues	There is little chance of getting an emotional reply which may be relevant to the issue understudy
The expert's view is consistent with their respective areas of expertise	Delphi is a technique for the foreseeable future, loss of reliability means lose hope and determination

Source: Adapted from Yousuf (2007) and Okoli and Pawlowski (2004).

As shown in Table 23, the Delphi technique can be performed easily and fast. The technique brings robustness to the research through the expert’s experience in the field of study. However, the data certification depends on the time available and efforts of the experts during the several survey rounds.

4.1.3 Method outline

The purpose of this study was to develop a consensus among experts on the use of cobot in SMEs. The procedure to perform the Delphi method of this work is adapted from Schmidt et al. (1997), Schmidt et al. (2001), Okoli and Pawlowski (2004). In addition, it is comprised of a three-step strategy (MURPHY; PERERA; HEANEY, 2015), to address the research question, getting expert opinions, and gain a group consensus about the use of cobot in SME. For the purpose of this work, three hierarchical process steps for optimum performance of the Delphi method is proposed based on author references gathering in the academic literature (ABEL; JESSEN;

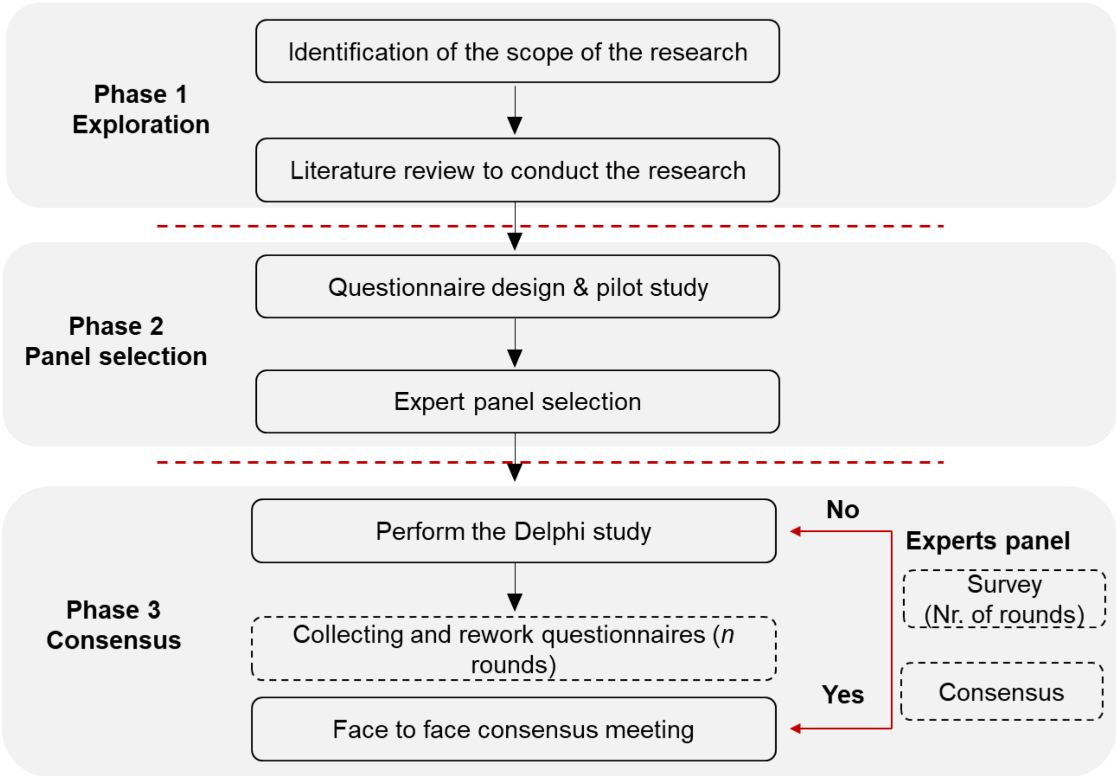
WENZEL, 2013, DARYANI, S. M.; AMINI, 2018, DONOHOE; NEEDHAM, 2009, LOO, 2002):

a. **Phase 1 – Exploration:** the researcher Identifies the research question. Availability criteria must be derived from a general problem defined in the research question. The proposed issues statement based on the literature serves as a basis for the expert panel survey rounds and consensus in carrying out state of art on industrial cobots.

b. **Phase 2 – Panel selection:** The basic question program is implemented in a formal questionnaire. A basic questionnaire for the first round is designed. The researcher to set up the focus groups of experts and design the next rounds of questionnaires for optimal results achieved with the method.

c. **Phase 3 – Utilization:** The researcher shall submit the questions to the expert panel and control the questionnaire's answer in two or more specified steps. During such steps, the questionnaire' is received, reviewed, and analyzed. The experts have the chance to review their previous responses in the final round survey iteration. A list of important information is identified. During the survey rounds, the anonymity of the participants is preserved. The formal Delphi process flowchart of this study is shown in Figure 12.

Figure 12 – Formal Delphi method process



Source: Adapted from Okoli and Pawlowski (2004) and Schmidt et al. (2001).

As shown in Figure 12, the Delphi method adopted to perform this work will guide the field research to address the research question. This implies the exploration of the use of cobot in SME's in a production environment.

4.1.4 Procedures for selecting experts

The main target of this sub-section is to select the participants in a panel of experts, regarding the adequacy of the theoretical model developed in this study. In fact, the goal of the expert panel in this study is to verify the suitability of the proposed model in Chapter 3 related to the real-world situations by the use of cobot in SME under the Brazilian scenario. As mentioned before, the Delphi method is a formal method of communication between researchers and a panel of experts to develop research in the field of study (MURPHY; PERERA; HEANEY, 2015, IDEN; LANGELAND, 2010). For the purpose of this dissertation, an "expert"' by definition is someone having comprehensive or authoritative knowledge or skill sets in a specific area (MURPHY; PERERA; HEANEY, 2015). An expert is one who has special skills or knowledge derived from experience in the field of study (HOFFMAN, 1998). According to the Cambridge Business English Dictionary (2011), an expert is" a person with a high level of knowledge or skill relating to a particular subject or activity".

In terms of population to perform the Delphi study, some researchers have argued that the literature recommends different expert group sizes to perform the Delphi survey rounds. For the purpose of this research, the primary features to perform the Delphi study follow the recommendation from Vidal, Marle and Bocquet (2011), Hallowell and Gambatese (2010) Okoli e Pawlowski (2004), and propose the size group between 9 and 18 participants. According to Vidal, Marle and Bocquet (2011), such group size allow relevant research conclusions and allows consensus among the experts.

Therefore, the panel size to perform the proposed Delphi study of this work is designed to have experts with a heterogeneous professional background, including age and professional experience (YANIV, 2011). Furthermore, in order to bring robustness to the research, the selection of experts predicts an active involvement with the SME environment and the industrial cobot applications in production systems. The researcher's professional experience in the field of industrial robots shall represent support to perform the research.

This dissertation follows work performed by Vidal, Marle and Bocquet (2011) and Okoli e Pawlowski (2004) to build four focus groups to perform the Delphi study, including an amount of 15 experts. They were selected to cover the fields of advanced robotics and the SME's environment and its features. The four-focus disciplines group selection criteria with the most highly qualified experts are summarized as follows:

a. **Focus group 1** – Robotics field: a practitioner expert with knowledge and experience in manufacturing, production systems, and industrial robotics applications. Typical position includes managing director and general manager and having working experience in automation projects with the use of industrial robots;
b. **Focus group 2** – Academia and research: expert with knowledge and experience in production engineering, membership of the industrial committee, writer of publication in academic journals related to the field of study. Industrial research investigations with the objective to identify the challenges faced by the manufacturing industry and production process;
c. **Focus group 3** – Industrial consultant: An external consultant with knowledge and experience to advice around areas of manufacturing,

statistics, industrial robotics, and SME features. Work experience in partnering projects with industry, associations, and the academy;

d. **Focus group 4** – SME environment: a practitioner expert with knowledge and experience with a focus on SME features and automation solutions for this company profile.

In terms of the expert's selection to attend the Delphi study, this dissertation follows work performed by Hallowell, Matthew and Gambatese (2010) to implement the Delphi method proposing a guideline requirements for the expert's identification and selection. The guideline content includes the previous expert's experience in working as a professional user representative in robotics projects or experience in academic life (KEIL; TIWANA; BUSH, 2002). Table 24 shown the guideline for expert selection applied in this work.

Table 24 – Guideline to select and build the expert's panel

Focus-group discipline	Degree	Basic requirements	Specific requirements
Group 1: Robotics field	Engineering	Professional registration and professional activities Employed in the field of study with at least 10 years of professional experience Manager position for company's roles and responsibilities Professional accomplishments in industrial robotics field	Invited to present at a conference Membership sponsored by any industry association Managing product innovation
Group 2: Academy and research	Advanced degree - Ph.D.	Professional registration and professional activities Employed in the field of study with at least 10 years of professional experience Membership or chair at any academic community organization	Conference presentation Peer-reviewed journal article Faculty member at an accredited university Writer of a book chapter, article or conference paper related to industrial research Invited to present at a conference sponsored by any academic community organization
Group 3: Industrial consultant	Engineering, Management, Marketing	Professional registration and professional activities Employed in the field of study with at least 10 years of professional experience Governmental or nongovernmental professional Strategic visibility of future of industrial automation	Conference presentation Invited to present at a conference Membership sponsored by any industries or governmental association Expertise in the provision of adoption of industrial robots and SME issues
Group 4: SME environment	Engineering	Professional registration and professional activities Employed in the field of study with at least 10 years of professional experience Manager position for company's roles and responsibilities Professional accomplishments in industrial robotics field	Managing product innovation Intention to innovate production process

Source: Adapted from Hallowell, Matthew and Gambatese (2010); Chan et al. (2001).

Because the aim of this dissertation is to explore the use of cobot in SMEs in a production environment, the industrial manufacturing experts shown in Table 24 are deemed the most appropriate respondents. This work focuses on achieving a degree of representativeness achieved through the selection of experts. The success of the Delphi method depends principally on the careful selection of the panel to apply the expert knowledge and experience to an issue (AKINS; TOLSON; COLE, 2005). Based on the criteria shown in Table 24, and to obtain the most valuable opinions, only experts who met all the criteria on the issues under this dissertation are located is in a position to be selected (CHAN et al., 2001). Once, only experts possessing more than one of the criteria are in a position to be selected to attend the survey rounds (AKINS; TOLSON; COLE, 2005). To design the expert panel, five steps of a procedure for selecting experts based on work performed by Okoli and Pawlowski (2004) are applied in this work. All five steps are summarized as follows:

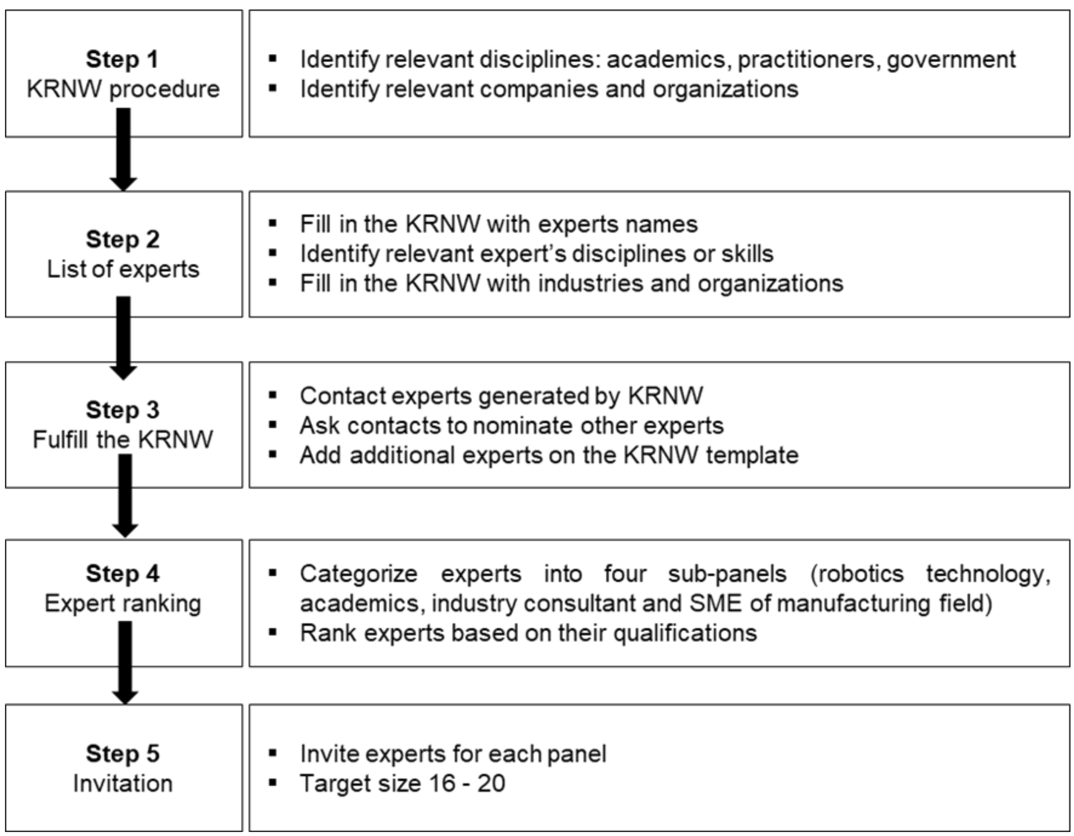
a. **Step 1 – develop KRNW**: build the knowledge resource nomination worksheet (KRNW). The purpose of the KRNW is to enable the categorization of the experts and organizations before selecting them (MURPHY; PERERA; HEANEY, 2015). The KRNW is a procedure to provide the researcher a roadmap to gather expert identification, focusing on qualification and expertise skills to deal with the research question of this work. As this research is targeted at the collaborative robot in SME, the expert categories involve basically engineers and academics from the production systems area;
b. **Step 2 – Populate the KRNW**: collect the potential experts' names of the four focus groups to generate the KRNW template (OKOLI; PAWLOWSKI, 2004), including the expert main degree, special qualifications, relevant specialization, and professional experience in the field of study;
c. **Step 3 – Expert nomination**: use the KRNW template to contact the selected experts to attend the entire number of the survey rounds. Additional experts could be contacted to full fill the KRNW template;

d. **Step 4 – Expert ranking**: build a ranking of the expert's qualifications (Degree, Mater, and Ph.D.) and add more additional experts on the KRNW in case of need. The experts shall be allocated into the four focal groups (robotics technology, academics, industry consultant, and SME of manufacturing field);

e. **Step 5 – Invitation**: the researcher organizes and submits an official and formal invitation to the experts with an individual approach by means of phone calls and e-mail.

The procedure for selecting experts to perform the Delphi is shown in Figure 13.

Figure 13 - Procedure for selecting experts applied to this work



Source: Adapted from Okoli and Pawlowski (2004) and Donohoe and Needham (2009).

Even so, in terms of the expert panel build and selection, a couple of criteria to address the issues were formulated to assess an assured level of gathering information from the specialist panel interviews. The panel selection based on the diversity amongst the specialists can indicate a variety of aspects related to the research question from different sets of perspectives (EISENHARDT; GRAEBNER, 2007). First, the scenarios of the knowledge of a perspective of various fields of competence and effective communication skills related to the research theme (ADLER; ZIGLIO, 1996), such as the academy, business-consulting office, robot manufacturer supplier, and Brazilian SMEs were assumed to build the specialist panel.

In the second, the respondent's professional knowledge and experience (at least with a minimum of 10 years of experience) in the field of competence where this dissertation is located shall meet the basic criteria of the selection (SKULMOSKI; HARTMAN; KRAHN, 2007, ADLER; ZIGLIO, 1996). The expert selection criteria shall include the time availability, capacity, and willingness of the attendant to participate in several rounds' questionnaires duo the expert's professional agenda (SKULMOSKI; HARTMAN; KRAHN, 2007). Besides that, the Brazilian SMEs selection criteria took into consideration the level of respondent's responsibility and leadership decision-making on the shop floor.

Furthermore, participants which belong to the manufacturing sector and industrial organizations were selected to bring relevant skills and experiences to the panel members based on the following core competence criteria:

a) Automation using industrial robots;
b) Collaborative robot applications;
c) Brazilian SMEs laws, regulation specialist;
d) Brazilian SMEs leaders;
e) Brazilian SMEs, which have adopted or have any plan to adopt cobots.

A qualitative approach has been chosen to conduct this subsection, and a semi-structured set of interviews has been conducted in a virtual environment with each expert to reach the group consensus (YOUSUF, 2007, GORDON, 1994). Table 25 shows the preliminary design of the expert panel focusing on experts based on the KRNW list of the four-focus group (MURPHY; PERERA; HEANEY, 2015) on the issues under the study of this work, including the characteristics focus groups and the profile of the experts.

Table 25 - KRNW overview of the selected expert panel

Focus-group	Organization/ Company	Sector	Respondent position	Experience in the field	Company business field
Discipline Group 1	Company 1A	Industrial	Key Account	+ 15 years	Robot supplier
	Company 1B	Industrial	Business Manager	+ 10 years	Robot supplier
	Company 1C	Industrial	Country Manager	+ 15 years	Robot supplier
	Company 1D	Industrial	Product Specialist	+ 10 years	Robot supplier
	Company 1E	Industrial	Marketing Manager	+ 15 years	Robot supplier
	Company 1F	Industrial	Product Manager	+ 15 years	Robot supplier
	Company 1G	Industrial	Sales Manager	+ 10 years	Robot supplier
	Company 1H	Industrial	Regional Sales Manager	+ 15 years	Robot supplier
	Company 1I	Industrial	Sales Manager	+ 15 years	Robot supplier
	Company 1J	Industrial	Manager	+ 15 years	System integrator
	Company 1K	Industrial	Manager	+ 10 years	System integrator
Discipline Group 2	Company 2A	Academy	Assistant professor	+ 20 years	Focus on I. 4.0
	Company 2B	Academy	Assistant professor	+ 20 years	Focus on Mft.
	Company 2C	Academy	Professor	+ 20 years	Focus on Mft.
Discipline Group 3	Company 3A	Public	Technical director	+ 20 years	Consulting
	Company 3B	Public	Industry specialist	+ 10 years	Consulting
Discipline Group 4	Company 4A	Industrial	Industrial manager	+ 15 years	Auto parts supplier
	Company 4B	Industrial	Industrial manager	10 years	Auto parts supplier
	Company 4C	Industrial	Industrial manager	10 years	Auto parts supplier
	Company 4D	Industrial	Industrial manager	+ 15 years	Auto parts supplier

Source: Author.

As described before, the selected expert panel shown in Table 25 is identified through their scholarly publications in case of the academics, and through contact with industries and professional associations in terms of the practitioners (MELNYK et al., 2009).

4.2 INTERVIEW PROTOCOL

The first step is to develop a timeline of tasks and key dates to conduct the interview rounds, including a margin to absolve potential late replies by experts. Based on the design of the timeline, the researcher intends to invite each expert with a personal invitation on behalf of the PPGEP – *Programa de Pós-Graduação em Engenharia de Produção* of the Universidade Nove de Julho – UNINOVE, to participate in the study as a member of the expert panel. The preliminary invitation should take the form of a phone call for the first approach follows by an official e-mail that explains the overall goal of the research. The invitation emphasizes the importance of the availability of time required from the expert to attend the study during the entire interview rounds.

Following the interview protocol, the researcher will explain to the experts the main purpose of the research to which there are invited to. At that moment in time, the researcher will introduce to the experts the conceptual techno-economic feasibility model developed in Chapter 3 to adopt cobot in SME, including the functionality of the model. After the introductory aspects of the proposed model were explained, the researcher asks the experts their impressions of the conceptual model, including recommendations about each domain of the proposed model. Based on the participant experience, the researcher requests their suggestions, shares their perspectives, and further improvements of the techno-economic domains of the conceptual model.

Based on the expert's opinions collected for analysis in the first-round survey, the researcher will review and analyze the data collected in order to check if a consensus opinion among experts is achieved. In case of a consensus among experts is reached, the Delphi study is finalized in the first-round and the researcher will incorporate in both models described in Chapter 3 the experts' consensus recommendations. In case of no achievement of group consensus in the first round, the researcher will provide adjustments in the model to incorporate the expert's suggestions and perform the interviews in two or more rounds. The next interview-rounds will be finalized only when the achievement of consensus is reached among experts.

4.2.1 Design of the interview protocol

The interview protocol is adapted from Jäger et al. (2016) and Veiler et al. (2019). For the purpose of this work, the interview protocol is divided into two main blocks with a few questions in each one. The interview protocol is organized in a power point template. In order to conduct the interviews focusing on keeping an alignment with the research question objectives of this work, the interview starts with an introductory section introducing the purpose of this work. Then, the first block of the protocol includes a guide, where experts were questioned based on their experience with automation with industrial robots, and approaches the self-assessment of the technical section of the conceptual model, as follows:

i. How do you assess the technical feasibility? Is it easier to be interpreted by the user?
ii. In which domains of the technical model do you see potentials for opportunities, and optimizations?
iii. There are any suggestions to optimize the technical model to be user-friendly?
iv. Is there anything that has been not discussed in the interview so far, but is important for adopting cobot in SME from a technical perspective?

The second block going into the economic section of the conceptual model, where the experts are asked to evaluate the return on investment based on the system acquisition costs and reduction of direct manpower, as follows:

i. How do you assess the economic feasibility? Is it easier to be interpreted by the user?
ii. In which domains of the economic model do you see potentials for opportunities, and optimizations?
iii. How do you release the investment to adopt cobot on the shop floor?
iv. Which financial resources do your company requirements for the cobot adoption? In addition, how are those provided?
v. Is there anything that has been not discussed in the interview so far, but is important for adopting cobot in SME under economic and financing perspective?

Proceeding with the interview, finally, the third block addresses general issues and comments from the expert's side related to the adoption of cobot in SME environment:

i. Is there anything that has been not discussed in the interview so far, but is important for adopting cobot from an economic and financing perspective?
ii. Is there anything that has been not discussed in the interview so far, but is important for adopting cobot from a technical perspective? How does your company already employ the use of industrial robots, especially the adoption of cobot on the production shop floor?

4.2.2 Interview protocol refinement

A pilot study was carried out focuses on refining and validating the interview protocol content. Following Jairath and Weinstein (1994), the validation of the protocol is an optional step, but according to the authors, it could support the researcher to identify divergences and improve the quality and feasibility of the protocol. Nevertheless, this study employs a protocol validation by asking a facilitator to express agreement with the researcher’s interpretation of the variables of the conceptual techno-economic model prior to performing the first-round interviews (OKOLI; PAWLOWSKI, 2004). Further, the pilot study was seeking to align the interview questions and research question.

For this purpose, a facilitator from the academy with more than twenty years of experience in manufacturing was invited to attend the pilot study focuses on analysis to validate the expert interview protocol. The pilot study lasted around one hour, and based on the feedback of the respondent, the interview questions were appropriate. Nevertheless, the respondent identified a set of refinements, which were properly incorporated in the revised protocol to perform the interviews. According to the respondent, the modifications in the model are intended to make the interviews maintain a dynamic flow. Hence, such refinements for the field interviews were identified as follows:

a. Translation of the protocol to the Portuguese language;
b. Inform the respondent about the desirable times of the interview ahead of it starts;
c. The interview should be planned for a maximum of 35 - 40 minutes, but never exceed 60 minutes. Finally, the interviewee sets the time for the section, and not the interviewer;
d. Emphasize that the research is focusing on SME only, and indicates that technical and economic data on large companies is not available for this work;
e. Be more concise while explaining the content of the conceptual model;
f. The presentation shall be performed by the researcher in around 10-15 minutes. Nevertheless, the researcher shall keep the remaining available time to collect the respondent impressions;
g. Slide 1: during the interview opening, the researcher introduces himself, talk about his professional and academic experiences and perspectives;

h. Slide 2: present the research objectives clearly;
i. Slide 3: add a flow chart to introduces an easier overview of the conceptual feasibility model;
j. Slide 4: Signalize that an industrial case study was applied to demonstrate the conceptual model. Address the company data which has attended the model demonstration. Here, the researcher should emphasize that the company has a workstation comprise of an injection-molding machine and 03 workers, and then, describe the rules of workers. Further, the researcher shall highlights that the company is investigating the feasibility of installing a cobot and restructuring the workstation to work in the future scenario based on layout configuration. The researcher shall add the layout explain briefly the its flow and the company analysis of cobot deployment, which could be more productive.
k. Slides 5 and 6: Presentation of the technical section of the conceptual mode. Explain the difference between mandatory and desirable requirements;
l. Slides 7 to 10: Presentation of the economic section of the conceptual mode. Here the researcher shall emphasis that the model's demonstration indicates the economic figures in Euro as this dissertation is being with a European member's committee. Therefore, the order of magnitude in Euro for such a demonstration is to facilitate the interpretation of the committee. Tables 19 and 20 shall be incorporated in the protocol in addition to Table 21 to illustrate where the economic figures come from.
m. It is not interesting to discuss the technical and economic section of the model separately while the presentation. It prolongs the interview and loses concentration on the model as a whole.

After the validation of the pilot study was concluded, the refined interview protocol structure was organized in a PowerPoint template format to perform the Delphi study. Finally, the research instrument was comprised of four phases:

a. Phase 1: Introduction of this work, including the purpose of this work, research questions, and objectives of the study;
b. Phase 2: Presentation of the purpose of the conceptual feasibility model;

c. Phase 3: Results of the model demonstration based on Alpha Company figures, including the proposed workstation to be automated;
d. Phase 4: explanation of the content of the techno-economic sections of the conceptual model.

5 RESULTS

The proposal of this chapter is to present the results of the Delphi study, which was performed to confirm the adequacy of the proposed techno-economic feasibility model introduced in Chapter 4. The next sections will introduce the results gathered from the two round interviews, and then provide the formulation of the final best practice feasibility model.

5.1 POPULATION OF THE KRNW

As stated before, the primary purpose of the Delphi study was to obtain inputs from "expert" individuals concerning problems or directions to verify the adequacy of the proposed model described in Chapter 3, collecting recommendations and priorities (KRUEGER, 2014, OKOLI; PAWLOWSKI, 2004). The Delphi study applied to this work sought a reliable consensus among persons with high knowledge about the use of cobot and SMEs, once expert's involvement increases the validity of information supposed to be gathered during the interviews (ROWLEY, 2012). Moreover, the expert's information provides reliability and validity to this study (DALKEY; HELMER, 1962; GIANNAROU; ZERVAS, 2014).

To enhance the visibility of the study related to this work, the population to build the Delphi study was composed of respondents with broad-based professional expertise (HALLOWELL; GAMBATESE, 2010), including faculty members in the field of industry 4.0 and industrial managers working in with industrial robotics. Therefore, as described in section 4.3, the experts selected to perform the research interviews were chosen depending on the level of individual's experience to deal with industrial robots, including a special focus on collaborative robots in the scenario of SMEs in Brazil (TAN; GUEDES, 2018).

An initial screening of candidates was created by the researcher through a KRNW Excel® template to be populated as shown in Figure 13 (OKOLI; PAWLOWSKI, 2004). Furthermore, the KRNW Excel® template was built following the focus-group approach designed to attend the aim of this work, which is included in the guideline to select and build the expert's panel shown in Table 25 (ROWLEY, 2012, HALLOWELL; MATTHEW;

GAMBATESE, 2010). At the same time, the initial screening of candidates comprised a preliminary selection list of 81 potential applicants with knowledge and experience in the field of competence related to this work (HALLOWELL; GAMBATESE, 2010). Such a list was gathered by the researcher based on his professional networking and possible contacts on Linkedin. After the first screening and preliminary contact with all potential candidates, 61 gave a positive response and demonstrated interest to populate the formal KRNW Excel® template with names to perform the interviews.

Then, in a second step, a communication process was performed by the researcher through a personal formal invitation, which was sent to each one of 61 potential respondents, following the guidelines shown in Table 25. The formal invitations were sent by e-mail in the middle of April 2021 (APPENDIX 2). Furthermore, the content of the formal invitation highlighted some information about the research's subject and the duration of the interview (MERGEL; EDELMANN; HAUG, 2019). In addition, the invitations were sent around 15 days before the tentative date for the interview, to accommodate the necessary interview time into the respondent's agenda.

As a result of the formal invitation, 16 candidates never returned the initial e-mail, 12 potential candidates declined the invitation due to the lack time to attend the study, 13 possible respondents declined because they deemed themselves unqualified. Therefore, the KRNW Excel® template was closed with 20 candidates which were eligible to participate in the study as shown Table 25. Unfortunately, due to unknown reasons, five candidates have never completed the first-round of interviews which ended up being held with 15 respondents, as shown Table 26.

Table 26 - KRNW of the first round interview

Focus-group	Organization/ Company	Sector	Respondent position	Experience in the field	Company business field
Discipline Group 1	-	-	-	-	-
	Company 1B	Industrial	Business Manager	+ 10 years	Robot supplier
	-	-	-	-	-
	Company 1D	Industrial	Product Specialist	+ 10 years	Robot supplier
	Company 1E	Industrial	Marketing Manager	+ 15 years	Robot supplier
	Company 1F	Industrial	Product Manager	+ 15 years	Robot supplier
	Company 1G	Industrial	Sales Manager	+ 10 years	Robot supplier
	Company 1H	Industrial	Regional Sales Manager	+ 15 years	Robot supplier
	-	-	-	-	-
	Company 1J	Industrial	Manager	+ 15 years	System integrator
	Company 1K	Industrial	Manager	+ 10 years	System integrator
Discipline Group 2	Company 2A	Academy	Assistant professor	+ 20 years	Focus on I. 4.0
	-	-	-	-	-
	Company 2C	Academy	Professor	+ 20 years	Focus on Mft.
Discipline Group 3	Company 3A	Public	Technical director	+ 20 years	Consulting
	Company 3B	Public	Industry specialist	+ 10 years	Consulting
Discipline Group 4	Company 4A	Industrial	Industrial manager	+ 15 years	Auto parts supplier
	Company 4B	Industrial	Industrial manager	10 years	Auto parts supplier
	Company 4C	Industrial	Industrial manager	10 years	Auto parts supplier
	-	-	-	-	-

Source: Author.

The second-round interviews were performed with the participation of 11 respondents. The remaining 04 participants from round one declined due the time restrictions to attend the interview, as shown Table 27.

Table 27 - KRNW of the second round interview

Focus-group	Organization/ Company	Sector	Respondent position	Experience in the field	Company business field
Discipline Group 1	-	-	-	-	-
	Company 1B	Industrial	Business Manager	+ 10 years	Robot supplier
	-	-	-	-	-
	Company 1D	Industrial	Product Specialist	+ 10 years	Robot supplier
	Company 1E	Industrial	Marketing Manager	+ 15 years	Robot supplier
	Company 1F	Industrial	Product Manager	+ 15 years	Robot supplier
	Company 1G	Industrial	Sales Manager	+ 10 years	Robot supplier
	-	-	-	-	-
	-	-	-	-	-
	Company 1J	Industrial	Manager	+ 15 years	System integrator
	Company 1K	Industrial	Manager	+ 10 years	System integrator
Discipline Group 2	-	-	-	-	-
	-	-	-	-	-
	-	-	-	-	-
Discipline Group 3	-	-	-	-	-
	Company 3B	Public	Industry specialist	+ 10 years	Consulting
Discipline Group 4	Company 4A	Industrial	Industrial manager	+ 15 years	Auto parts supplier
	Company 4B	Industrial	Industrial manager	10 years	Auto parts supplier
	Company 4C	Industrial	Industrial manager	10 years	Auto parts supplier
	-	-	-	-	-

Source: Author.

The interview process was carried out between the end of April and middle of July 2021. After the Delphi study was finalized, a formal personal e-mail was sent by the researcher to each panelist acknowledging the time spent to perform the study and emphasizing the importance of their effective participation (APPENDIX 3).

5.1.1 Ethics considerations

As this kind of research involves different experts, with opinions, personal experience, and individual values (Yin, 2017), all participants agreed to take part in the Delphi study with voluntary participation. Nevertheless, to prevent harm and loss of privacy, to proceed with the interviews the researcher ensured that all participants had granted their consent so that their opinions and comments could be included in this work (COOPER; SCHINDLER, 2006). Furthermore, the ethical approval for this study was granted by the PPGEP at UNINOVE.

5.2 DATA COLLECTION PROCEDURES

This section introduces the procedures to conduct the interviews and indicates the findings from the Delphi study gathered from the two-round interviews. This section demonstrates the procedures used to establish expert consensus about the proposed model to attend the research objectives of this work.

5.2.1 Interview protocol

As described in Chapter 4, to certify the research protocol, an experimental interview was conducted with one academic. The purpose was to validate the interview protocol to discover unclear questions and allow a better understanding related to the context of the protocol statements. The purpose of obtaining feedback on the interview protocol is to enhance its reliability as a research instrument (CASTILLO-MONTOYA, 2016). As mentioned in Chapter 4, the interview protocol was built to explore how experts consider the structure, content, and language of the proposed feasibility model described in Chapter 3, seeking to give a particular impression of the value of that item. As mentioned in Chapter 4, once the pilot study was finalized and revisions were incorporated into the revised protocol, the final version was then used to conduct the interviews the experts.

As mentioned in Chapter 4, the refined protocol was written in Portuguese and all interviews were conducted in that language. The researcher ran the interviews, including the discussions and questions expressed in the everyday language of the interviewees (KVALE; BRINKMANN, 2009). The introductory section of the interview protocol presented to the panelists the main purpose of this dissertation, covering its main topics, including the research question and primary objective. In addition, to keep the original content of the model, a flowchart explaining the entire concept of the proposed model prior to the interview question was shown.

During each interview, the researcher spent between 10 to of 15 minutes to make the protocol content presentation including the details of the technical and economic feasibility model. The script of the interview protocol was based on a PowerPoint template as the presentation guide. Freedom was given to the interviewees to ask questions at the end of the presentation and to recommend changes to the proposed feasibility model. Before finalizing the interview, all participants were invited to express their opinion and perspective, or any remarks to improve what was presented.

5.2.2 Interview process

As the interviews are means of collecting data, this tool is assumed in this work in order to conduct qualitative research to allow the researcher to collect opinions, experiences, processes, or behaviors from interviewees (DÖRINGER, 2020, HANNA, 2012, ROWLEY, 2012), always keeping the conversation moving to focus on the research issue. Prior to the interviews, the experts received information about the requirements for the interview including the time lapse involved. The interview process was kept as flexible as possible to adapt to the professional peculiar approach used.

To perform the interviews, the researcher used a virtual conference software (Google Meet) due to COVID-19 face-to-face contact limitations (DODDS; HESS, 2020). The respondents stayed at their work locations in their own offices and the researcher in the University premises.

Following Rowley (2012), to allow the researcher to conduct interviews and collect the necessary data in a minimum amount of time, the length of each interview took between 35 and 60 minutes. Each interview round was conducted once, and it was based on responses from the previous one. They were conducted ensuring that each expert felt comfortable with the process, bringing natural interaction between the researcher and the expert It included open communication between participants, rigorously observing the time management during each interview (HANNA, 2012). After a brief deliberation with the respondents, the researcher demonstrated his interest in expert's knowledge to better contribute to the outputs of this study.

In general, the researcher and respondents had an open and informal conversation to generate more in-depth responses regarding sensitive topics. However, just a few (2) felt not so comfortable or gave answers in a rush, keeping the interview in a formal atmosphere. Notwithstanding, such respondents received an incentive from the researcher based on the open-ended questions to return with their perspective related to each area of the conceptual model.

5.2.3 Expert's profile to perform the Delphi study

In summary, all respondents of this study were Brazilian citizens working for industries of private sector, Brazilian Universities, and local manufacturing organizations. As the quality of data is dependent on the expertise of the participants of the Delphi studies (KRUEGER, 2014), the majority of respondents were senior executives with engineering degrees and additional Master's degrees. All academics had at least Doctoral degrees with senior positions in Universities as professors and researchers. The experience reported by the practitioners at using cobot is quite homogeneous, and most of the participants have more than 10 years of experience in the industrial robotics field, while academics reported experience in the industrial field for more than 20 years.

At the time in which the interviews took place, private Brazilian companies or Universities employed all respondents. All the 15 experts interviewed in the first-round provided relevant knowledge and experience, sharing their knowledge and professional experiences with the researcher. Among them were senior researchers (universities $n = 2$) and senior managers working for a worldwide robot manufacturer (robot supplier $n = 6$; 40 %). Some respondents worked for robotics system integrator companies (system integrator $n = 2$; 13,3 %), or for a local SME (end-user $n = 3$; 20 %). In addition, two of the experts were formal members of robot related industrial association (consulting $n = 2$; 13,3 %). However, according to the respondent experience, only a feel of them had scientific publications in the field of study ($n = 2$; 13,3 %). Table 28 shows the profile characteristics of the attendants in each round.

Table 28: Profile characteristics of the attendants

	Round 1 $n = 15$	Round 2 $n = 11$
Country of residence		
Brazil	100%	100%
Gender		
Male	93.3%	90,9%
Female	6.7%	9,1%
Age average	42,9 years	39,5 years
Current role		
Robot Manufacturer	40,0%	45,5%
Academic	13,3%	-
Robot integrator	13,3%	18,2%
Consultant	13,3%	9,1%
Robot end user	20,0%	27,3%
Education		
Engineering degree	33,3%	45,5%
Doctoral degree	13,3%	-
Master degree	20,0%	9,1%
Marketing & Administration	20,0%	27,3%
MBA	13,3%	18,2%
Years working in the field		
20 + years	20,0%	-
15 to 20 years	46,7%	36,4%
10 + years	33,3%	63,6%

Source: Author.

5.2.4 Interview transcription

As mentioned in the previous subsection, the participants were presented with the areas of technical and economic feasibility model identified in the literature search. The interviewees were asked how the proposed conceptual model to perform a techno-economic feasibility study works in a practical environment to foster the utilization of cobot in the Brazilian SME scenario. Following the interview protocol, the expert panel members were asked to recommend facilitators and barriers that may impact the implementation of the suggested initiatives. The names of the participants were not identifiable to ensure anonymity between participants. As mentioned above, due to the nature of the research, interviewees were informed that data would be included in the analysis at each round to inform subsequent rounds.

As the transcription of the interviews is central to the process (PARAMESWARAN; OZAWA-KIRK; LATENDRESSE, 2020). Therefore, all transcripts were audio-recorded with the previous approval of all respondents. During the interviews, the researcher had the opportunity to get feelings, perceptions, body expressions and gestures, or beliefs through the open-ended questions to obtain insights based on the issues introduced to the experts. Through the open-ended questions, during the interview and after the narrative sequence of the respondents, the researcher checked if the conference covered the entire protocol before finalizing the section. Finally, all transcripts were written directly by the researcher because there was no assistant to support the interview.

5.2.5 Measure of consensus

Delbecq, Van de Ven and Gustafson (1975) suggest that a two or three iteration Delphi is sufficient to reach the most research objectives. However, if the goal is to understand nuances (a goal in qualitative research) and the sam ple is homogeneous, then fewer than three rounds could be enough to reach a consensus between panelists (THOMSON, 1990). Stability of consensus was considered reached if the between round group responses varied by ≤ 10 % (DUFFIELD, 1993). The participants of this study were presented with defined aspects of the technical and economic model, which were gathered in the literature search.

The issues selected for discussion at the face-to-face meeting originated from the model’s demonstration gathered from Alpha company. To this work, the assumption to reach the measure of consensus is based on acceptance of the model based on the Interview questions protocol shown in Chapter 4. Finally, each expert contributed to this research to an assessment for each item of the proposed model in order to build a measure of consensus after two rounds interviews.

5.3 THE DELPHI ROUNDS

To this research, a two-round Delphi study was performed, including 15 individual participants in the first interview round and 11 individual participants in the second. All panelists were asked to give their professional opinion and comments on relevant issues they felt might be missing from the content of the model to explore or expose different insights to generate a consensus among the respondents (ROWE; WRIGHT, 1999, DELBECQ; VAN DE VEN; GUSTAFSON, 1975).

5.3.1 Statements generated from round 1

The purpose of the first round was to generate statements of the competencies the experts deemed necessary for using properly the proposed feasibility model and to develop the second-round interviews. According to the Cambridge Business English Dictionary (2011) statement means "*something that someone says or writes officially, or an action done to express an opinion*". Therefore, the statements across nine domains of the mandatory requirements of the technical model were verified. In the first round of this study, each panelist was asked to give statement of each domains of the proposed feasibility model. On average, 14 participants agreed with the proposed model domains**.** Beyond that, 11 participants expressed their opinion of whether these strategies would work positively in general around another field of Brazilian industry.

Thoughtful and detailed responses were giving by the respondents related to the mandatory requirements. It is important to emphasize that the statements collected of all interviewees during round one related to the domains of mandatory requirements of the technical model reached unanimous consensus. Especially among robot selection as primary diagnosis prior to adopting cobot, all panelists reached a consensus on the following major conditions of the mandatory model domains: ISO 10218 standards as a primary requirement to design an industrial robot, and the technical specification ISO/TS 15066 to be applied as a guideline to design the collaborative workstation. As main results, panelists-oriented consensus towards maintaining usual activities related to the domain of a thorough risk assessment prior to adopting cobot in an industrial environment.

Following standards, a special attention were gave by participants concerning the specific Brazilian regulatory standard NR-12, which addresses safety of machinery and equipment, including the safety requirements to adopt industrial robots in shop floor. Under this domain a highest degrees of consensus were reached between panelists as the most critical standard to be followed prior design a robotic cell under Brazilian environment. In summary, based on the statements of the respondents, none of the mandatory measures listed in the technical model were seen a barrier to adopt cobot. As the conceptual model will be applied in Brazil, 04 participants required to add the name of NR-12 standards in such domain.

Panelists did not achieve consensus related to the domain of “Robot system design and safety requirements”. Here, based on the statement 9 of the experts, this domains refers to the ISO standards and those specialist recommend to incorporate such domain in the “Robot design and system integration according to ISO 10218 (International Safety Standards - parts 1 and 2)”. Moreover, no consensus was reached between panelists among the domain of “Robot design with a lightweight material technology”, which refers to the fabrication of robot arms in light composite material as a design feature. The recommendation received from 11 of the panelists was to incorporate it into the domain of the ISO 2018 standards.

One respondent suggested to add in the domain “Design and usability of collaborative workstation and operational layouts”, the logistic layout of the collaborative workstation as well, to certify the material handling movements necessary nearby to the human worker. Table 29 shown the statements of the panelists related to the domains of mandatory requirements, indicating with (Y) for fully consensus reached and with (N) for no full consensus reached among specialists.

Table 29 - Expert statements related to the mandatory requirements

Design principles	Experts statements															Consensus
	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	
ISO / TS 15066 technical specifications to introduce safety standards	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	100%
Robot design and system integration according to ISO 10218 (International Safety Standards - parts 1 and 2)	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	100%
HRC rules: collaborative workstation design according to the types of collaborative operation	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	100%
Compliant risk assessment: evaluate potential contact between portions of the robot system and a human operator	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	100%
Robot system design and safety requirements	*N*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*N*	*Y*	86,7%
Robot design with a lightweight material technology	*N*	*Y*	*Y*	*Y*	*Y*	*Y*	*N*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*N*	*Y*	80%
Safety configuration of a collaborative workstation	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	100%
Design and usability of collaborative workstation and operational layouts	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*Y*	*N*	*Y*	93,3%
Public policy towards cobot technology for each country	*Y*	*Y*	*N*	*Y*	*Y*	*N*	*Y*	*N*	*Y*	*Y*	*N*	*Y*	*Y*	*Y*	*Y*	73,3%

Source: Author.

Following the design of the conceptual feasibility model, the experts were asked to give their comments on eleven domains of the desirable requirements of the technical model. On average, 13 of participants were in accordance with the proposed model domains. Nevertheless, the panelists did not achieve consensus regarding the first domain of the desirable requirements related to the technical feasibility model related to the “Design phase criteria”. The comments provided mainly from the cobot’s experts indicated that the shape and features of the product to be handled by the robot arm, such as load and unload parts nearby to the human coworker should be collaborative as well to avoid risks to the humans. The experts emphasize the relevance to select the right product to be assembled in a collaborative mode, avoiding products with fine edge design areas, for example, which could cut things very easily. Therefore, following the expert's recommendations, this domain should be added to the mandatory requirements.

Five respondents, including the academics, proposed to add a column in the technical feasibility part of the model to indicate the benefits that each domain of the desirable’s requirements could bring during the automation process implementation based on cobot in case the company acquired it. Moreover, the respondents requested the company to rank the desirable requirements in terms of prioritization of the acquisition of such requirements, including issues related to financing, market demand, and staff training, for instance.

Related to the domain of “Degree of automation, flexibility (attributes between human and robot)”, 3 experts proposed to incorporate the classification of HRC (MÜLLER; VETTE; GEENEN, 2017), as shown in Table 2 from Chapter 2, during the identification of attributes between human and robot in a collaborative workstation. An intermediate consensus among experts were achieved related to the domain of “Warnings and safety work concepts (lamps, etc.)”. According to the comments collected from six panelists, this item could be attempted in the domain of “Markings, signs and written warnings additional to the risk assessment”.

Related to the domain of “Training for the Production engineers”, according to the impressions collected from two respondents, the training should approach the entire technical staff of the company, and not limited to those employees, which have an engineering degree. General comments received among experts related to the domains

“Operation phase criteria - supports remote connection and performance software” and “Availability of Industry 4.0 enabler to increase performance and competitiveness”, indicated that such items appear currently as a financial barrier for Brazilian SMEs to promote investment in digital technologies. Table 30 shown the comments of the panelists related to the domains of desirable requirements, indicating with (Y) for fully consensus reached and with (N) for no full consensus reached among them.

Table 30 - Expert statements related to the desirable requirements

Design principles	Experts statements															Consensus
	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	
Design phase criteria - map the manual process to be automated and translate this manual task into a robotic task	Y	Y	Y	N	N	Y	N	N	Y	Y	N	Y	Y	Y	Y	66,7%
Integration phase criteria - it is possible to automate a whole application with a short setup time	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100,0%
Operation phase criteria - supports remote connection and performance software	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100,0%
Batch production (specified groups or amounts of products)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100,0%
Degree of automation, flexibility (attributes between human and robot)	Y	Y	Y	N	N	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	80,0%
Availability of Industry 4.0 enabler to increase performance and competitiveness	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100,0%
Lack of expertise: robot programming expert	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100,0%
Markings, signs and written warnings additional to the risk assessment	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100,0%
Warnings and safety work concepts (lamps, etc.)	Y	Y	Y	N	N	Y	N	N	Y	Y	N	Y	Y	N	Y	40,0%
Training for the Production engineers	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	86,7%
In-house software robotics expertise	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100,0%

Source: Author.

Following the technical side evaluation, the experts were asked to give their statements across four domains of the economic model. Over 12 of the participants fully agreed with the content of the economic section of the proposed model. However, the panelists did not achieve consensus regarding the content of the variable's domain in terms of the premises assumed in the model to perform the ROI calculation. The statement provided by almost all experts emphasizes the relevance in incorporating potential gains with the use of cobots besides the employee's costs, such as gains with an increase of productivity and cost savings generated with reduction of scrap or rework during assembly tasks. Moreover, three experts from robotics field suggested to replace the nomenclature “Cobot acquisition cost” indicated in Table 19 for “Cobot system acquisition cost” once the sensors and robot end-effector are incorporated in the cobot arm. Table 31 shows the statements of the panelists related to the four domains of economic requirements, indicating consensus reached or not in each domain of this section of the model.

Table 31 - Expert statements related to the economic model

Domain	Expert statements															Consensus
	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	
Cobot acquisition cost	Y	Y	N	Y	Y	Y	Y	N	Y	Y	Y	N	Y	Y	Y	80%
Collaborative workstation	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100%
Variables	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100%
Feasibility analysis	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100%

Source: Author.

5.3.2 Statements generated from Round 2

As mentioned before, for the purpose of this research, the second-round Delphi study was performed, including 11 individual participants, which also attended the first-round interviews. Following Rowe and Wright (1999), all participants of the second round gave their professional opinions and comments on the domains which did not reach the group consensus during the first-round interviews, after the proper adjustments were implemented in the original model as suggested by them.

The purpose of the round 2 was to establish consensus among experts of aspects that are essential of previous round to apply to the proposed feasibility model, focusing on the technical section of the proposed model. To this work, the second round achieved the consensus recommendations (THOMSON, 1990) following the stability of consensus among group responses with a variation by ≤ 10 % (DUFFIELD, 1993). Therefore, the following statements across the domains of the mandatory requirements of the technical model were certified among experts:

a) Robot system design and safety requirements;
b) Robot design with a lightweight material technology;
c) Design and usability of collaborative workstation and operational layouts;
d) Public policy towards cobot technology for each country;
e) Design phase criteria - map the manual process to be automated and translate this manual task into a robotic task.

On average, 10 of the 11 participants were in accordance with the five proposed model domains subject to discussions during the second round interviews. Table 32 shows the statements of the panelists related to the five domains of mandatory requirements as mentioned above, indicating the consensus level reached in each domain of this section of the technical model.

Table 32 - Expert statements related to the mandatory requirements

Design principles	Experts statements											Consensus
	01	02	03	04	05	06	07	08	09	10	11	
Robot design and system integration according to ISO 10218 (International Safety Standards - parts 1 and 2) and safety requirements	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100%
Design phase criteria - map the manual process to be automated and translate this manual task into a robotic task	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100%
Robot design with a lightweight material technology	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	90,9%
Design and usability of collaborative workstation and operational layouts	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100%
Public policy towards cobot technology for each country, including regulatory standard NR-12 for Brazil	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100%

Source: Author.

Based on the comments collected from the first interview round, the following statements across the domains of the desirable requirements of the technical model were certified among experts:

a) Degree of automation, flexibility (attributes between human and robot);
b) Warnings and safety work concepts (lamps, etc.);
c) Training for the Production engineers;
d) Benefits to adopt the desirable requirement.

On average, 2 of participants were in accordance with the four proposed model domains subject to discussions during the second round interviews. Table 33 shows the statements of the panelists related to the four domains of desirable requirements, indicating a consensus group reached in each domain of this section of the technical model.

Table 33 - Expert statements related to the desirable requirements

Design principles	Experts statements											Consensus
	01	02	03	04	05	06	07	08	09	10	11	
Degree of automation, flexibility (attributes between human and robot) based on HRC classification	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100%
Markings, signs and written warnings additional to the risk assessment, warnings and safety work concepts	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	90,9%
Training for the technical staff	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100%
Benefits to adopt the desirable requirement.	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	100%

Source: Author.

The results of the first and second rounds of the Delphi study have achieved the consensus recommendations among all participants. Therefore, the expert group reached a unanimous consensus related to the economic model. Moreover, the group consensus was reached in almost every domain of the techno feasibility model.

5.4 FINAL BEST PRACTICE TECHNO-ECONOMIC MODEL

The consensus statement among experts was collected after two rounds of feedbacks, including an opportunity for revision. The agreement with statements related to each domain of the proposed model has achieved around 98 % or higher agreement. To attend to the aim of this work, the recommendations made by the experts were adopted to propose the updated design architecture in order to introduce best practice feasibility model. Hence, the design scheme provides an advanced stage of the conceptual model proposed in Chapter 3, with defined thresholds for consensus. Despite this, the best practice assessment of the feasibility model keeps the domains drawn from the literature regarding the technical and economic sections of the model.

It is important to emphasize that the domains of the best practice feasibility model have an appropriate guideline-based on individual opinions transformed into the group consensus among specialists. Each section of the best practice feasibility model is detailed in Tables 34, 35, 36, and 37.

Table 34: Best practice feasibility model – technical

Mandatory Requirements	Yes	No
ISO / TS 15066 technical specifications to introduce safety standards	X	
Robot design and system integration according to ISO 10218 (International Safety Standards - parts 1 and 2) and safety requirements. Its included Robot design made in lightweight material technology	X	
Design phase criteria - map the manual process to be automated and translate this manual task into a robotic task	X	
HRC rules: collaborative workstation design according to the types of collaborative operation	X	
Compliant risk assessment: evaluate potential contact between portions of the robot system and a human operator	X	
Safety configuration of a collaborative workstation	X	
Design and usability of collaborative workstation and operational layout and material flow layout (logistics)	X	
Public policy towards cobot technology for each country, including regulatory standard NR-12 for Brazil	X	

Desirable Requirements	Yes	No	Benefits to adopt the requirement
Integration phase criteria - it is possible to automate a whole application with a short setup time			
Operation phase criteria - supports remote connection and performance software			
Batch production (specified groups or amounts of products)			
Degree of automation, flexibility (attributes between human and robot) based on HRC classification			
Availability of Industry 4.0 enabler to increase performance and competitiveness			
Lack of expertise: robot programming expert			
Markings, signs and written warnings additional to the risk assessment, warnings and safety work concepts			
Training for the technical staff			
In-house software robotics expertise			

Source: Author.

Table 35: Best practice feasibility model – system acquisition

Subject	Qt.	Supplier	Investment cost (in EURO)
UR 10 cobot		Universal Robots	
Robot end-effector		Schunk / Robotiq	
Sensors		Sick	
Robot programming	h	In-company	
Training on cobot	h	Universal Robots	
Cobot system acquisition cost			
Collaborative workbench		Steel fabrication under design	
Engineering design costs	h	System integrator	
Automatic measuring device		External contractor	
Documentation	h	System integrator	
Installation costs	h	System integrator	
Risk assessment, ISO/TS 15066	h	In-company	
Training on process assembly	h	In-company	
Production support		System integrator	
Collaborative workstation cost			**€**

Source: Author.

Table 36 - Variables for production costs

Variables	Before cobot adoption (manual station)	After cobot installation	Cost savings in EURO
Employees per shift			
Employees per day			
Operator monthly wage			
Total monthly cost			
Annual labour cost			
% cost reduction			**%**

Source: Author.

Table 37 - Best practice feasibility model – economic

INCOME STATEMENT						
	Year					
(Values in R$)	**0**	**1**	**2**	**3**	**4**	**5**
Total cost savings due to cobot utilization						
Additional contribution margin due to cobot utilization						
Total additional income						
Operational costs and expenses due to cobot Utilization						
- Depreciation						
- Cobot Maintenance						
- Cobot energy Consumption						
- Technical adjustments required						
-						
Total operational costs and expenses		**0,0**	**0,0**	**0,0**	**0,0**	**0,0**
Additional gross profit due to cobot utilization						
- Income tax						
Additional net profit due to cobot utilization		**0,0**	**0,0**	**0,0**	**0,0**	**0,0**

CASH FLOW						
	Year					
(Values in R$)	**0**	**1**	**2**	**3**	**4**	**5**
Initial investment to acquire the cobot						
Initial investment to install the collaborative workstation						
Other startup costs						
Total Investment						
Additional net profit due to cobot utilization						
- Depreciation						
- Other Incomes (a)						
- Other Expenses (a)						
Net cash flow	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**

What is the minimum return rate would you like this investment to bring back to your company (% per year)		IRR (% per year)	
What is the maximum period would you like this investment to return back to your company (in months)		Payback period (months)	

Source: Author.

6 DISCUSSIONS

This chapter evaluates the outputs of the field research, focusing on the analysis of the feedback received from the interviews carried out as part of the Delphi method to check the adequacy of the proposed conceptual model. The remainder of this chapter presents a comprehensive analysis of the finds related to the design principles of the conceptual model, converging on the aspects of the main model domains.

6.1 OVERVIEW

This work provided a practical scenario that encompasses the utilization of a techno-economic approach to adopt cobots in SMEs. Therefore, the aim of this research is to add a contribution to the body of the literature about the use of industrial automation, by targeting at an approach to allow the use of cobots in SMEs. Furthermore, this research seeks to contribute to the knowledge about HRC by considering the development of industrial automation based on cobots.

RQ. *How to develop a techno-economic feasibility approach to implement collaborative robots in Small and Medium-sized Enterprises in Braz*il?

Moeuf et al. (2018) and Zanchettin et al. (2015) argue that SMEs have only recently started to explore the HRC on the shop floor. Furthermore, a gap in the use of cobots in SMEs was identified in the systematic literature review described in Chapter 2, reason why the use of cobot has been discussed throughout this dissertation.

As stated in Table 9 of Chapter 2, despite the focus of researchers in proposing approaches and models to use cobot in SME’s (FACCIO; BOTTIN; ROSATI, 2019; ACCORSI et al., 2019), none of them proposed a feasibility model to adopt cobots based on the Brazilian SMEs environment. Accordingly, this work provided a scenario that encompasses the spectrum of human-robot collaboration, introducing a novel techno-economic feasibility approach, which was designed based on the data collected from the literature to adopt and integrate cobots into real-world applications of SMEs.

As mentioned above, the purpose of the qualitative Delphi study developed here was to verify the adequacy of a model develop based on the literature to foster the utilization of cobots in SMEs confirming the findings of Cencen, Verlinden and Geraedts (2018), Moeuf et al. (2018) and Zanchettin et al. (201). Amongst other factors, with the rise of Industry 4.0, the manufacturing sector is seeking to adjust the shop floor to the new digital technologies as per Bruno and Antonelli (2018), Qin, Liu and Grosvenor (2016). Such digital technologies, as the cobots (CHRYSSOLOURIS, 2016; PEDERSEN et. al., 2016), are changing the landscape of how industrial automation has been performed in manufacturing companies currently (WANG; TAO; LIU, 2018). In the spectrum of this work, a set of technical and economic requirements gathered from the literature was used to design the principles for modeling the feasibility conceptual approach to allow the use of cobot in SMEs. It is important to emphasize that despite the simplicity of the generated best practice model, a wide range of quality information was incorporated into it, prior conduct a selection and planning of a collaborative workstation by production engineers from end-users.

According to the information collected form panelists, the model should be able to show conformability to collect information before the deployment of a collaborative workstation based on cobot solution. Thus, one important evaluation includes the approach of each domain of the model to identify problems from unexpected circumstances. In addition, it should provide decision support to engineers in face of the right scenario to mitigate risks while investigating an automation solution based on the collaborative robot in a collaborative environment. Whenever possible during the interview section, the respondents were asked to give their own inputs related to the proposed feasibility model. Hence, the observations gathered from 10 of the 11 experts lead to the conclusion that the pragmatic design and easier handle of the model are the main positive features compared to other technological innovation models.

Moreover, the novelty of this dissertation is to provide the scientific and industrial communities with a detailed walkthrough of the proposed techno-economic feasibility model, which can be promptly adapted to a variety of industrial SMEs using a technology model. In terms of innovation, Davis (1989) developed the Technology Acceptance Model (TAM), which proposes to measure the perceived usage and usefulness from a technology adopter perspective. But, in general, TAM does not provide enough clarification from the standpoint of providing system development engineers with the information necessary to create user acceptance of new technologies (MATHIESON, 1991), and encompass different interpretations. According to McCoy, Galletta and King (2007), the adoption of TAM is not worldwide applicable and might not have the capacity to predict the new technology utilization in different cultures and countries.

While the technological innovation models referred to in the literature are more related to a conceptual interpretation (LUARN; LIN, 2005), this research proposed a feasibility model with a compact shape and design principle which allow the engineers to predict process automation based on cobots focusing on the intention to use that technology with a perceived credibility. Especially those requirements in terms of system features, process development, training, and investments (VENKATESH; DAVIS, 2000). Moreover, the results of this study add support to elaborate a techno-economic feasibility study to allow the use of cobot in SMEs (MOEUF et al., 2018).

Another interesting aspect of the proposed model is that the design principles covered in such model leaves the experts completely free regarding the integration of it prior adopt cobot in an SME environment. Based on the experimental trial performed in Alpha company, and according to the perspective of all experts, in many cases such conceptual model will lead to a much more understanding about the scope and rules for automation based on cobots. A common understanding among specialists during interviews generated recommendations to apply such as feasibility model at the very first stage in the automation development process. That statement validates the hypotheses of this work to apply the model prior to start developing a collaborative workstation, particularly those aspects regarding the support in identifying goals and priorities during planning phase of the collaborative workstation. Even dealing with several domains of the model, the usage of it demonstrated practical and not tedious.

6.2 RELIABILITY AND VALIDITY OF MODEL

Interviews with experts and respondent remarks are common tools of qualitative research. Following worked performed by Bitsch (2005), the reliability and validity of the proposed model is limited to general criteria for the evaluation of qualitative research. A techno-economic feasibility model was proposed by this work based on literature and on exploratory research, then tested with experts with large professional experience in the field of industrial manufacturing. The feasibility model validity was based on respondents' experience during two-round interviews.

Within this work, all design principles collected from the literature were cross-checked with the feedback of the respondents of the interview rounds prior to generating the formulation of the best practice model, which is demonstrated in Chapter 5, resulted from the Delphi study. This was accomplished through the utilization of experts' opinions and behaviors selected from an interview panel as shown in Table 25. Therefore, according to the observations collected from experts, a primary outcome indicates that the design of the proposed model introduces pragmatic characteristics, aimed at quick and simplified applications because this is the environment that the work was proposed for, application of the model in the SME environment.

In terms of the checking the adequacy of the proposed model, and as described in Chapter 4, experts were chosen to build the panel depending on the level of knowledge of the respondent in the industrial robotics field and experience with SME in Brazil, in order to perform the interviews rounds. The outcomes of the Delphi study mentioned in Chapter 5 are evaluated in terms of the expertise of panelists to validate the best practice model, once the expert panel to perform this work indicated that there was no expert outside of the field of industrial robotics. Further, the following overreaching themes represented the essence of the respondents included in the KRNW:

a) 9 experts appear to have high insight in aggregated in specific knowledge in industrial robotics;
b) while 6 have demonstrated high insight in aggregated specific knowledge in the development and implementation of robotics solutions in an HRC environment.

Another strength noted in the group of panelists is that 3 experts had direct decision power before implementing an automatic industrial process on the shop floor. Other 8 have very specific technical knowledge related to standards and solutions based on cobots. In addition, almost all attendants of the interview rounds had a trace of enthusiastic and motivated persons, eager to cooperate and exchange information. To certify the results of the interviews, another strength of the panelists resides in the fact that following the feedback collected from respondents, all experts stated that there were no personal preferences related to any specific robot brand. It can therefore be concluded that the respondent's professional position and roles did not cause any negative impact on the quality results during the interview process.

6.3 DESIGN PRINCIPLES OF THE MODEL

This research adopted principles gathered in the literature as well as end-user-centered design philosophy to propose a techno-economic feasibility model to ensure that primary technical and economic factors identified in the literature review are considered while developing manufacturing systems for operating with robots alongside humans. As explained in Chapter 3, the design principles of the conceptual model architecture consist of two separated strands: technical and economic. Additionally, the design choice of building the model was having separate requirements for each of its phases. Hence, those design principles comprises three primary sections, which are identified in the conceptual model as (a) mandatory requirements, and (b) desirable requirements related to the technical model, and (c) economic inputs to calculate the return on investment in automation solutions based on cobot.

As the primary focus of this work focuses on the certification of each domain of the conceptual model, one main task of the Delphi study was to verify the adequacy of the conceptual functions of each domain to reach measurable progress to design its final version, which is described in Chapter 5. Moreover, following the feedback received from almost all the panelists during the interviews, the tasks that need to be checked across to the domains are perfectly clear and user-friendly. Additionally, to address the conceptual model utilization in the manufacturing environment, the feedback from the expert panel indicates that the its design content has an intelligible and iterative process that applies to both strands of the feasibility model.

Another finding based on the results presented in Chapter 5 indicates that the model is an effective approach to give guidelines and directions to production engineers. Beyond the limits of the techno-economic approach, the conceptual model provides a means of information when adapting concepts from the literature for a real manufacturing environment to enable digital technologies to develop the SME field of industry (MASOOD; SONNTAG, 2020, HERMANN; PENTEK; OTTO, 2016). Hence, the findings of this study suggest a better understanding of how to deploy a collaborative workstation using cobot as part of an automation solution. Based on the results, another relevant finding of the Delphi study is that both, the industrial and the academic community recognize the conceptual model as very promising in demonstrating the applicability of the theoretical methodology to reach the final design of a collaborative workstation.

Overall, this work draws inspiration from several key concepts of models identified across the literature review described in Chapter 2 to enable the use of cobot in SMEs (OBERC et al. 2019; FACCIO; BOTTIN; ROSATI, 2019, ACCORSI et al. 2019, MATEUS et al. 2020). By analyzing the data from the interviews, the respondents from the academic community mentioned that the selection and evaluation of the design principles of the proposed model promotes value-added to the literature on the state of the art in using cobot in SME (MOEUF et al., 2018). Likewise, this work add knowledge to the practice domain through systematic review. Additionally, utilizing the experts' knowledge, a detailed understanding of each domain of the conceptual model was achieved to reach measurable progress to build the final version of the feasibility model.

About the industrial issues, the experts have a consensus that performs the iterative application of the proposed model will be priceless to establish confidence and understand the HRC environment uncertainty prior to selecting an automation process eligibility with cobots a shared workspace (GERVASI; MASTROGIACONNO; FRANCESCHINI, 2020, SCHOLER; VETTE; RAINER, 2015). Nevertheless, another outcome of the interviews indicates that, the proposed design of the conceptual model does not limit the user to investigate other phenomena during the investigation of an automated process based on cobot and addresses the use of the conceptual model for more acknowledgment of the use of cobot in SME (MASSOD; SONNTAG, 2020).

According to another outcome form the interviews, the experts agreed that it would be expected that the adoption of the proposed model allow engineers to achieve better design proficiency of a collaborative workstation than one without the application of such a feasibility model. After two rounds of the Delphi study, the experts confirmed the design principle and the nature of each model domain contributes to supporting SMEs in adopting the use of cobots in a collaborative workspace (MOEUF et al., 2018).

6.3.1 Evaluation of technical design principles

As mentioned above, the findings enable the application of the conceptual model and promote its viability in the SME environment. The selection of design principles required to perform the technical feasibility study gathered in the literature were classified for the purpose of this work as "*mandatory requirements*" of the proposed technical model. Such mandatory requirements are comprised of 09 domains.

The objectives of mandatory requirements are to build a collaborative workstation to achieve the best qualities and attributes of humans and robots during a collaborative assembly task (GROOVER, 2017), and assuring the safety of human operators in manufacturing (SCHOLER; VETTE; RAINER, 2015; MARVEL, 2013). In terms of the proposed model's domains, the results have shown that all experts confirmed that the mandatory domains are the most prominent requirements prior to adopting cobots. Most interestingly, all variables included in the domains of the mandatory requirements remain in agreement with all panelists. This condition is especially true once the attendance to the mandatory requirements allows the collaborative robot *work side-by-side with humans* on the assembly station unhindered by a safety fence, assuring human safety, which is the major issue for an HRC implementation (ROBLA-GÓMEZ et al., 2017, MARVEL; FALCO; MARSTIO, 2014).

One further consideration to establish a technical feasibility model is the public policy, which is necessarily different from country to country, especially the Brazilian regulatory standard called as NR-12, which is not known in other countries.

All additional elements to perform the technical feasibility study gathered in the literature were classified as "*desirable requirements*" of the technical model were comprised of 11 domains. This research explores whether the proposed desirable requirements to support SMEs in developing an automation solution based on cobots. The general barrier faced by SMEs related to the desirable requirements is the lack of investment in information technology (IT) to support innovation strategies for remaining competitive (MASSOD; SONNTAG, 2020) in terms of productivity, connectivity, and business intelligence (HERMANN; PENTEK; OTTO, 2016). Following respondents, financial restrictions faced by SMEs are a barrier to allow the use of industry 4.0 digital technologies (QIN; LIU; GROSVENOR, 2016, DRATH; HORCH, 2014). Such financial barriers are more relevant under the current economic Brazilian scenario, even though economic situation was not verified experimentally in this research.

The existing literature contributed to the use of ISO directives to the application of safety standards on cobots utilization (MAGRINI et al., 2020). A technical barrier faced by SMEs complies with a lack of expertise on global ISO regulations, specifically those related to the technical specification ISO/TS15066 applied for HRC (CHEMWENO; PINTELON; DECRE, 2020). Further, the accordance with the Brazilian regulatory requirements related to the standard NR-12 was emphasized by the respondents as a barrier as well. Another output from the evaluation of the results shows that the domain related to training the staff suffers from SMEs' poor skilled workforce. It might also be possible to compare such scenarios with many Brazilian manufacturing environments.

A further insight provided by the results is that the findings are consistent with the domains of the desirable requirements. As mentioned above, the financial issues to allow investments is the main barrier faced by Brazilian SMEs. Nevertheless, following the experts' feedback, it is important to incorporate in the technical section of the proposed model the benefits of adopting each domain, even if all them are characterized as desirable. The focus is to emphasize to the management a desirable domain that could be helpful in a long-term perspective.

The outcomes received from interviews allowed the researcher to identify any inconsistency in each domain of the model, and distinguish the concept of both, mandatory and desirable requirements of the technical model.

6.3.2 Evaluation of economic design principles

All essential elements to perform the economic feasibility study gathered in the literature compare the initial investment expenditures to acquire the cobot and the installation costs of the collaborative workstation. Such requirements are comprised of 4 domains.

Participants agreed that the proposed template to perform the economic feasibility calculation is a positive instrument for SMEs, supporting the decision-makers based on ROI. Nevertheless, a common weakness of the results of the economic model related to Alpha Company is that an acceptable payback in the manufacturing community is around 25 months. Therefore, to demonstrate the full functionality of the model in calculating the payback, the respondents suggested taking into consideration the potential savings related to increasing quality based on cost reductions related to scraps, followed by the gains linked to the increase of workstation productivity and quality. Hence, the proposed feasibility model demonstrated that the compensation strategies within an approach to adopt cobot in SME should have realistic and attainable targets to reach a reasonable payback and ROI.

6.4 RECOMMENTATIONS

The results of the study are compatible with the domains of the conceptual techno-economic feasibility model. To demonstrate the benefits that can be obtained through the proposed conceptual model, this research provided qualitative evidence of the state of the art through a systematic literature review on the features to support the construction of the proposed feasibility model. The technical and the economic domains of such a conceptual model support the robotics community and the decision makers to investigate in advance the requirements to conduct a design of a collaborative workstation prior to release any investment in automation.

After conducting the field research, the interviews with experts confirmed the relevance of the techno-economic analysis model for the implementation of the cobot in Brazilian SMEs for several reasons. A summary took from the data analysis of the results includes the following recommendations:

a. The advances in industrial robotics allow the utilization of digital technologies from industry 4.0 in the collaborative automation environment (PECH; VRCHOTA, 2020);
b. Analysis of process which needs to be automated by the application engineers of the end-user in cooperation with experts in robotics (GROOVER, 2017, LOTTER, 2012), and the safety and health engineers to figure out the best way for an automation solution;
c. The model brings new perspectives to enabling the use of collaborative robots in Brazil (VIDO; LUCATO; MARTENS, 2019).

In summary, the findings are aligned with what was identified in the literature review, and the results provided directions for the selection of the right cobot, including the proper use of safety devices, and the most proper application of the robot end-effector (MAGRINI et al., 2020). Still, according to the findings, the selection of a qualified system integrator, which has the most knowledge on automation, to integrate the automation solution is considered a relevant issue to design a collaborative workstation focusing on preventing issues during the HRC (MARVEL; FALCO; MARSTIO, 2014).

7 CONCLUSIONS

In this chapter, the major conclusions drawn from the research are presented. This chapter provides also the contributions of the present work, identify limitations, and proposes suggestions for future research.

7.1 OVERVIEW

Considering the specific objectives that this research intended to reach, this work contemplated a conceptual model for techno-economic feasibility analysis to evaluate the adoption of collaborative robots in Brazilian SMEs. The results of this work demonstrate, through the literature review, a lack of a techno-economic feasibility models for the implementation of cobot specifically in SMEs. There are several authors, who proposed conceptual models in the specific literature to allow the use of cobots in manufacturing companies. However, the findings of this work indicated a gap in the literature since no feasibility model for implementing collaborative robots in SMEs was found. Therefore, this work proposed a techno-economic feasibility model comprised of several domains gathered from the literature to spread out the use of cobot in SME's located specifically in Brazil.

To verify the adequacy of the theoretical model developed, a Delphi study was carried out with the support of experts in the academy, industrial robot manufacturers, consultants, and end-users. The overall conclusion of this dissertation is that the model initially originated from the extant literature and improved by the suggestions and comments gathered in the Delphi filed research can be considered a relevant and easy-to-use tool for practitioners in the manufacturing automation area when considering the adoption of cobots in their facilities. Furthermore, this approach can allow the SMEs to easily evaluate the technical and economic aspects of adopting collaborative robots in the factory floor, showing all requirements and financial elements involved in the decision process of its possible utilization.

7.2 SUMMARY OF CONTRIBUTIONS

Throughout the observations collected during this work a collection of contributions was identified. This qualitative research study contributes to knowledge as it advances the state of the art in the use of collaborative robots proposing a model to help SMEs to spread its use in the factory floor. The outcomes showed in here bring additional knowledge so far not existent in the literature.

Accordingly, this work introduces a contribution to the academic community and the industrial sector, in proposing a technology adoption model that presents as main features the design based on the ease of data interpretation and friendly-user.

The contribution in the production engineering field allows the industrial community to enable automation applications toward collaborative robots outside the classical domain of the automotive industry. As automation is an ongoing trend, the proposed model provides inputs to allow the use of cobots from a day-by-day perspective. The conceptual model contributes to the engineers during the deployment and commissioning of the collaborative workstation following the right development stages of the HRC.

For the environment and society, as this work foster the widespread utilization of cobots, it will allow manufacturing operators to perform tasks avoiding a non-ergonomic, dirty, or dangerous jobs. In fact, the adoption of collaborative operation in those areas release the employees of all of the repetitive tasks, where humans are allowed to work with machine quite in a natural manner. The HRC allows the human coworker to perform and focus on essential and indispensable tasks, where human creativity remains essential.

7.3 LIMITATIONS OF THE WORK

Although the feasibility model was tested to allow its use, such conceptual model does not fully ensure their viable application in all types of SMEs Industries. Another specific limitation is the fact of its application was only carried out under the Brazilian environment, which does not guarantee that a feasibility study toward the proposed model can be equally effective in other techno-economic environments. More specifically, those related to the employment environment, labor issues in manufacturing, occupational safety of employees, and work health legislation.

With the pressure faced by the current COVID - 19 pandemic, face-to-face meetings were not allowed to perform the Delphi study, and this scenario contributed as another limitation of this work.

7.4 STATEMENTS FOR FURTHER RESEARCH

This is a first attempt to integrate the literature on feasibility model to adopt cobot in Brazilian SMEs from the manufacturing field. The most population of industrial robots installed currently in Brazil is connected to large manufacturing corporations, such as the automotive industry. Therefore, the research was aimed to propose a techno-economic conceptual model to adopt the use of robots in SMEs from the manufacturing sector. As a suggestion for future work, SME's from other fields of industry (such as pharmaceutical, logistics, and chemical, for instance) could be considered to further evaluate the use of that conceptual model to adopt cobot.

Another future extension of this work would be the development of an computerized algorithm to be incorporated into the model, attempting to collect data of robot movements beyond human spaces during the deployment of the collaborative workstation. It could include more clarification of assembly tasks during the risk assessment phase and contribute to check details about each domain of the model, while potentials to improve robot movements to optimize speed to update cycle time and the correlated human safety during HRC. Moreover, identify how the collaborative robot can maximize the value when connecting humans with advance technologies from industry 4.0.

REFERENCES

ABEL, D.; JESSEN, U.; WENZEL, S. Delphi Study on evaluating information in simulation studies for manufacturing and logistics planning. **Journal of Simulation**, v. 7, n. 4, p. 240-248, 2013.

ACCORSI, R. et al. An application of collaborative robots in a food production facility. **Procedia Manufacturing**, v. 38, p. 341-348, 2019.

ADLER, M.; Z.O, E. **Gazing into the oracle: The Delphi method and its application to social policy and public health**. Jessica Kingsley Publishers, 1996.

AGHAEI C., A.; SALEHI, H., YUNUS, M.; FARHADI, H.; FOOLADI, M.; FARHADI, M.; ALE EBRAHIM, N. A comparison between two main academic literature collections: Web of Science and Scopus databases. **Asian Social Science**, v. 9, n. 5, p. 18-26, 2013.

AKINS, R. B.; TOLSON, H.; COLE, B. R. Stability of response characteristics of a Delphi panel: application of bootstrap data expansion. **BMC medical research methodology**, v. 5, n. 1, p. 1-12, 2005.

AKKALADEVI, S. C.; PLASCH, M.; PICHLER, A. Skill-based learning of an assembly process. **e & i Elektrotechnik und Informationstechnik**, v. 134, n. 6, p. 312-315, 2017.

ALKHORAIF, A.; RASHID, H.; MCLAUGHLIN, P. Lean implementation in small and medium enterprises: Literature review. **Operations Research Perspectives**, v. 6, p. 100089, 2019.

ANDRISANO, A. O.; LEALI, F.; PELLICCIARI, M.; PINI, F.; VERGNANO, A. Hybrid Reconfigurable System design and optimization through virtual prototyping and digital manufacturing tools. **International Journal on Interactive Design and Manufacturing (IJIDeM)**, v. 6, n. 1, p. 17-27, 2012.

AVELLA, J. R. Delphi panels: Research design, procedures, advantages, and challenges. **International Journal of Doctoral Studies**, v. 11, n. 1, p. 305-321, 2016.

BALLARD, L. A.; SABANOVIC, S.; KAUR, J.; MILOJEVIC, S. George Charles Devol, jr. **IEEE Robotics & Automation Magazine**, v. 19, n. 3, p. 114-119, 2012.

BALLOU, R. H.; SRIVASTAVA, S. K. Business logistics/supply chain management: planning, organizing, and controlling the supply chain. Pearson Education India, 2007.

BARD, J. F. An assessment of industrial robots: capabilities, economics, and impacts. **Journal of operations Management**, v. 6, n. 2, p. 99-124, 1986.

BASKARAN, S.; NIAKI, F. A.; TOMASZEWSKI, M.; GILL, J. S.; CHEN, Y.; JIA, Y.; ... KROVI, V. Digital human and robot simulation in automotive assembly using siemens process simulate: a feasibility study. **Procedia Manufacturing**, v. 34, p. 986-994, 2019.

BAUSE, K.; RADIMERSKY, A.; IWANICKI, M.; ALBERS, A. Feasibility studies in the product development process. **Procedia CIRP**, v. 21, p. 473-478, 2014.

BECKERLE, P.; BIANCHI, M.; CASTELLINI, C.; SALVIETTI, G. Mechatronic designs for a robotic hand to explore human body experience and sensory-motor skills: a Delphi study. **Advanced Robotics**, v. 32, n. 12, p. 670-680, 2018.

BDIWI, M.; PFEIFER, M.; STERZING, A. A new strategy for ensuring human safety during various levels of interaction with industrial robots. **CIRP Annals-Manufacturing Technolo**gy, 2017.

BITSCH, V. Qualitative research: A grounded theory example and evaluation criteria. **Journal of agribusiness**, v. 23, n. 345-2016-15096, p. 75-91, 2005.

BLOSS, R. Collaborative robots are rapidly providing major improvements in productivity, safety, programing ease, portability and cost while addressing many new applications. **Industrial Robot: An International Journal**, 2016.

BOGNER, K.; PFERSCHY, U.; UNTERBERGER, R.; ZEINER, H. Optimised scheduling in human–robot collaboration–a use case in the assembly of printed circuit boards. **International Journal of Production Research**, v. 56, n. 16, p. 5522-5540, 2018.

BOGUE, R. Europe continues to lead the way in the collaborative robot business. **Industrial Robot: An International Journal**, v. 43, n. 1, p. 6-11, 2016.

BRITISH AUTOMATION & ROBOT ASSOCIATION (BARA). Introduction to industrial robots. Available in < http://www.ppma.co.uk >. Accessed in: 24 Sep. 2020.

BROGARDH, T. Present and future robot control development - An industrial perspective. **Annual Reviews in Control**, v. 31, n. 1, p. 69-79, 2007.

BROSSOG, M.; BORNSCHLEGL, M.; FRANKE, J. Reducing the energy consumption of industrial robots in manufacturing systems. **The International Journal of Advanced Manufacturing Technology**, v. 78, n. 5-8, p. 1315-1328, 2015.

BROWN, S; BESSANT, J. The manufacturing strategy-capabilities links in mass customisation and agile manufacturing–an exploratory study. **International Journal of Operations & Production Management**, 2003.

BRUNO, G.; ANTONELLI, D. Dynamic task classification and assignment for the management of human-robot collaborative teams in workcells. **The International Journal of Advanced Manufacturing Technology**, v. 98, n. 9-12, p. 2415-2427, 2018.

CAMBRIGE. **Cambridge Business English Dictionary**. Cambridge, UK: Cambridge University Press, 2011.

CASADO-BELMONTE, M. D. P.; MARÍN-CARRILLO, G. M.; TERÁN-YÉPEZ E.; CAPOBIANCO-URIARTE, M. D. L. M. What Is Going on with the Research into the Internationalization of Small and Medium-sized Enterprises (SMEs)? An Intellectual Structure Analysis into the State-of-the-Art (1990–2018). **Publications**, v. 8, n. 1, p. 11, 2020.

CASTILLO-MONTOYA, M. Preparing for Interview Research: The Interview Protocol Refinement Framework. **Qualitative Report**, v. 21, n. 5, 2016.

CEBI, F.; KAHRAMAN, C. Single and Multiple Attribute Fuzzy Pareto Models. **Journal of Multiple-Valued Logic & Soft Computing**, v. 19, 2012.

CENCEN, A.; VERLINDEN, J. C.; GERAEDTS, J. M. P. Design methodology to improve human-robot coproduction in small-and medium-sized enterprises. **IEEE/ASME Transactions on Mechatronics**, v. 23, n. 3, p. 1092-1102, 2018.

CERIANI, N. M.; ZANCHETTIN, A. M.; ROCCO, P.; STOLT, A.; ROBERTSSON, A. Reactive task adaptation based on hierarchical constraints classification for safe industrial robots. **IEEE/ASME Transactions on Mechatronics**, v. 20, n. 6, p. 2935-2949, 2015.

CHEMWENO, P.; PINTELON, L.; DECRE, W. Orienting safety assurance with outcomes of hazard analysis and risk assessment: A review of the ISO 15066 standard for collaborative robot systems. **Safety Science**, v. 129, p. 104832, 2020.

CHEN, F.; SEKIYAMA, K.; CANNELLA, F.; FUKUDA, T. Optimal subtask allocation for human and robot collaboration within hybrid assembly system. **IEEE Transactions on Automation Science and Engineering**, v. 11, n. 4, p. 1065-1075, 2013.

CHERUBINI, A.; PASSAMA, R.; CROSNIER, A.; LASNIER, A. FRAISSE, P. Collaborative manufacturing with physical human–robot interaction. **Robotics and Computer-Integrated Manufacturing**, v. 40, p. 1-13, 2016.

COBO, M. J.; LÓPEZ-HERRERA, A. G.; HERRERA-VIEDMA, E.; HERRERA, F. Science mapping software tools: Review, analysis, and cooperative study among tools. **Journal of the American Society for information Science and Technology**, v. 62, n. 7, p. 1382-1402, 2011

COOPER, D. R.; SCHINDLER, P. S.; SUN, J. **Business research methods**. New York: Mcgraw-hill, 2006.

CONSELHO NACIONAL DA INDÚSTRIA (CNI**)**. **Produtividade na indústria**. Available in < http://www.portaldaindustria.com.br/estatisticas/importancia-da-industria/>. Accessed in: 13 Jun 2020.

CRESWELL, J. W. **Investigação Qualitativa e Projeto de Pesquisa-: Escolhendo entre Cinco Abordagens**. Penso Editora, 2014, 341 p.

DALKEY, N.; HELMER, O. An experimental application of the Delphi method to the use of experts. **Management science**, v. 9, n. 3, p. 458-467, 1963.

DARYANI, S. M.; AMINI, A. Identification and prioritisation of managerial tools and techniques in impact on quality improvement. **International Journal of Manufacturing Research**, v. 13, n. 3, p. 227-256, 2018.

DAVIS, F. D. Perceived usefulness, perceived ease of use, and user acceptance of information technology. **MIS quarterly**, p. 319-340, 1989.

DE JESUS PACHECO, D. A.; TEN CATEN, C. S.; JUNG, C. F.; NAVAS, H. V. G.; CRUZ-MACHADO, V. A. Eco-innovation determinants in manufacturing SMEs from emerging markets: Systematic literature review and challenges. Journal of Engineering and Technology Management, v. 48, p. 44-63, 2018.

DELBECQ, A. L.; VAN DE VEN, A. H.; GUSTAFSON, D. H. **Group techniques for program planning: A guide to nominal group and Delphi processes**. Scott, Foresman, 1975.

DE OLIVEIRA, A. C.; KAMINSKI, P. C. A reference model to determine the degree of maturity in the product development process of industrial SMEs. **Technovation**, v. 32, n. 12, p. 671-680, 2012.

DJURIC, A. M.; URBANIC, R. J.; RICKLI, J. L. A framework for collaborative robot (CoBot) integration in advanced manufacturing systems. **SAE International Journal of Materials and Manufacturing**, v. 9, n. 2, p. 457-464, 2016.

DYERSON, R.; SPINELLI, R.; HARINDRANATH, G. Revisiting IT readiness: an approach for small firms. **Industrial Management & Data Systems**, 2016.

DODDS, S.; HESS, A. C. Adapting research methodology during COVID-19: lessons for transformative service research. **Journal of Service Management**, 2020.

DONOHOE, H. M.; NEEDHAM, R. D. Moving best practice forward: Delphi characteristics, advantages, potential problems, and solutions. **International Journal of Tourism Research**, v. 11, n. 5, p. 415-437, 2009.

DÖRINGER, S. 'The problem-centred expert interview'. Combining qualitative interviewing approaches for investigating implicit expert knowledge. **International journal of social research methodology**, p. 1-14, 2020.

DRATH, R.; HORCH, A. Industrie 4.0: Hit or hype? **IEEE industrial electronics magazine**, v. 8, n. 2, p. 56-58, 2014.

DRESCH, A.; LACERDA, D. P.; ANTUNES, J. A. Valle. Design science research. In: **Design science research**. Springer, Cham, 2015. p. 67-102.

DUFFIELD, C. The Delphi technique: a comparison of results obtained using two expert panels. **International journal of nursing studies**, v. 30, n. 3, p. 227-237, 1993.

EISENHARDT, K. M.; GRAEBNER, M. E. Theory building from cases: Opportunities and challenges. **Academy of management journal**, v. 50, n. 1, p. 25-32, 2007.
EISENHARDT, Kathleen M. Building theories from case study research. **Academy of management review**, v. 14, n. 4, p. 532-550, 1989.

EUROPEAN COMMISSION: Growth: Internal market, industry, entrepreneurship and SMEs. Available in < https://ec.europa.eu/growth/access-to-finance_en (2020) > Accessed in: 13 May 2021.

FACCIO, M.; BOTTIN, M.; ROSATI, G. Collaborative and traditional robotic assembly: a comparison model. **The International Journal of Advanced Manufacturing Technology**, v. 102, n. 5-8, p. 1355-1372, 2019.

FACCIO, M., MINTO, R.; ROSATI, G.; BOTTIN, M. The influence of the product characteristics on human-robot collaboration: a model for the performance of collaborative robotic assembly. **The International Journal of Advanced Manufacturing Technology**, v. 106, n. 5, p. 2317-2331, 2020.

FAHIMNIA, B.; SARKIS, J.; DAVARZANI, H. Green supply chain management: A review and bibliometric analysis. **International Journal of Production Economics**, v. 162, p. 101-114, 2015.

FERNANDEZ G.C; GUTIERREZ S.M.; RUIZ E.S.; PEREZ F.M.; Gil M.C. Robotics, the new industrial revolution. **IEEE Technology and Society Magazine**, v. 31, n. 2, p. 51-58, 2012.

FREWER, L. J.; VAN DER LANS, I. A.; FISCHER, A. R., REINDERS, M. J.; MENOZZI, D., ZHANG, X.; ZIMMERMANN, K. L. Public perceptions of agri-food applications of genetic modification–a systematic review and meta-analysis. **Trends in Food Science & Technology**, v. 30, n. 2, p. 142-152, 2013.

GADALETA, M.; PELLICCIARI, M.; BERSELLI, G. Optimization of the energy consumption of industrial robots for automatic code generation. **Robotics and Computer-Integrated Manufacturing**, v. 57, p. 452-464, 2019.

GARCIA, E.; JIMENEZ, M. A.; DE SANTOS, P. G.; ARMADA, M. The evolution of robotics research. **IEEE Robotics & Automation Magazine**, v. 14, n. 1, p. 90-103, 2007.

GASPARETTO, A.; SCALERA, L. From the Unimate to the Delta robot: the early decades of Industrial Robotics. In: **Explorations in the History and Heritage of Machines and Mechanisms**. Springer, Cham, 2019. p. 284-295.

GEORGAKELLOS, D. A.; MACRIS, A. M. Application of the semantic learning approach in the feasibility studies preparation training process. **Information Systems Management**, v. 26, n. 3, p. 231-240, 2009.

GERVASI, R.; MASTROGIACONNO, L.; FRANCESCHINI, F. A conceptual framework to evaluate human-robot collaboration. **International Journal of Advanced Manufacturing Technology**, 2020.

GIANNAROU, L.; ZERVAS, E. Using Delphi technique to build consensus in practice. **International Journal of Business Science & Applied Management (IJBSAM)**, v. 9, n. 2, p. 65-82, 2014.

GODINHO FILHO, M.; GANGA, G. M. D.; GUNASEKARAN, A. Lean manufacturing in Brazilian small and medium enterprises: implementation and effect on performance. **International Journal of Production Research**, v. 54, n. 24, p. 7523-7545, 2016.

GOPINATH, V.; JOHANSEN, K. Risk assessment process for collaborative assembly–a job safety analysis approach. **Procedia CIRP**, v. 44, p. 199-203, 2016.

GORDON, T. J. The Delphi method. **Futures research methodology**, v. 2, n. 3, p. 1-30, 1994.

GRAU, A.; INDRI, M.; BELLO, L. L.; SAUTER, T. Industrial robotics in factory automation: From the early stage to the Internet of Things. In: **IECON 2017-43rd Annual Conference of the IEEE Industrial Electronics Society**. IEEE, 2017. p. 6159-6164.

GROOVER, M, P. **Automation, Production Systems, and Computer-Integrated Manufacturing**. 4° edition. Harlow Ingland. Prentice Hall, Inc., Pearson Education. (809 p), 2017.

GROSFELD-NIR, A.; RONEN, B.; KOZLOVSKY, N. The Pareto managerial principle: when does it apply? **International Journal of Production Research**, v. 45, n. 10, p. 2317-2325, 2007.

GUALTIERI, L.; RAUCH, E., VIDONI, R.; MATT, D. T. Safety, Ergonomics and Efficiency in Human-Robot Collaborative Assembly: Design Guidelines and Requirements. **Procedia CIRP**, v. 91, p. 367-372, 2020.

GUIOCHET, J.; MACHIN, M.; WAESELYNCK, H. Safety-critical advanced robots: A survey. **Robotics and Autonomous Systems**, v. 94, p. 43-52, 2017.

GUZ, A. N.; RUSHCHITSKY, J. J. Scopus: A system for the evaluation of scientific journals. **International Applied Mechanics**, v. 45, n. 4, p. 351, 2009.

JACOBS, F. R.; CHASE, R. B.; AQUILANO, N. J. Operations Management for competitive advantage, 11th Edition. **Boston: Mc-Graw Hill**, v. 64, p. 70, 2005.

JÄGER, J.; SCHÖLLHAMMER, O.; LICKEFETT, M.; BAUERNHANSL, T. Advanced complexity management strategic recommendations of handling the “Industrie 4.0” complexity for small and medium enterprises. **Procedia CIRP**, v. 57, p. 116-121, 2016.

JOVANE, F.; KOREN, Y.; BOER, C. R. Present and future of flexible automation: towards new paradigms. **CIRP Annals**, v. 52, n. 2, p. 543-560, 2003.

HA, I. C. Kinematic parameter calibration method for industrial robot manipulator using the relative position. **Journal of mechanical science and technology**, v. 22, n. 6, p. 1084, 2008.

HALLOWELL, M. R.; GAMBATESE, J. A. Qualitative research: Application of the Delphi method to CEM research. **Journal of construction engineering and management**, v. 136, n. 1, p. 99-107, 2010.

HANNA, P. Using internet technologies (such as Skype) as a research medium: A research note. Qualitative research, v. 12, n. 2, p. 239-242, 2012.

HEILALA, J.; VOHO, P. Modular reconfigurable flexible final assembly systems. **Assembly Automation**, 2001.

HENTOUT, A.; AOUACHE, M.; MAOUDJ, A., AKLI, I. Human–robot interaction in industrial collaborative robotics: a literature review of the decade 2008–2017. **Advanced Robotics**, v. 33, n. 15-16, p. 764-799, 2019.

HERMANN, M.; PENTEK, T.; OTTO, B. Design principles for industrie 4.0 scenarios. In: **System Sciences (HICSS), 2016 49th Hawaii International Conference on**. IEEE, 2016. p. 3928-3937.

HOFFMAN, R. R. How can expertise be defined? Implications of research from cognitive psychology. In: **Exploring expertise**. Palgrave Macmillan, London, 1998. p. 81-100.

HSU, C. H.; CHANG, A. Y.; LUO, W. Identifying key performance factors for sustainability development of SMEs–integrating QFD and fuzzy MADM methods. **Journal of Cleaner Production**, v. 161, p. 629-645, 2017.

HUANG, J.; PHAM, D. T.; WANG, Y.; JI, C.; XU, W.; LIU, Q.; ZHOU, Z. A strategy for human-robot collaboration in taking products apart for remanufacture. **FME Transactions**, v. 47, n. 4, p. 731-738, 2019.

HULL, T.; MINARCIN, M. A. Considerations in collaborative robot system designs and safeguarding. **SAE International Journal of Materials and Manufacturing**, v. 9, n. 3, p. 545-551, 2016.

IDEN, J.; LANGELAND, L. Setting the stage for a successful ITIL adoption: A Delphi study of IT experts in the Norwegian armed forces. **Information systems management**, v. 27, n. 2, p. 103-112, 2010.

INTERNATIONAL FEDERATION OF ROBOTICS (IFR). **World Robotics 2017 Service Robots**. Available in < http://www.ifr.org >. Accessed in: 12 Nov. 2020.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. ISO 10218: Robots for Industrial Environments: Safety Requirements. Part 1: Robot, ISO 10218-1. 2011. Available in < http://www.iso.org>. Accessed in: 14 Dez 2020.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. ISO 10218: Robots and Robotic Devices: Safety Requirements. Part 2: Industrial Robot Systems and Integration, ISO 10218-2. 2011. Available in < http://www.iso.org>. Accessed in: 14 Dez 2020.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. ISO 15066: Robots and robotic devices- Collaborative robots. 2016. Available in < http://www.iso.org>. Accessed in: 14 Dez 2020.

IBARGUREN A.; MAURTUA, I.; PÉREZ, M. A.; SIERRA, B. Multiple target tracking based on particle filtering for safety in industrial robotic cells. **Robotics and Autonomous Systems**, v. 72, p. 105-113, 2015.

JAIRATH, N.; WEINSTEIN, J. The Delphi methodology (Part one): A useful administrative approach. **Canadian journal of nursing administration**, v. 7, n. 3, p. 29-42, 1994.

KAMINSKI, P. C.; DE OLIVEIRA, A. C.; LOPES, T. M. Knowledge transfer in product development processes: a case study in small and medium enterprises (SMEs) of the metal-mechanic sector from Sao Paulo, Brazil. **Technovation**, v. 28, n. 1-2, p. 29-36, 2008.

KARUPPIAH, K.; SANKARANARAYANAN, B., ALI; S. M., CHOWDHURY, P.; PAUL, S. K. An integrated approach to modeling the barriers in implementing green manufacturing practices in SMEs. **Journal of Cleaner Production**, v. 265, p. 121737, 2020.

KEIL, M.; TIWANA, A.; BUSH, A. Reconciling user and project manager perceptions of IT project risk: a Delphi study 1. **Information systems journal**, v. 12, n. 2, p. 103-119, 2002.

KHALID, A.; KIRISCI, P.; KHAN, Z. H.; GHRAIRI, Z.; THOBEN, K. D., PANNEK, J. A methodology to develop collaborative robotic cyber physical systems for production environments. **Logistics Research**, v. 9, n. 1, p. 23, 2016.

KHALID, A.; KIRISCI, P.; KHAN, Z. H.; GHRAIRI, Z.; THOBEN, K. D., PANNEK, J. Security framework for industrial collaborative robotic cyber-physical systems. **Computers in Industry**, v. 97, p. 132-145, 2018.

KIM, J. H.; CHOI, S. H.; PARK, I. W.; ZAHEER, S. A. Intelligence technology for robots that think [application notes]. **IEEE Computational Intelligence Magazine**, v. 8, n. 3, p. 70-84, 2013.

KOOTBALLY, Z. Industrial robot capability models for agile manufacturing. **Industrial Robot: An International Journal**, v. 43, n. 5, p. 481-494, 2016.

KRAJEWSKI, L.; RITZMAN, L. Operations Management: Strategy and Analysis Sixth Edition Addison. 2002.

KRÜGER J.; LIEN T.K.; VERL A. Cooperation of human and machines in assembly lines. **CIRP Annals - Manufacturing Technology** 58 (2009) 628–646.

KRUEGER, R. A. **Focus groups: A practical guide for applied research**. Sage publications, 2014.

KUMAR, M.; KHURSHID, K. K.; WADDELL, D. Status of Quality Management practices in manufacturing SMEs: a comparative study between Australia and the UK. **International Journal of Production Research**, v. 52, n. 21, p. 6482-6495, 2014.

KVALE, S.; BRINKMANN, S. **Interviews: Learning the craft of qualitative research interviewing**. Sage, 2009.

LANDE, M.; SHRIVASTAVA, R. L.; SETH, D. Critical success factors for Lean Six Sigma in SMEs (small and medium enterprises). **The TQM Journal**, 2016.

LENZ, J.; MACDONALD, E.; HARIK, R.; WUEST, T. Optimizing smart manufacturing systems by extending the smart products paradigm to the beginning of life. **Journal of Manufacturing Systems**, v. 57, p. 274-286, 2020.

LI, R.; PHAM, D. T.; HUANG, J.; TAN, Y.; QU, M.; WANG, Y.; ... LIU, Q. Unfastening of Hexagonal Headed Screws by a Collaborative Robot. **IEEE Transactions on Automation Science and Engineering**, 2020.

LIENENLÜKE, L.; GRÜNDEL, L.; STORMS, S.; HERFS, W.; KONIGS, M.; SERVOS, M. Temporal and Flexible Automation of Machine Tools. In: **2018 IEEE 22nd International Conference on Intelligent Engineering Systems (INES)**. IEEE, 2018. p. 000335-000340.

LIAO, Y.; DESCHAMPS, F.; LOURES, E. D. F. R.; RAMOS, L. F. P. Past, present and future of Industry 4.0-a systematic literature review and research agenda proposal. **International journal of production research**, v. 55, n. 12, p. 3609-3629, 2017.

LIEN, T. K.; RASCH, F. O. Hybrid automatic-manual assembly systems. **CIRP Annals-Manufacturing Technology**, v. 50, n. 1, p. 21-24, 2001.

LJASENKO, S.; FERREIRA, P.; JUSTHAM, L.; LOHSE, N. Decentralised vs partially centralised self-organisation model for mobile robots in large structure assembly. **Computers in Industry**, v. 104, p. 141-154, 2019.

LOO, R. The Delphi method: a powerful tool for strategic management. **Policing: An International Journal of Police Strategies & Management**, 2002.

LOPEZ-HAWA, H.; VANPELT, A.; EMMANUEl, S.; YIHUN, Y. Automated scanning techniques using UR5. **Journal of Robotics**, v. 2019, 2019.

LOTTER, B., 2012. **Manuelle Montage von Großgeräten**. In: Lotter, B., Wiendahl, H.-P. (eds.) Montage in der industriellen Produktion. Ein Handbuch für die Praxis. VDI-Buch, 2nd edn., pp. 147–165. Springer, Berlin, Heidelberg.

LUARN, P.; LIN, H. H. Toward an understanding of the behavioral intention to use mobile banking. **Computers in human behavior**, v. 21, n. 6, p. 873-891, 2005.

LUCATO, W.C. Gestão de empresas com dificuldades financeiras. Artliber, São Paulo, Brazil, 2013.

LUCATO, W. C.; COSTA, E. M.; DE OLIVEIRA NETO, G. C. The environmental performance of SMEs in the Brazilian textile industry and the relationship with their financial performance. JOURNAL OF ENVIRONMENTAL MANAGEMENT, v. 203, p. 550-556, 2017.

LUND, B. D. Review of the Delphi method in library and information science research. **Journal of Documentation**, 2020.

MAGRINI, E.; FERRAGUTI, F.; RONGA, A.J., PINI, F.; DE LUCA, A.; LEALI, F. Human-robot coexistence and interaction in open industrial cells. **Robotics and Computer-Integrated Manufacturing**, v. 61, p. 101846, 2020.

MALIK, A. A.; BREM, A. Digital twins for collaborative robots: A case study in human-robot interaction. **Robotics and Computer-Integrated Manufacturing**, v. 68, p. 102092, 2021.

MALIK, A. A.; BILBERG, A. Complexity-based task allocation in human-robot collaborative assembly. **Industrial Robot: the international journal of robotics research and application**, 2019.

MARZOUK, M.; AMER, O.; EL-SAID, M. Feasibility study of industrial projects using Simos' procedure. **Journal of Civil Engineering and Management**, v. 19, n. 1, p. 59-68, 2013.

MARVEL, J. A. Performance metrics of speed and separation monitoring in shared workspaces. **IEEE Transactions on automation Science and Engineering**, v. 10, n. 2, p. 405-414, 2013.

MARVEL, J. A.; FALCO, J.; MARSTIO, I. Characterizing task-based human–robot collaboration safety in manufacturing. **IEEE Transactions on Systems, Man, and Cybernetics: Systems**, v. 45, n. 2, p. 260-275, 2014.

MASOOD, T.; SONNTAG, P. Industry 4.0: Adoption challenges and benefits for SMEs. **Computers in Industry**, v. 121, p. 103261, 2020.

MATEUS, J. C.; CLAEYS, D.; LIMÈRE, V.; COTTYN, J.; AGHEZZAF, E. H. Base part centered assembly task precedence generation. **The International Journal of Advanced Manufacturing Technology**, v. 107, n. 1, p. 607-616, 2020.

MATHIESON, K. Predicting user intentions: comparing the technology acceptance model with the theory of planned behavior. **Information systems research**, v. 2, n. 3, p. 173-191, 1991.

MCCOY, S.; GALLETTA, D. F.; KING, W. R. Applying TAM across cultures: the need for caution. **European Journal of Information Systems**, v. 16, n. 1, p. 81-90, 2007.

MELNYK, S. A.; LUMMUS, R. R.; VOKURKA, R. J.; BURNS, L. J.; SANDOR, J. Mapping the future of supply chain management: a Delphi study. **International Journal of Production Research**, v. 47, n. 16, p. 4629-4653, 2009.

MERGEL, I.; EDELMANN, N.; HAUG, N. Defining digital transformation: Results from expert interviews. **Government Information Quarterly**, v. 36, n. 4, p. 101385, 2019.

MICHALOS, G.; MAKRIS, S.; SPILIOTOPOULOS, J., MISIOS, I.; TSAROUCHI, P.; CHRYSSOLOURIS, G. Robo-partner: Seamless Human-Robot cooperation for intelligent, flexible and safe operations in the assembly factories of the future. **Procedia CIRP**, v. 23, p. 71-76, 2014.

MICHALOS, G.; KOUSI, N., KARAGIANNIS, P.; GKOURNELOS, C., DIMOULAS, K.; KOUKAS, S. MAKRIS, S. Seamless human robot collaborative assembly–An automotive case study. **Mechatronics**, v. 55, p. 194-211, 2018.

MITTAL, S.; KHAN, M. A.; ROMERO, D.; WUEST, T. A critical review of smart manufacturing & Industry 4.0 maturity models: Implications for Small and Medium-sized Enterprises (SMEs). **Journal of Manufacturing Systems**, v. 49, p. 194-214, 2018.

MODRAK, V.; SOLTYSOVA, Z.; POKLEMBA, R. Mapping requirements and roadmap definition for introducing I 4.0 in SME environment. In: **Advances in Manufacturing Engineering and Materials**. Springer, Cham, 2019. p. 183-194.

MOEUF, A.; PELLERIN, R.; LAMOURI, S.; TAMAYO-GIRALDO, S.; BARBARAY, R. The industrial management of SMEs in the era of Industry 4.0. **International Journal of Production Research**, v. 56, n. 3, p. 1118-1136, 2018.

MOEUF, A.; LAMOURI, S.; PELLERIN, R.; TAMAYO-GIRALDO, S.; TOBON-VALENCIA, E.; EBURDY, R. Identification of critical success factors, risks and opportunities of Industry 4.0 in SMEs. **International Journal of Production Research**, v. 58, n. 5, p. 1384-1400, 2020.

MOHER, D.; LIBERATI, A.; TETZLAFF, J.; ALTMAN, D. G. Reprint—preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. **Physical therapy**, v. 89, n. 9, p. 873-880, 2009.

MUKHERJEE, M; ROY, S. Feasibility studies and important aspect of project management. **International Journal of Advanced Engineering and Management**, v. 2, n. 4, p. 98-100, 2017.

MÜLLER, R.; VETTE, M.; GEENEN, A. Skill-based dynamic task allocation in Human-Robot-Cooperation with the example of welding application. **Procedia Manufacturing**, v. 11, p. 13-21, 2017.

MÜLLER, J.; VOIGT, K. I. Industry 4.0—Integration strategies for Small and Medium-sized Enterprises. In: **Proceedings of the 26th International Association for Management of Technology (IAMOT) Conference, Vienna, Austria**. 2017. p. 14-18.

MURPHY, M. E.; PERERA, S.; HEANEY, G. Innovation management model: a tool for sustained implementation of product innovation into construction projects. **Construction Management and Economics**, v. 33, n. 3, p. 209-232, 2015.

MURRY JR, J. W.; HAMMONS, J. O. Delphi: A versatile methodology for conducting qualitative research. **The review of higher education**, v. 18, n. 4, p. 423-436, 1995.

NAIR, V. V.; KUHN, D.; HUMMEL, V. Development of an easy teaching and simulation solution for an autonomous mobile robot system. **Procedia Manufacturing**, v. 31, p. 270-276, 2019.

NETO, G. C. O.; LEITE, R. R.; SHIBAO, F. Y.; LUCATO, W. C. Framework to overcome barriers in the implementation of cleaner production in Small and Medium-sized Enterprises: Multiple case studies in Brazil. **Journal of Cleaner Production**, v. 142, p. 50-62, 2017.

OBERC, H.; PRINZ, C.; GLOGOWSKI, P.; LEMMERZ, K.; KUHLENKÖTTER, B. Human Robot Interaction–learning how to integrate collaborative robots into manual assembly lines. **Procedia Manufacturing**, v. 31, p. 26-31, 2019.

OKOLI, C.; PAWLOWSKI, S. D. The Delphi method as a research tool: an example, design considerations and applications. **Information & management**, v. 42, n. 1, p. 15-29, 2004.

OLIFF, H.; LIU, Y. Towards industry 4.0 utilizing data-mining techniques: a case study on quality improvement. **Procedia CIRP**, v. 63, p. 167, 2017.

OLIVEIRA, G. A.; TAN, K. H.; GUEDES, B. T. Lean and green approach: An evaluation tool for new product development focused on small and medium enterprises. **International Journal of Production Economics**, v. 205, p. 62-73, 2018.

OYESOLA, M.; MPOFU; K.; MATHE, N. A techno-economic analytical approach of laser-based additive manufacturing processes for aerospace application. **Procedia Manufacturing**, v. 35, p. 155-163, 2019.

ÖZDEMIR, V; HEKIM, N. Birth of industry 5.0: Making sense of big data with artificial intelligence, "the internet of things" and next-generation technology policy. **Omics: a journal of integrative biology**, v. 22, n. 1, p. 65-76, 2018.

QIN, J.; LIU, Y.; GROSVENOR, R. A categorical framework of manufacturing for industry 4.0 and beyond. **Procedia CIRP**, v. 52, p. 173-178, 2016.

PACCHINI, A. P. T.; LUCATO, W. C.; FACCHINI, F.; MUMMOLO, G. The degree of readiness for the implementation of Industry 4.0. **Computers in Industry**, v. 113, p. 103125, 2019.

PAOLI, F. M.; OLIVEIRA NETO, G. C.; LUCATO, W. C. Economic and environmental gains resulting from the utilization of the design for the environment (DfE). **Espacios**, v. 34, n. 12, p. 1-11, 2013.

PECH, M.; VRCHOTA, J. Classification of small-and medium-sized enterprises based on the level of industry 4.0 implementation. **Applied Sciences**, v. 10, n. 15, p. 5150, 2020.

PARAMESWARAN, U. D.; OZAWA-KIRK, J. L.; LATENDRESSE, G. To live (code) or to not: A new method for coding in qualitative research. **Qualitative social work**, v. 19, n. 4, p. 630-644, 2020.

PEDERSEN, M. R.; NALPANTIDIS, L.; ANDERSEN, R. S.; SCHOU, C.; BØGH, S.; KRÜGER, V., MADSEN. Robot skills for manufacturing: From concept to industrial deployment. **Robotics and Computer-Integrated Manufacturing**, v. 37, p. 282-291, 2016.

PEDROCCHI, N., VICENTINI, F., MATTEO, M., TOSATTI, L. M. Safe human-robot cooperation in an industrial environment. **International Journal of Advanced Robotic Systems**, v. 10, n. 1, p. 27, 2013.

PELLICCIARI, M.; BERSELLI, G.; LEALI, F.; VERGNANO, A. A method for reducing the energy consumption of pick-and-place industrial robots. **Mechatronics**, v. 23, n. 3, p. 326-334, 2013.

PÉREZ, L.; RODRÍGUEZ-JIMÉNEZ, S.; RODRÍGUEZ, N.; USAMENTIAGA, R.; GARCÍA, D. F.; WANG, L. Symbiotic human–robot collaborative approach for increased productivity and enhanced safety in the aerospace manufacturing industry. **The International Journal of Advanced Manufacturing Technology**, v. 106, n. 3-4, p. 851-863, 2020.

PESHKIN, M.A., COLGATE, J. E., WANNASUPHOPRASIT, W., MOORE, C.A., GILLESPIE, R. B., AKELLA, P. Cobot architecture. **IEEE Transactions on Robotics and Automation**, v. 17, n. 4, p. 377-390, 2001.

PESSÔA, M. V. P.; BECKER, J. M. J. Smart design engineering: a literature review of the impact of the 4th industrial revolution on product design and development. **Research in engineering design**, p. 1-21, 2020.

PEREIRA, A. C.; ROMERO, F. A review of the meanings and the implications of the Industry 4.0 concept. **Procedia Manufacturing**, v. 13, p. 1206-1214, 2017.

RAUCH, E.; SPENA, P. R.; MATT, D. T. Axiomatic design guidelines for the design of flexible and agile manufacturing and assembly systems for SMEs. **International Journal on Interactive Design and Manufacturing**, v. 13, n. 1, p. 1-22, 2019.

ROBLA-GÓMEZ, S., BECERRA, V.M., LLATA, J.R., GONZALEZ-SARABIA, E., TORRE-FERRERO, C., PEREZ-ORIA, J. Working together: A review on safe human-robot collaboration in industrial environments. **IEEE Access**, v. 5, p. 26754-26773, 2017.

ROBOTIC INDUSTRIES ASSOCIATION (RIA). Defining the industrial robot industry and All It Entails. Available in < http://www.robotics.org >. Accessed in: 24 Jan 2021.

ROSA, P.; SASSANELLI, C.; URBINATI, A.; CHIARONI, D.; Terzi, S. Assessing relations between Circular Economy and Industry 4.0: a systematic literature review. **International Journal of Production Research**, v. 58, n. 6, p. 1662-1687, 2020.

ROSATI, G.; FACCIO, M.; CARLI, A.; ROSSI, A. Fully flexible assembly systems (F-FAS): a new concept in flexible automation. **Assembly Automation**, 2013.

ROWLEY, J. Conducting research interviews. **Management research review**, 2012.

SALUNKHE, O.; STENSÖTA, O.; ÅKERMAN, M.; BERGLUND, Å. F.; ALVEFLO, P. A. Assembly 4.0: Wheel Hub Nut Assembly Using a Cobot. **IFAC-PapersOnLine**, v. 52, n. 13, p. 1632-1637, 2019.

SAMANEZ, C.C. (2009). *Engenharia econômica*. Pearson, São Paulo, Brazil.

SANDERS, R. The Pareto principle: its use and abuse. **Journal of Services Marketing**, 1987.

SAMPIERI, R. H., COLLADO, C. F., LUCIO, P. B. **Metodologia de pesquisa**. 5° edição. Porto Alegre. Editora penso, 2013. 624 p.

SCHMIDT, F. C.; ZANINI, R. R.; KORZENOWSKI, A. L.; SCHMIDT JUNIOR, R.; XAVIER DO NASCIMENTO, K. B. Evaluation of sustainability practices in small and medium-sized manufacturing enterprises in Southern Brazil. **Sustainability**, v. 10, n. 7, p. 2460, 2018.

SCHMIDT, R.; LYYTINEN, K.; KEIL, M.; CULE, P. Identifying software project risks: An international Delphi study. **Journal of management information systems**, v. 17, n. 4, p. 5-36, 2001.

SCHMIDT, R. C. Managing Delphi surveys using nonparametric statistical techniques. **decision Sciences**, v. 28, n. 3, p. 763-774, 1997.

SERVIÇO BRASILEIRO DE APOIO ÀS MICRO E PEQUENAS EMPRESAS (SEBRAE). Panorama dos pequenos negócios. Available in < https://m.sebrae.com.br/Sebrae/Portal%20Sebrae/UFs/SP/Pesquisas/Panorama_dos_Pequenos_Negocios_2018_AF.pdf >. Accessed in: 24 Mai 2020.

SHEN, L. Y.; TAM, V. W.; TAM, L.; JI, Y. B. Project feasibility study: the key to successful implementation of sustainable and socially responsible construction management practice. **Journal of cleaner production**, v. 18, n. 3, p. 254-259, 2010.

SCHOLER, M.; VETTE, M.; RAINER, M. A lightweight robot system designed for the optimisation of an automotive end-off line process station. **Industrial Robot: An International Journal**, 2015.

SHIN, J.K., SIEGEL, J.G. (2009). *Modern cost management & analysis*. 3rd ed. Barrons, Hauppauge, NY, USA.

SILVA, M. E.; FIGUEIREDO, M. D. Practicing sustainability for responsible business in supply chains. **Journal of Cleaner Production**, v. 251, p. 119621, 2020.

SKULMOSKI, G. J., HARTMAN, F. T., KRAHN, J. The Delphi method for graduate research. Journal of Information Technology Education: Research, v. 6, n. 1, p. 1-21, 2007

STANKALLA, R.; KOVAL, O.; CHROMJAKOVA, F. A review of critical success factors for the successful implementation of Lean Six Sigma and Six Sigma in manufacturing small and medium sized enterprises. **Quality Engineering**, v. 30, n. 3, p. 453-468, 2018.

SULLIVAN, W.G., WICKS, E.M., KOELLING, C.P. (2018). *Engineering Economy*. 17th ed. Pearson, London UK.

TAKATA, S.; HIRANO, T. Human and robot allocation method for hybrid assembly systems. **CIRP Annals-Manufacturing Technology**, v. 60, n. 1, p. 9-12, 2011.

TERZIOVSKI, M. Innovation practice and its performance implications in small and medium enterprises (SMEs) in the manufacturing sector: a resource-based view. **Strategic Management Journal**, v. 31, n. 8, p. 892-902, 2010.

THÜRER, M.; GODINHO FILHO, M.; STEVENSON, M.; FREDENDALL, L. D. Small manufacturers in Brazil: competitive priorities vs. capabilities. **The International Journal of Advanced Manufacturing Technology**, v. 74, n. 9-12, p. 1175-1185, 2014.

THOMSON, B. R. Appropriate and inappropriate uses of humor in psychotherapy as perceived by certified reality therapists: A Delphi study. **Journal of Reality Therapy**, 1990.

TRANFIELD, D.; DENYER, D.; SMART, P. Towards a methodology for developing evidence-informed management knowledge by means of systematic review. **British journal of management**, v. 14, n. 3, p. 207-222, 2003.

TSAROUCHI, P.; MAKRIS, S.; CHRYSSOLOURIS, G. Human–robot interaction review and challenges on task planning and programming. **International Journal of Computer Integrated Manufacturing**, v. 29, n. 8, p. 916-931, 2016.

TUROFF, M.; LINSTONE, H. A. The Delphi method-techniques and applications. 2002.

VANALLE, R. M.; GANGA, G. M. D.; GODINHO FILHO, M.; LUCATO, W. C. Green supply chain management: An investigation of pressures, practices, and performance within the Brazilian automotive supply chain. **Journal of cleaner production**, v. 151, p. 250-259, 2017.

VASIC, M.; BILLARD, A. Safety issues in human-robot interactions. In: **2013 IEEE International Conference on Robotics and Automation**. IEEE, 2013. p. 197-204.

VEILE, J. W.; KIEL, D.; MÜLLER, J. M.; VOIGT, K. I. Lessons learned from Industry 4.0 implementation in the German manufacturing industry. **Journal of Manufacturing Technology Management**, 2019.

VENKATESH, V.; DAVIS, F. D. A theoretical extension of the technology acceptance model: Four longitudinal field studies. **Management science**, v. 46, n. 2, p. 186-204, 2000.

VIDAL, L. A.; MARLE, F.; BOCQUET, J. C. Measuring project complexity using the Analytic Hierarchy Process. **International Journal of Project Management**, v. 29, n. 6, p. 718-727, 2011.

VIDO, M.; LUCATO, W.C.; MARTENS, M.L. O robô colaborativo na indústria 4.0: conceitos para a interação humano-robô em um posto de trabalho. In: ENEGEP – Encontro Nacional de Engenharia de Produção, XXXIX., 2019, Santos. **Anais eletrônicos**... Rio de Janeiro: ABEPRO, 2019. Disponível em: <http://www.abepro.org.br/biblioteca/TN_STO_290_1634_37074.pdf>. Accessed in: Dez. 11 2020.

VILLANI, V.; PINI, F.; LEALI, F.; SECCHI, C. Survey on human–robot collaboration in industrial settings: Safety, intuitive interfaces and applications. **Mechatronics**, v. 55, p. 248-266, 2018.

VOSS, C., TSIKRIKTSIS, N., FROHLICH, M.: Case research in operations management. Int. J. Oper. Prod. Manage. 22(2), 195 (2002).

WALLÉN, J. **The history of the industrial robot**. Linköping University Electronic Press, 2008.

WANG, L., GAO, R., VÁNCZA, J., KRÜGER, J., WANG, X.V., MAKRIS, S., CHRYSSOLOURIS, G. Symbiotic human-robot collaborative assembly. **CIRP annals**, v. 68, n. 2, p. 701-726, 2019.

WANG, T. M.; TAO, Y.; LIU, H. Current Researches and Future Development Trend of Intelligent Robot: A Review. **International Journal of Automation and Computing**, v. 15, n. 5, p. 525-546, 2018.

WANG, X. V.; KEMÉNY, Z.; VÁNCZA, J.; WANG, L. Human–robot collaborative assembly in cyber-physical production: Classification framework and implementation. **CIRP annals**, v. 66, n. 1, p. 5-8, 2017.

WANG, Y.; WANG, G.; ANDERL, R. Generic procedure model to introduce Industrie 4.0 in Small and Medium-sized Enterprises. In: **Proceedings of the world congress on engineering and computer science**. 2016.

WEISS, A.; HUBER, A.; MINICHBERGER J.; IKEDA, M. First Application of Robot Teaching in an Existing Industry 4.0 Environment: Does It Really Work? **Societies**, v. 6, n. 3, p. 20, 2016.

WOJTYNEK, M.; STEIL, J. J.; WREDE, S. Plug, Plan and Produce as Enabler for Easy Workcell Setup and Collaborative Robot Programming in Smart Factories. **KI-Künstliche Intelligenz**, v. 33, n. 2, p. 151-161, 2019.

WUEST, T.; THOBEN, K. D. Information management for manufacturing SMEs. In: **IFIP International Conference on Advances in Production Management Systems**. Springer, Berlin, Heidelberg, 2011. p. 488-495.

YANIV, I. Group diversity and decision quality: amplification and attenuation of the framing effect. **International Journal of Forecasting**, v. 27, n. 1, p. 41-49, 2011.

YIN, R. K. **Estudo de caso - Planejamento e Métodos**. Porto Alegre. 5° edição. Editora Bookman, 2015. 290 p.

YIN, R. K. **Case study research and applications: Design and methods**. Sage publications, 2017.

YOUSUF, M. I. Using experts opinions through Delphi technique. **Practical assessment, research, and evaluation**, v. 12, n. 1, p. 4, 2007.

ZANCHETTIN, A. M.; CERIANI, N. M.; ROCCO, P., DING, H.; MATTHIAS, B. Safety in human-robot collaborative manufacturing environments: **Metrics and control**. , v. 13, n. 2, p. 882-893, 2015.

ZHANG, H. D.; LIU, S. B.; LEI, Q. J.; HE, Y.; YANG, Y.; BAI, Y. Robot programming by demonstration: a novel system for robot trajectory programming based on robot operating system. **Advances in Manufacturing**, v. 8, p. 216-229, 2020.

ZHANKAZIEV, S.; GAVRILYUK, M.; MOROZOV, D.; ZABUDSKY, A. Scientific and methodological approaches to the development of a feasibility study for intelligent transportation systems. **Transportation Research Procedia**, v. 36, p. 841-847, 2018.

APPENDIX 1 – ECONOMIC FEASIBILITY ANALYSIS

INCOME STATEMENT						
	Year					
(Values in EURO)	0	1	2	3	4	5
Total cost savings due to cobot utilization						
Additional contribution margin due to cobot utilization						
Total additional income						
Operational costs and expenses due to cobot Utilization						
- Depreciation						
- Cobot Maintenance						
- Cobot energy Consumption						
- Technical adjustments required						
-						
Total operational costs and expenses		**0,0**	**0,0**	**0,0**	**0,0**	**0,0**
Additional gross profit due to cobot utilization						
- Income tax						
Additional net profit due to cobot utilization		**0,0**	**0,0**	**0,0**	**0,0**	**0,0**

CASH FLOW						
	Year					
(Values in EURO)	0	1	2	3	4	5
Initial investment to acquire the cobot						
Initial investment to install the collaborative workstation						
Other startup costs						
Total Investment						
Additional net profit due to cobot utilization						
- Depreciation						
- Other Incomes (a)						
- Other Expenses (a)						
Net cash flow	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**	**0,0**

What is the minimum return rate would you like this investment to bring back to your company (% per year)	
What is the maximum period would you like this investment to return back to your company (in months)	

IRR (% per year)	
Payback period (months)	

APPENDIX 2 – EXPERT PANEL INVITATION LETTER

Dear Mr.

As previously mentioned, in addition to my professional activity at WETRON Automation, I am a part of the researcher's team from the Master's and Doctoral Program in Production Engineering (PPGEP) here at UNINOVE. Within our research area, we address some of the most interesting topics at the moment for Production Engineering, including among others the industry 4.0 (I 4.0) and collaborative robotics.

I am getting in touch because I am finishing field research together with my supervisor, Prof. Dr. Wagner Lucato, to finalize my dissertation. The theme addresses I 4.0 and the propagation of the collaborative robot in small and medium-sized companies (SME) in Brazil. The field research related to this work is based on the Delphi Method to gather information on the subject from industry and academic experts.

Therefore, we would like to invite you to participate in an interview online mode (via Google Meet) about this topic, and in this way, be able to count on your experience for my research! During the interview (~30 minutes), we will present the idea of the theme and the proposed model of our work for dissemination of cobot in SMEs for your considerations and remarks.

We will set up the meeting based on your availability! For that, could you propose the best convenient date based on your agenda?

Best regards,

Marcos Vido

Pesquisador - PPGEP
Universidade Nove de Julho - UNINOVE
marcosvido8@uni9.edu.br
(11) 9 4458-1363
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APPENDIX 3 – EXPERT PANEL THANK-YOU LETTER

Dear Mr.

On behalf of UNINOVE's PPGEP and my supervisor, Prof. Dr. Wagner Lucato, I would like to thank you for your time and participation in the development of my research work, thus contributing to enriching my academic learning process.

I'd like to emphasize the importance of your professional experience and feedback provided in order to optimize the content of the theoretical model proposed in my work. People like you enable contributions to scientific knowledge.

Best regards,

Marcos Vido

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APPENDIX 4 – BENEFITS OF INDUSTRIAL ROBOTS VS. COBOTS

Feature	Industrial Robots	Cobots
Move parts around	x	x
Follow a path/trajectory	x	x
Work autonomously for extended periods of time	x	x
Increase productivity and product quality	x	x
Reduce musculoskeletal injuries in workers (e.g. RSI)	x	x
Require sensors and/or fencing for safety	x	
Require extensive robotics knowledge to integrate	x	
Take up lots of floor space	x	
Are expensive	x	
Are easy for non-experts to program		x
Are easy to slot into your existing workspace		x
Are easy to reconfigure for new tasks		x
Are easy to move from one task to another		x
Are quick to set up		x