UNIVERSITY OF BRASILIA
TECHNOLOGY COLLEGE
MECHANICAL ENGINEERING DEPARTMENT
POSTGRADUATE PROGRAM IN MECHATRONIC SYSTEMS

<u>THESIS</u>

BRUNA FELIPPES CORRÊA

PROPOSAL OF THE CUBE-4.0 READINESS MODEL FOR ENGINEERING COMPANIES THROUGH DIGITAL TRANSFORMATION CONTEXT

ADVISOR: SANDERSON CÉSAR MACÊDO BARBALHO, Dr. Eng.

THESIS WORK
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THESIS SUBMITTED TO THE MECHANICAL ENGINEERING DEPARTMENT OF TECHNOLOGY COLLEGE OF THE UNIVERSITY OF BRASILIA

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Abstract

This thesis proposes a new Readiness Model, called CUBE-4.0, to assess the current state of readiness and guide improvement strategies, in an innovative way, in engineering companies (industries) of any size, type, and readiness level, in the digital transformation context.

A systematic literature and theory review was conducted to select, with a Bibliographic Synonyms Test (BST) and a specific 8-Step Search Flow (both created by the Author), concrete information from 486 relevant studies found in 10 renowned databases, considering 63 existing maturity and readiness models and the entire scientific literature on this subject worldwide.

Based on the existing maturity and readiness models' shortcomings and after pre-design and systematization, the CUBE-4.0 Readiness Model was developed as an essential contribution to this research stream. This includes its **Framework** (dimensions, sub-dimensions, elements, readiness levels, radar chart, score calculation, and data collection methodology), **Questionnaire**, and **Roadmap**. Besides, this Model provides a practical and easily applicable methodology, with 3 dimensions (*X = Organizational Enabler, Y = Technological Enabler, and Z = Process Maturity Enabler*), 6 sub-dimensions, and 21 elements. Furthermore, it has a scale from 0 to 5 to assess the company readiness level, defined and structured in an unprecedented way, besides considering, for the first time, maturity as an "input" enabler for the company readiness evaluation, and not as an "output" as in all other existing models. Also, a "CUBE-4.0 Questionnaire" was developed, based on these CUBE-4.0 concepts, to collect data and survey engineering firms about their readiness for digital transformation. Finally, with a "CUBE-4.0 Roadmap", based on the CUBE-4.0 Questionnaire results, this Model can also help corporate boards to guide strategies and plan improvements in their companies in this Industrial 4.0 (I4.0) Age.

After presenting some deductive hypotheses, a pre-test with the CUBE-4.0 Questionnaire and CUBE-4.0 Roadmap was applied in six steps, whose satisfactory results will be presented in this thesis. Then, the CUBE-4.0 Model was reviewed and applied in three renowned engineering companies, enabling its complete validation, using theoretical and practical methods.

Last, this thesis will present the main discussion about the results. This includes the falsifiability of the hypotheses, concluding that CUBE-4.0 Model is complete, useful, inexpensive, and efficient, and could help companies to improve their readiness through the digital transformation context.

Keywords: READINESS, MATURITY MODEL, ENGINEERING COMPANY, INDUSTRY 4.0, DIGITAL TRANSFORMATION

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SUMMARY

1. Introduction

"The hundreds of hours of study devoted to research will serve only as a small piece to put together a giant puzzle. The value of his study will be determined by how it fits the past researchers' efforts and by the questions that his findings leave for future research". Cooper [1]

Digital Transformation (DT) is the digital technology integration into all areas of a company, mainly changing the way its production systems, organizational aspects (business and culture), and operation processes (with customers and consulting companies), are operated [2]. In this context, there is an increasing number of authors advocating that companies must have a certain maturity degree to succeed in a smart manufacturing environment [3] [4]. Maturity Models (MMs) are useful for both science and practice because they help systematically gather information about a company's current state and its strategies for DT. This data can be used to compare companies and their performance, develop better implementation methodologies, and understand current pitfalls. In practice, MMs are an established approach to help companies evaluate themselves within a specific interest area and to plan improvements [5]. The MMs application as self-assessment is currently proposed for the DT endeavor [6] [7] [8] [9] [4] [10].

Therefore, this research proposed the "CUBE-4.0 Readiness Model" development, which relates technological, organizational, and process maturity enablers as dimensions for evaluating an engineering company's readiness to implement the DT. Thus, this thesis compared existing maturity and readiness models, identified the current problems and limitations in these approaches, and described the new CUBE-4.0 Model as an essential contribution to this research (see Appendix B).

1.1 Justification and Motivation

The theme's importance was self-understood since Industry 4.0 (I4.0) is evolving, but many companies have not started their digitalization journey. This research is an original approach due to the construction of a different relationship between “readiness” and “maturity” through a hypothetical-deductive approach [156]. And finally, the model applicability was tested and evolved as presented next.

According to Pereira [17], a scientific investigation is justified when there are gaps in knowledge about a subject, and there is the possibility of adding something to it with the research. Regarding the shortcomings of the existing models, the scientific literature considers the main problems below:

(a) Are preliminary works

For Leyh et al. [18], the literature presents an initial model proposal and somehow the development process is described more or less extensively, while for Amaral and Peças [19], there is no tool for a systematic approach that predicts a company's hurdles in implementing I4.0. Similarly, Li et al. [20] express that SMEs have no one-size-fits-all self-assessment tool solution.

For Leyh et al. [18], the analysis of the identified articles about maturity showed that the models have an average of five stages and numerically very different dimension characteristics per stage. On the other hand, according to Renteria et al. [3], some models do not even have a description for each dimension level and do not provide essential information about their enablers, structure, items, variables, dimensions, stages, layers, or evaluating levels. Hence, most of them only present a general description for each stage and do not have their clauses mapped synergically. Finally, most existing MMs are uni-dimensional which makes the final evaluation difficult.

Similarly, Liebrecht et al. [21] say that many existing models lack transparency on how to apply MM, so a model development should be built on a multiple research method approach.

For Caiado et al. [22], regarding the MM design process, some procedure models need to develop ready-to-use instruments to assess and improve maturity, highlighting that the usefulness and practical applicability of these instruments depends on MMs design principles for a prescriptive purpose. For example, defined improvement measures are quite useful, but the selection of these measures is often associated with a company's performance or business context. Thus, this prescriptive use of MMs requires the ability to adapt to the specific organization's characteristics. Besides, for Caiado et al. [22], providing good documentation of its application also makes the model easier to understand and use, which was also revealed as being rare in existing I4.0 MMs.

(b) Have only a theoretical development

To Amaral and Peças [19], not all MMs follow a concrete process model in their development, and most lack a thorough evaluation, especially regarding their usage in practice.

In the same way, to Mittal et al. [23], theoretical applications are limited in the I4.0 maturity literature and need to allow more realistic representations of the real-world environment, corroborating the need for more practical I4.0 MMs.

(c) Focus on technology only

For Amaral and Peças [19], existing tools have focused essentially on advanced technologies.

In line with Leyh et al. [18], some of the analyzed MMs contain, in part, related and relevant approaches. However, these mostly do not necessarily cover all the required functionality and content of a highly integrative and organization-wide digitalization for application in the I4.0 field.

After analyzing the main 17 MMs in their study, Simetinger and Zhang [24] also affirm that existing MMs can help in I4.0, but there are still tasks that must be handled and do not require only technical excellence.

Similarly, Margariti et al. [25] state that most models do not deal with all organizational aspects and organizational interoperability barriers and concerns, without proposing a specific approach to solve organizational level interoperability problems and not identifying any assessment construct to measure and benchmark organizational interoperability. So, none of these models that have been developed and implemented by different researchers, in national and international organizations, discuss specific measures to assess the interoperability of organizational aspects.

In this way, Li et al. [20] say that MMs presented by Schumacher et al. [6] and Lichtblau et al. [26] are simpler to apply and require less knowledge about I4.0 for the companies themselves, compared to the maturity index presented by Schuh et al [7]. The latter is limited because it lacks a holistic approach and does not include an emphasis on organizational issues, which is important when it comes to implementing I4.0 enabling technologies.

Leyh et al. [18] could not identify a MM that deals with or has an explicit focus on the I4.0 requirements in combination with the IT system landscape of an enterprise and its partners in the value chain.

Caiado et al. [22], through a systematic literature review, could demonstrate that there is currently no MM that addresses the needs of manufacturing 4.0 in terms of socio-technical skills, production operations management, and supply-chain, considering the context of emergent countries.

Thus, in the logistic sector, all existing readiness models only evaluate in detail the internal logistics area [27], while in the web security, existing models on the market are scarce and lack a post-evaluation follow-up [28].

(d) Have high implementation costs

In this critical analytics context, Felch and Asdecker [29] results (see Figure 1) showed that current MMs are considered too strategic (⌀+0.43, SD=1.01, n=30) and are not customizable (⌀+0.31, SD=0.97, n=29). The least important reason is the lack of need for such models (⌀-0.80, SD=1.03, n=30) and their expected usefulness (⌀-0.68, SD=1.01, n=31).

Reason	Avg., SD, n
Cost factor (acquisition)	-0.23, 0.97, n=30
Cost factor (application)	+0.20, 1.06, n=30
Do not understand the model	-0.10, 0.88, n=30
Limited resources	-0.07, 1.17, n=30
Limited time	+0.10, 1.03, n=30
MMs not useful	-0.68, 1.01, n=31
MMs not required at the moment	-0.80, 1.03, n=30
Too standardized, not customizable	+0.31, 0.97, n=29
Too strategic, no operational focus	+0.43, 1.01, n=30

Figure 1: Reasons for not applying existing MMs (Source: Felch and Asdecker [29]).

Therefore, in this thesis, a new Model for the DT readiness analysis has been proposed. The Model relates technological, organizational, and process maturity enablers to understand the gaps and possible guidelines for DT implementation in engineering companies.

1.2 General and Specific Objectives

This research had the following main objective: to propose, apply and validate the "CUBE-4.0 Readiness Model" in the Digital Transformation context.

The following specific objectives (OB) enabled the general objective:

- **OB.1:** Compare existing maturity and readiness models, and identify the current problems and limitations in traditional approaches;
- **OB.2:** Develop a new CUBE-4.0 Model, to address these limitations and provide more benefits, better results, and easier ways to apply in

engineering enterprises, as an unprecedented contribution to the scientific literature related to this theme;

- **OB.3:** Propose and validate a "CUBE-4.0 Questionnaire", based on these CUBE-4.0 concepts, for data collection and survey in engineering companies about their readiness for DT; and
- **OB.4:** Propose and validate a generical "CUBE-4.0 Roadmap", based on the CUBE-4.0 Questionnaire results, to help corporate boards to guide strategies and plan improvements in their companies in this I4.0 Era.

As the relationship between "readiness" and "maturity" is central to our Model, the following research proposals were also presented to guide the development of this project:

- **PROP1:** "Maturity" is different from "readiness" when analyzing whether a company is prepared to implement DT.
- **PROP2:** Process maturity is "input" when analyzing whether a company is prepared to implement I4.0 technologies in its operations.

1.3 Research Relevance and Originality

The research relevance may be associated with several factors, such as the theme's importance, the approach's originality, and the results' applicability [17]. For Ramos et al. [30], "all professionals stressed that the evaluation models aimed at I4.0 are essential to avoid too many trials and errors".

The main innovative contributions of this CUBE-4.0 Model are as follows:

- it will provide a rigorous procedure for the Model's construction and a practical, transparent, and easily applicable methodology, with dimensions, sub-dimensions, elements, enablers, and granularity levels, defined and structured in an unprecedented way;

- it will, for the first time, consider process maturity as an “input” enabler for the company readiness evaluation, and not as an “output” like in all other existing models. So, the new Model will focus on a clear differentiation among enablers and a processual view, including maturity analysis of each core production process (engineering, research, development, prototype production, purchasing, manufacturing, supply chain, sales and operations, quality management system). For this unprecedented dimension of process maturity, our model can quant-qualify maturity in a more complete way and at various levels. The Model will focus on the concept of readiness once a company must be ready to implement DT advancements, and this readiness must not only be on the technical side. On the other hand, the concept of maturity, derived from the quality management field, is not appropriate to communicate the challenges a company faces when trying to implement I4.0, especially in emerging countries. It is not appropriate to say that a company is mature to implement something that is evolving, and no researcher or consultant knows exactly how it will progress. This reasoning motivated us to propose a readiness model where maturity is a necessary input dimension for a company to understand whether is ready to implement I4.0 technologies effectively. In our Model, maturity analysis must be in the Product-Service Development and Order Fulfillment processes;
- this thesis will present, for the first time, a framework with the difference between “maturity” and “readiness” for DT;
- with a new type of “General Readiness Roadmap”, this model will also help corporate boards to plan improvements and developments in their companies;

- it will relate three enablers (technological, organizational, and process maturity) to readiness, enabling engineering companies of any type, size, and with any readiness level, to systematically increase their quality results in the DT context;
- it will use, for the first time, the method created by the Author, called Bibliographic Synonyms Test (for bibliograph review); and
- readiness will be measured more objectively, that is, using a tri-dimensional vector score indicating whether or not the company is ready for DT.

1.4 Thesis Structure

Beyond this introduction chapter, this document covers the following topics:

- **Chapter 2:** describes the systematic bibliographic review for this project, as well as the main methods for the studies' selection, quanti-qualitative results, future trends, and clusters, besides the theoretical foundations and state-of-the-art of the main concepts related to this thesis;
- **Chapter 3:** outlines the methodology classification and all steps of this research;
- **Chapter 4**: details the model development stages, as is, preconception, systematization, and pre-design of the model, as well as some deductive hypotheses and six pretests for the new CUBE-4.0 Model;
- **Chapter 5:** describes the CUBE-4.0 Model's validation, by applying it in three engineering companies, including describing all the characteristics of the validated CUBE-4.0 Model, such as the Framework (dimensions, levels, graphics, readiness calculation,

and data collection method), CUBE-4.0 Questionnaire, and CUBE-4.0 Roadmap - all in Final Version;

- **Chapter 6:** outlines the analysis of the results and discussions; and
- **Chapter 7:** demonstrates the results of falsifiability tests and the main conclusions of this thesis, as well as proposes future work on this theme.

Finally, Appendix A, B, C, and D will be shown after the references used for this thesis.

2. Bibliograph and Theoretical Review

This chapter covers the literature review, as well as the main theoretical concepts related to the subject under analysis. Based on the methodology described in Chapter 3, the research protocol selected for this study is a “systematic bibliographic review”, which is “a way to identify, evaluate and interpret all available research that is relevant to a particular research issue, or area, or phenomenon of interest” [31] [32] [33]. So, for Kitchenham [31], there are some reasons for choosing a systematic review:

- Summary existing evidence involving treatment or technology, for example, to sum up empirical evidence on the benefits and limitations of a specific agile development method;
- Identify gaps in current research to suggest areas for future investigations. Khan et al. [34] corroborate this view and state that “by identifying what is known and what is not known, systematic reviews help to plan new primary research”;
- Provide a background to properly position new research activities; and
- Examine how much empirical evidence contradicts/confirms theoretical hypotheses, or even supports the process of generating new hypotheses.

According to Ercole at el. [35], it is one of the main judicious methods of research that produces the best scientific knowledge of a given problem to support decision-making. That is, when quantitative and qualitative analyses are included, it is possible to map the origins of existing concepts, point out the main theoretical lenses used to investigate a subject, raise the methodological tools used in previous work, analyze their respective results, and synthesize recent findings and position research about the academic debate, situating researchers about the true contribution of the study. In addition, according to Vouga and Amatucci [36], a good literature review, as is the case of a systematic review, should be able to address problems to be investigated in future research, because scientific knowledge is developed gradually, cooperatively, and cumulatively. Being at the top of the scientific evidence hierarchy, systematic review studies, with or without meta-analysis, generally tend to provide stronger evidence, that is, they are more appropriate studies to answer questions about any topic [37].

2.1 Systematic Bibliographic Review Main Results: studies selection

As the existing systematic reviews found (based on the methodology described in Chapter 3) are very limited, repeat almost the same studies, and also have obsolete information, there was a need to develop a robust bibliographic review.

Of all the existing platforms, based on the methodology described in Chapter 3, the Portal for the Improvement of Personnel Coordination Higher Education (CAPES) - CAFe Network (Federated Academic Community) was chosen for this study, considering that it is a multidisciplinary virtual library that gathers and makes available the best of international scientific production.

In the same way, ten of the most common scientific databases that provide a bibliographic analysis were searched: **Scopus** - which features studies from 1997 to now; Web of Science (**WoS**) - from 1945 to now; **Science Direct** (SD) - from 1992 to now; Educational Resources Information Centre (**ERIC**) - from 2001 to now; **EBSCO**host (Academic Search Premier-ASP) - from 1887 to now; Wiley Online Library (**Wiley**) - from 1992 to now; American Association for the Advancement of Science (**AAAS**) - no information available; **Springer** Link - from 1991 to now; Research Gate (**RG**) - no information available; ACM Digital Library (**ACM**) - from 1908 to now.

Based on the methodology described in Chapter 3, the software Mendeley and Vos Viewer were selected for use in this thesis.

For all selected databases, the search was conducted in June/2021 and considered all existing studies, since the oldest default date in each database. After the search with the Boolean Equations (see Appendix A), as a result of the methodology described on topic 3.2.1.5 (Bibliographic Synonyms Test), it can be seen in Table 1 the number of studies found, highlighting in blue the final quantity of studies considered for each database (resulting in a total of 486 studies).

Table 1 - Search Strategies and Results by June/2021 (Source: Author).

NUMBER OF STUDIES										
Eq.	**SCOPUS**	**WoS**	**S. DIRECT**	**SPRINGER**	**WILEY**	**EBSCO**	**AAAS**	**ACM**	**RG**	**ERIC**
(IE)	0	2	NA	339	**27**	**25**	0	**18**	**12**	0
(1)	0	0	**44**	**182**	9	5	0	1	100*	0
(2)	**122**	**55**	224	540	39	16	0	14	100*	**1**
(3)	155	110	225	540	39	16	0	14	100*	1
(4)	231	149	336	598	47	34	0	52	100*	1

Notes:
- **IE**: Initial Equation.
- AAAS were discarded because presented null results.
*Maximum allowed by the software of this database.

After 8-Step Search Flow (see Chapter 3), eight databases were found, with their respective 137 studies. The first stage of the 8-Step Search Flow can be seen in Figure 2.

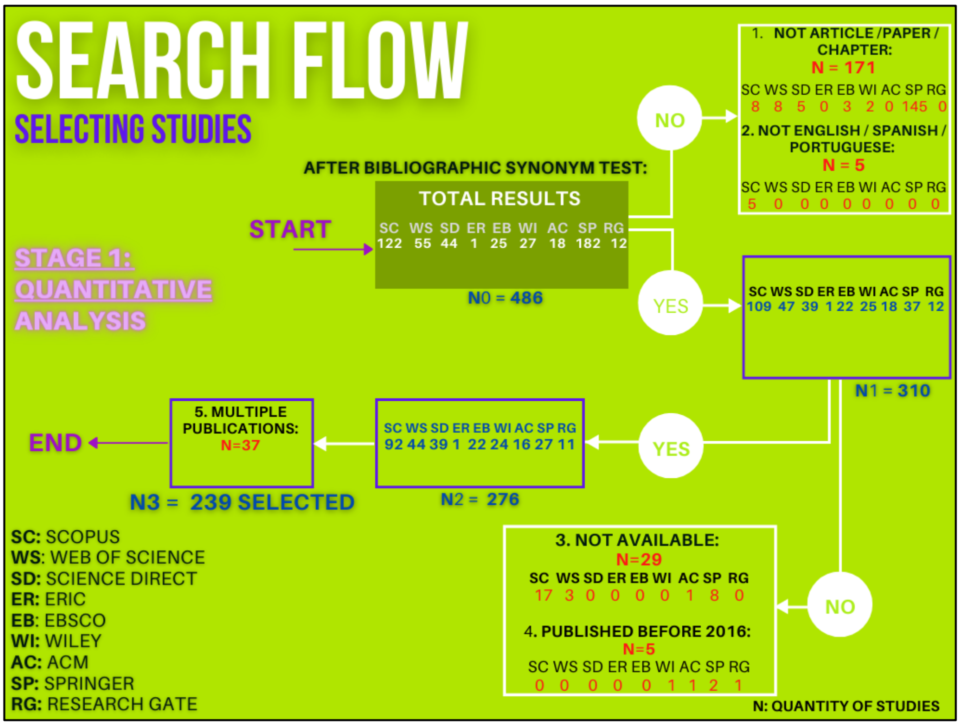


Figure 2: Search Flow - STAGE 1: Basic Features Analysis (Source: Author).

Considering that there are publications that only accept studies with a bibliographic source dated up to five years earlier, we opted to diversify the selection requirements using this exclusion criterion, “so as not to rely solely on citation practice, which has strong influences such as publication language, subject area, and international collaboration” [100].

The second stage of the 8-Step Search Flow can be seen in Figure 3.

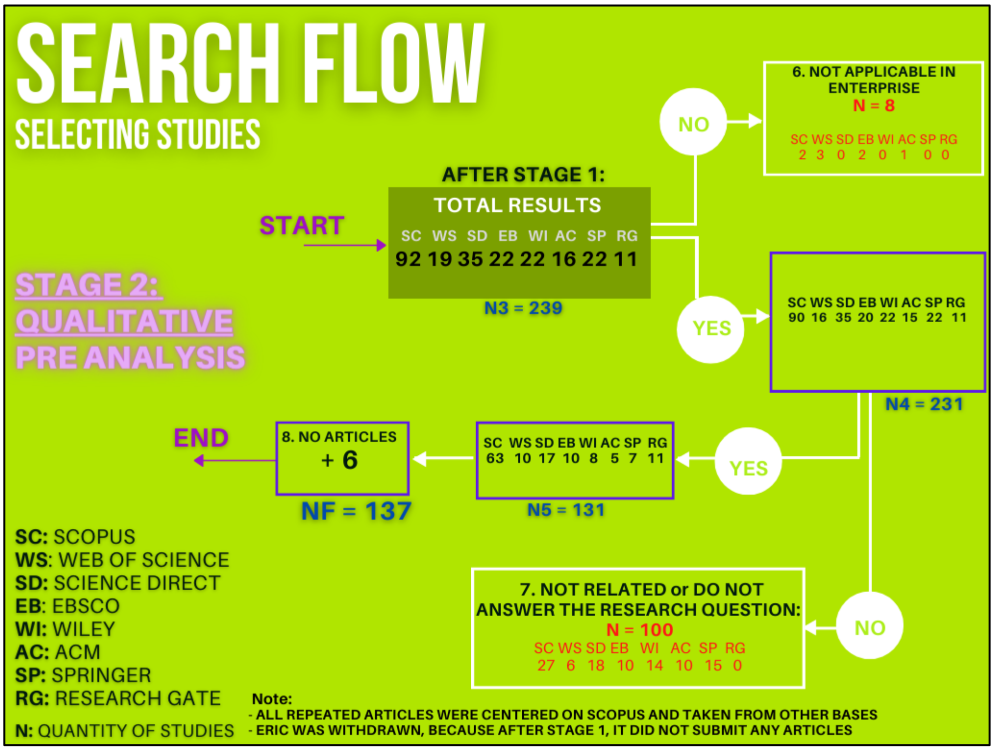


Figure 3: Search Flow - STAGE 2: Qualitative Pre-Analysis (Source: Author).

Due to their importance, six “non-articles” were selected regardless of the year of publication, which are famous models and recognized in the I4.0 context but are not scientific articles presented in the databases. They are indexed from companies, based on Ambrosio et al. [39].

Then, the results after analyzing these 137 studies were totaled into 63 maturity and readiness models, which were analyzed and qualitatively discussed in this work (see topic 2.3.3). Common bibliometric indicators such as main authors, journals, keyword networks, highlighted countries, and institutions were also generated, but it was not in this thesis’s scope.

With this selected protocol (see Chapter 3), a satisfactory number of studies were chosen in a systematic, reliable, grounded, and replicable way, obtaining a notion of: the temporal and geographical evolution of this subject, interest by researchers (through the number of studies and citations), how is the current situation of access type and studies type, the theme's influence in the most reputable databases, the main terms (keywords) in the scientific environment, and the current situation of clusters and future trends.

2.2 Selected Studies Quantitative Analysis

In Table 2, it can be seen that the Scopus, WoS, and Science Direct bases are more similar to each other, with a higher number of duplicate studies. For instance, it was observed that Scopus and WoS had 25 equal studies, while Scopus and Science Direct had four equal studies and WoS and Science Direct had two equal studies.

Table 2 - Correlation table between Databases (Source: Author).

DATABASES	# Studies	Replicate with Scopus	Replicate with WoS	Replicate with SD
Scopus	63	-	25	4
WoS	10	25	-	2
Science Direct	17	4	2	-
EBSCO	10	-	-	-
Wiley	8	2	1	-
ACM	5	1	-	-
Springer	7	5	1	-
RG	11	-	-	-
No Articles	6	-	-	-
TOTAL:	**137**	-	-	-

Thus, Figure 4 shows the relevance and prominence of the Scopus database, which accounts for 46% of the total studies found (137 studies) and 70% of the total citations (2,212 citations), confirming that Scopus is one of the main databases used in the world. However, unlike expected, WoS did not perform as well as Scopus, which was followed by Science Direct and Research Gate in terms of the number of selected studies and citations.

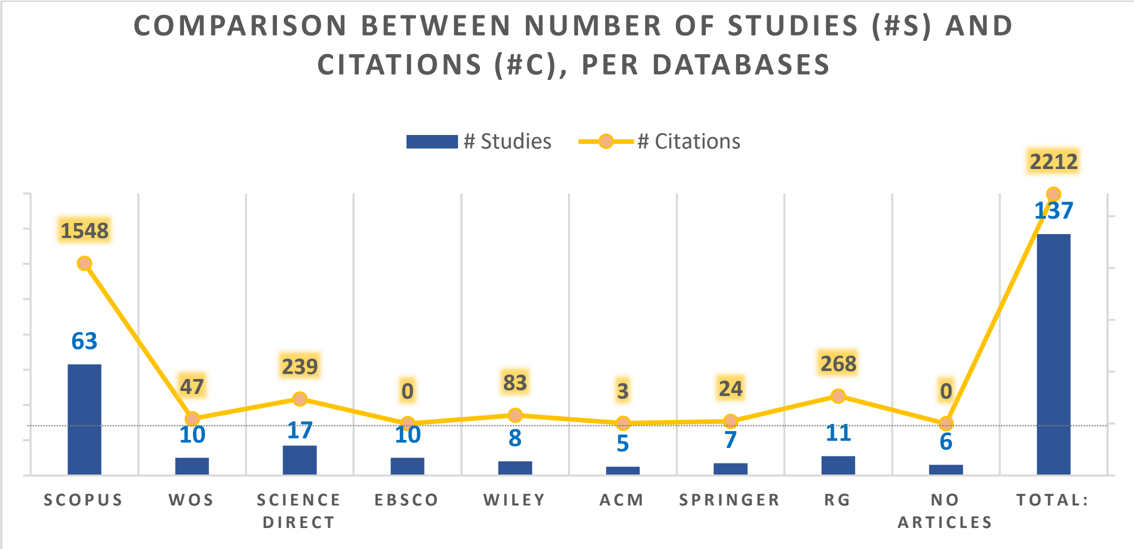


Figure 4: Comparison of studies and citations quantity, for each selected Database (Source: Author).

It can be observed in Figure 5 that, although the first studies on this topic started in 2013, it was only in 2016 that the number of studies began to grow and peaked in 2019, while the number of citations had its maximum value in 2016, probably indicating that there are some relevant studies published in this year. Therefore, until June/2021, 2019 was the most productive year for this research theme (see Figure 5). Future research can prove whether there was a decrease in the number of studies in 2020 and again an increase in 2021, or whether the trend of decreasing the number of studies and citations remained since 2020. However, it was also possible to confirm that the relevance and interest in the theme have been growing in recent years.

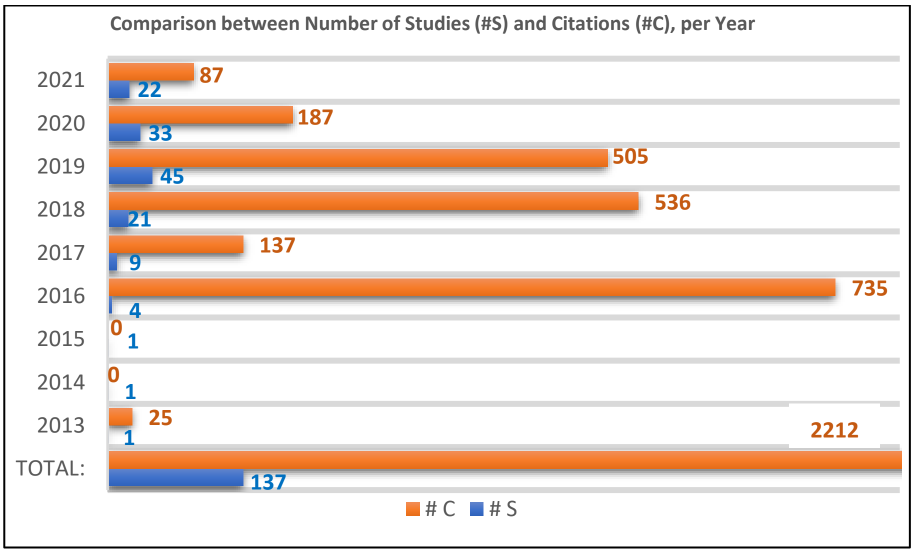


Figure 5: Comparison of studies and citations quantity, for each Year (Source: Author).

In Figure 6, it is possible to observe that Germany has the largest number of studies, with 17% of total studies (137 studies), which helps to explain the vast majority of studies in the English language and the relevance of the contributions from this country to the evolution of this subject. In addition, practically all continents are represented in these 137 studies selected, which confirms that it is a relevant and interesting topic worldwide. So, it can be seen that different opinions from different countries were considered in this study, which added even more value to the results. However, care should be taken with this type of analysis, as the countries that sponsor the major databases, for example, may have more studies published, but not necessarily of higher technical quality.

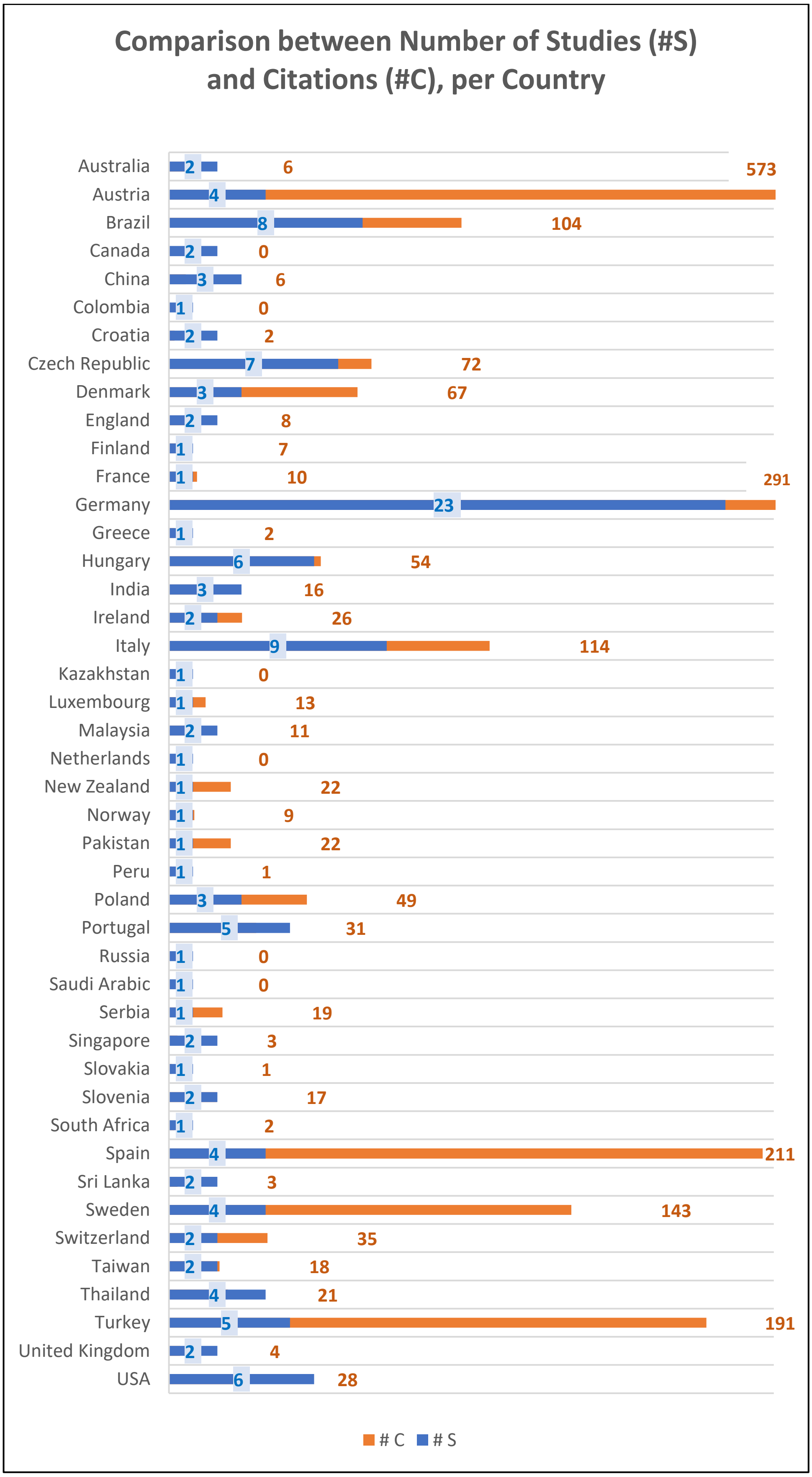


Figure 6: Comparison of studies and citations quantity, for each Country that originated the study (Source: Author).

It can be observed in Figure 7 that, although articles (from Journals) still represent the majority of scientific studies, it is recommended not to discard the chapters (from Books) and papers (from Conferences) in researcher analysis, because nowadays they already have a relevant role in the academic world. Besides, it was noticed that some chapters and papers are more cited than articles.

It is important to notice that normally Journals take longer to publish because the article passes through a larger sieve than that of Conference Papers, and this helps to explain why some authors send more researches to Conferences Papers than to Journals. Also, new and not yet consolidated topics (like MMs for I4.0), are still being discussed more at conferences and, after a certain maturation, will be published in Journals with increasing frequency. For this same reason, one can be seen that there are still few publications (about MM) in books, which publish only the most consolidated and exhaustively tested subjects.

In addition, it can also be seen that the number of studies with open access is greater than closed access, which helps to explain the fact that there is decreasing the culture of valuing more restricted and paid studies. Thus, over the years, it has been perceived that many countries are already more adept at open-access studies. Therefore, studies with open access are often more widely read and consequently more cited, but not necessarily with higher technical quality.

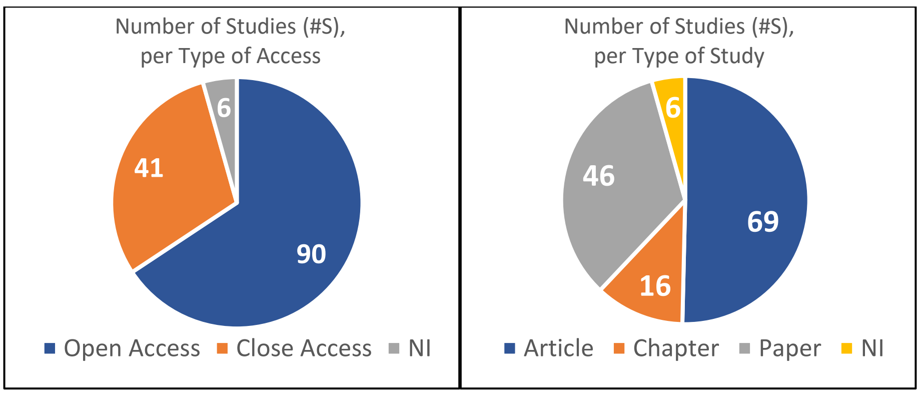


Figure 7: Analysis of the study type (left) and study access (right) (Source: Author).

Note: **NI** - No Information.

However, not only the quantity but also the quality of studies is seen as a differential factor [38]. Then, in the next topics, these 137 studies were reviewed and analyzed qualitatively.

2.3 Selected Studies Qualitative Analysis

Before starting the qualitative analysis, itself, the main theoretical concepts related to the theme of this thesis were detailed. Then, the qualitative analysis was divided into "Introduction to the main concepts", "Future trends and Clusters analysis" and "Analysis of the 63 maturity models found in the Literature".

2.3.1 Introduction to the Main Concepts

At this moment, it is important to detail concepts related to the main objects of this study, based on the studies found in the bibliographic review. Considering its recent existence, the concepts associated with DT are still undergoing transformations and present divergences in the academic, scientific, and corporate worlds. For this reason, it is important to define the main concepts considered by this thesis, differing "4th Industry Revolution", "Digital Transformation", "Industry 4.0", "Digitalization" and "Servitization".

a) "4th Industry" Revolution

According to Bandara et al. [40], it can be observed in Figure 8 that the 1st Industrial Revolution included steam power, waterpower, and mechanization, while in the 2nd Industrial Revolution, it evolves into mass production, assembly line, and electricity. Then, in the 3rd Industrial Revolution, the computerization and automation were introduced, and the 4th Industrial Revolution is the movement towards self-optimizing digitalization.

The 4th Industrial Revolution is called to pull applications and push technologies that enable a high degree of sustainability needed in the future's worlds. It solves today's challenges related to resources and energy efficiency, urban production, and demographic change, enabling continuous resource productivity and efficiency [42].

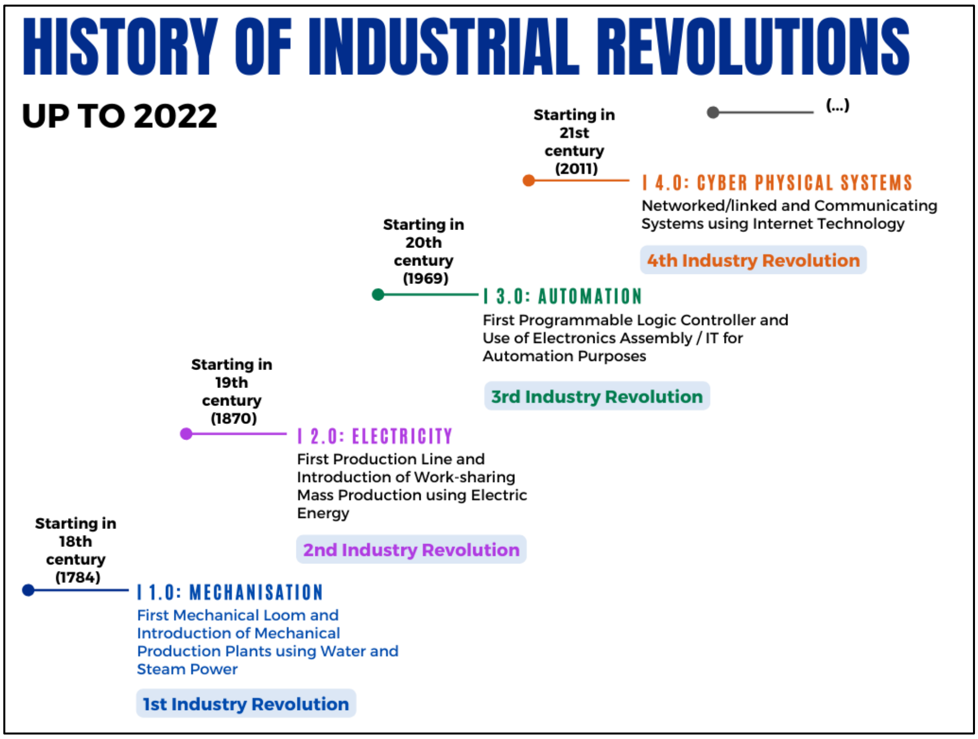


Figure 8: History of Industrial Revolutions (Source: Author, based on Leyh et al. [18] and Gökalp et al. [41]).

New technology paradigms and market pressure have transformed production processes and led to the emergence of new business models [12]. In the 4^{th} Revolution Era, there is a new stage in the organization and management of the entire value chain throughout a product's lifecycle, which is geared towards customers' increasing desire for customization. This encompasses everything from the original concept to order, development, manufacture, delivery to the end customer, and recycling, as well as all the associated services [43].

b) Digital Transformation

Although this thesis disagrees, for many authors "Digital Transformation" and "Industry 4.0" are even the same concept. On the other hand, DT's concept also varies enormously from one company to another. Nonetheless, there are some general definitions, one of which is as follows: DT is the integration of digital technology into all areas of business, mainly changing how it is operated and its value is delivered to its customers. This is more than an I4.0 transformation. It is also a cultural change that requires organizations to continually challenge the status quo, experiment often, and be comfortable with failure. This sometimes means abandoning long-standing business processes that companies were built upon in favor of relatively new practices that are still being defined [2].

For Büyüközkan and Güler [44], the DT is the journey of using digital technologies to develop new business models and strategies. So, DT aims to achieve a competitive advantage and realize activities that will create efficiency in the corporate value chain.

In this context, for Bandara et al. [40] and SIMME 4.0 model [18], the focus is on improving automation, flexibility, and individualization of the products, production, and connected business processes, including the characteristics detailed in Figure 9:

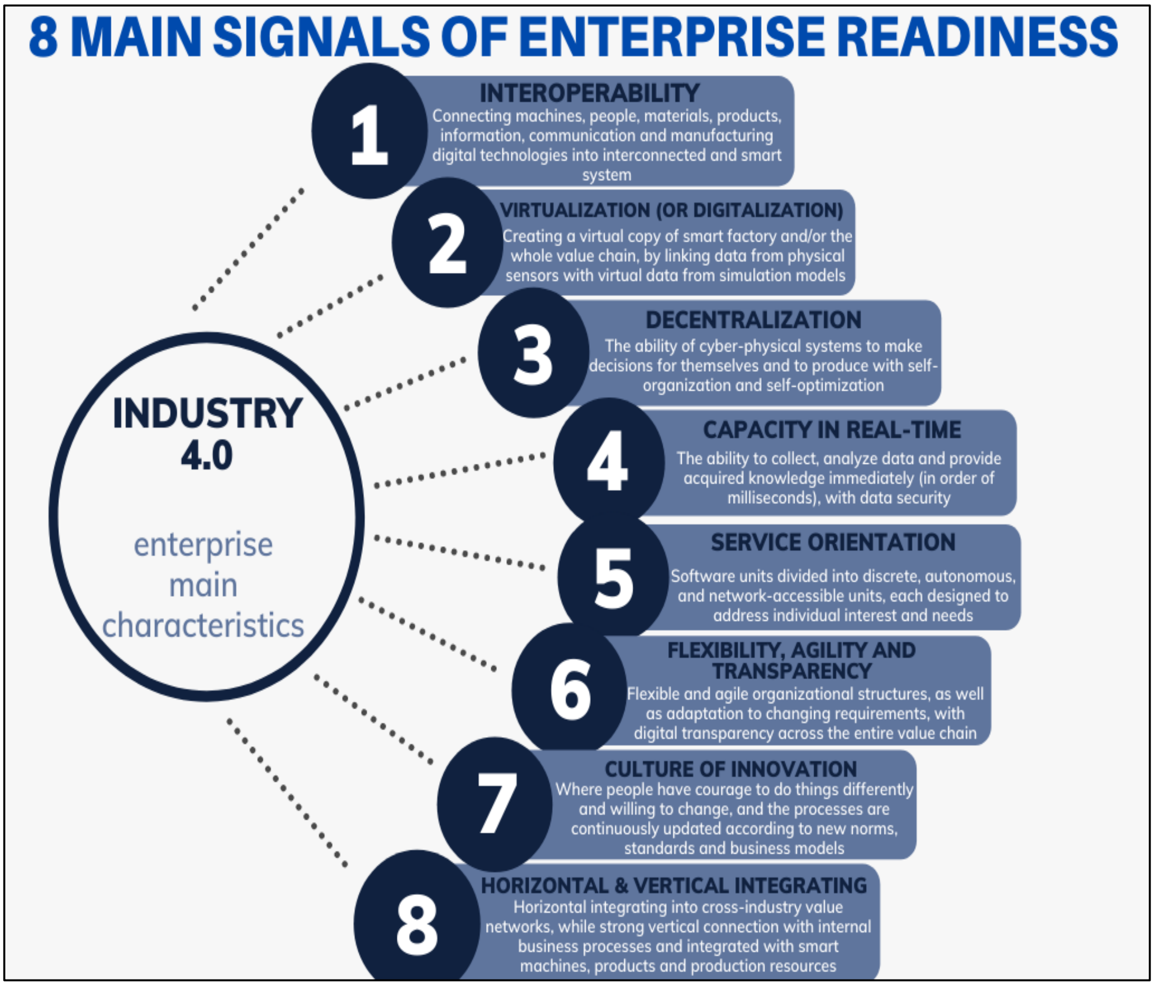


Figure 9: The signals of a company I4.0 readiness (Source: Author, based on Leyh et al. [18] and Bandara et al. [40]).

These challenges need industrial enterprises (engineering companies) that are capable of managing their whole value chain in an agile and responsive manner. Companies need virtual and physical structures that allow for close cooperation and rapid adaption along the whole lifecycle, from innovation to production and distribution.

c) Industry 4.0

The current I4.0 can be understood as a relevant process of merging the physical, digital, and biological worlds through DT technologies and Cyber-Physical Systems – CPS [45]. It represents a new stage in the organization and control of the industrial value chain, since new technology paradigms and market pressure have transformed production processes and respective business models, moving towards a smart world [12].

The topic “I4.0” has gained more importance and has spread with all its diversity in enterprises [18]. However, there is no universal definition for the term “I4.0”. Despite this, from the aforementioned descriptions and further characteristics of I4.0, Leyh et al. [18] considered: “Industry 4.0 describes the transition from centralized production towards one that is very flexible and self-controlled. Within this production, the products and all affected systems, as well as all process steps of the engineering, are digitized and interconnected to share, pass and distribute the information along the vertical and the horizontal value chains, and even beyond that in extensive value networks”.

This current discussion was derived from the German introduction of “Industrie 4.0”, presented at the Hannover Fair in 2011. It denotes the intention of the German Government’s Federal Ministry of Education and Research to increase the alignment of local production systems to the fast-advancing new technologies [11]. So, I4.0 is happening globally and concurrently through different “words” characterized by the same ideas [46], detailed in Table 3.

Table 3 - Industry 4.0 terms per Country (Source: Author, based on Pacchini et al. [46] and Kumar et al. [47]).

Country	*"Industry 4.0 term"*
Germany	Industrie 4.0
France	Nouvelle France Industrielle or Industrie Du Futur
Sweden	Produktion 2030
Italy	Fabbrica Intelligente or Industria 4.0
Belgium/Holland	Made Different
Spain	Industria Conectada 4.0
Austria	Produktion der Zukunft
USA	Industry Connected 4.0, Advanced Manufacturing Partnership or Advanced Manufacturing 2.0
China	Made in China 2025
South Korea	MOTIE Manufacturing Innovation 3.0 or Smart Factory
Dutch	Smart Industry
United Kingdom	Catapult or Smart factory
Japan	Industrial Value Chain (IVI), Connected Manufacturing or E-factory
Chzech Republic	Prumsyl 4.0
Switzerland	Intelligent Manufacturing Systems
Norway	Future of Manufacturing
India	Samarth Udyog or Samarth Udyog Bharat 4.0
Poland	Initiatives for Polish I4.0 or Future Industry Platform (Morawiecki Plan)
Lithuania	Pramone 4.0

Analyzing the countries in Table 3, it was possible to verify the localities that develop the most on scientific topics related to I4.0. As there are several relative terms, during the bibliographic review, it was important to evaluate the best ones to select in the search strings for the databases, in order to cover as many countries and, consequently, studies as possible. The term "industry" is the most frequent. Given the emergence of platform-based ecosystems in the I4.0 field, the experts from Germany and the USA – the two countries that are currently the leading suppliers of I4.0 solutions – have highlighted the risk of developing products that lack market relevance [7]. Many MMs are from different European countries, mostly from Germany [48].

I4.0 has technological enablers (automation and data exchange in the manufacturing technologies) for new production systems, like Big Data Analytics, Cloud Computing, Artificial Intelligence (AI), Industrial Internet of Things (IIoT), and

Cybersecurity [49]. Additionally, based on the Gamache [50] and Tortora et al. [51] investigations, there are some technologies associated with I4.0 (see Figure 10):

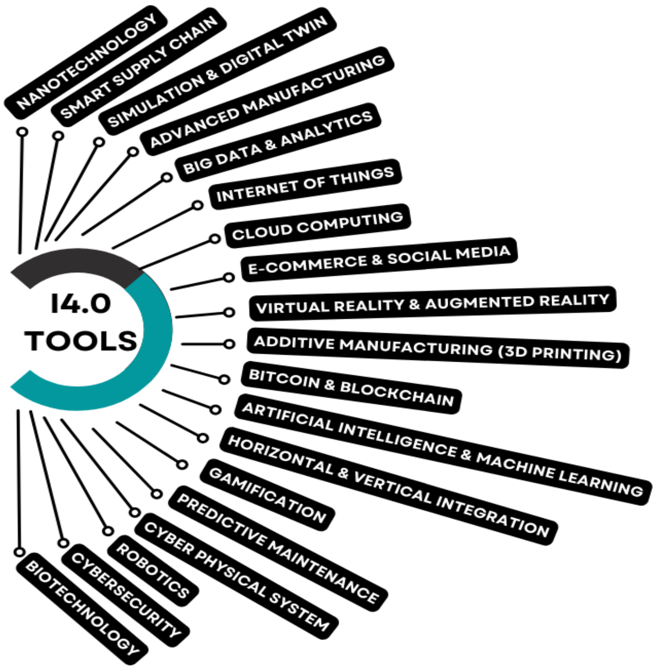


Figure 10: Main Tools associated with I4.0 (Source: Author, based on Gamache [50] and Tortora et al. [51]).

Ratifying these tools in the figure above, more recently Oltra-Mestre et al. [52] also said that I4.0 features a series of enabling technologies categorized into 10 pillars: advanced manufacturing solutions, augmented reality, IoT, Big Data analytics, cloud computing, cybersecurity, additive manufacturing, simulation, horizontal and vertical integration, and other enabling technologies.

Therefore, I4.0 denotes the "traditional" industries' transformation by data-driven. Rigid value chains are being transformed into highly flexible value networks in the value creation process, together with the ability to use this data to determine the optimal value stream at any given time. It requires new forms of cooperation between companies (both nationally and globally), with dynamic, real-time optimized, and self-organizing cross-company value networks. Real-time networking of products, processes, people, objects, systems, and infrastructure is ushering in the I4.0. So, supply, manufacturing, maintenance, delivery, and customer service are all connected and can be optimized based on different criteria such as cost, availability, and resource consumption [43].

d) Digitalization and Servitization

Although DT promises to deliver high-quality jobs, stable economic growth, and new opportunities for demographic sustainable and resource-efficient business, it also poses several major challenges for businesses, with a focus on networking and digitalization [7]. In contrast to this improvement in software development maturity, the digitalization process, that is, the integration of digital technology into any business area [7], is not having the expected success.

At this point, it is important to make a distinction between digitalization and servitization, as these are concepts that are very confusing in the literature.

Servitization can be understood as the increasing value process by adding services to a firm’s offerings. Some authors claim that the servitization process can be viewed as the development of new organizational innovative capabilities in the sense that, rather than merely offering products, the organization can provide customers with complete Product - Service Systems (PSS). In this context, Information and Communication Technologies (ICTs) have had a major impact. ICT has increased efficiency and effectiveness in terms of New Product Development (NPD) and contributed to the emergence of new product-service types. Servitization and digitalization have a mutual influence and a joint effect on the transformation of business models, and consequently, facilitate the Digital Business Models (DBMs) emergence.

Digitalization makes it possible to turn the product into parts of a smart service system, in places where digitalization and servitization intersect, such as the Internet of Things and digital service delivery. This leads to the digital technologies development embedded in the servitized product firms (digital servitization). In this context, DBMs are characterized by digital services, digital information systems (digital ecosystems), and digital platforms. There is a strong correspondence between servitization and digitalization. Future research paths can include empirical analysis aimed at studying the relationship between servitization and digitalization, as well as their effects on DBMs in different industrial sectors [53].

e) Capability, Maturity, and Readiness Models

In 1973, Nolan [54] presented his staged Model with the first notions of a Maturity Model for managing the computer resources in organizations. In 1993, the concept of capability models was first developed by the Software Engineering Institute at Carnegie Mellon University [55], as a tool for objectively assessing the ability of government contractors' processes to perform a contracted software project. This Capability Maturity Model (CMM) [55] describes the principles and practices underlying software process maturity and is intended to help software organizations improve the maturity of their software processes in terms of an evolutionary path from ad hoc and chaotic processes into mature and disciplined software processes. The CMM was conformed by three source models:

- The Capability Maturity Model for Software (SW-CMM);
- The Systems Engineering Capability Model (SE-CM); and
- The Integrated Product Development Capability Maturity Model (IPD-CMM).

Although these models have proved useful to organizations, using multiple models has been problematic [5]. The CMM Integration (CMMI) project was formed to sort out the problem of using multiple CMMs, whose combination into a single improvement framework was intended for use by organizations in their pursuit of enterprise-wide process improvement. In fact, more than eight MMs have CMMI origin (such as Schumacher et al. [6]; Kerrigan [56]; Schuh et al. [7]; De Carolis et al. [15]; Canetta et al. [10]; Sjödin et al. [57]; Pirola et al. [14]; Bandara et al. [40]; and Li et al. [20] – see Appendix B).

Although initially focused on software development, CMMI has been successfully applied to other process areas. It was also designed to support the future integration of other disciplines (like systems engineering, software engineering, software acquisition, workforce management, and development) and to be consistent and compatible with the ISO/IEC 15504 Technical Report for Software Process Assessment [5].

According to Barbalho and Dantas [58], the way a company implements I4.0 could generate a phenomenon called “performance islands”, which occur when a serious effort in improvements approaches a specific area but is limited by the poor performance of the other areas. As a whole, the system does not reach its possible excellence.

This partial and not general improvement effort is dealt with by the Capability Maturity Model Integration - CMMI [5], which suggests that it has two possible directions for process improvements: a sector-specific improvement approach based on capability assessment (Chrissis et al. [5]; Schuh et al. [7]; Barbalho & Rozenfeld [59]) and a real company improvement based on maturity levels (Agca et al. [8]; De Carolis et al. [15]), which is generally more commonly applied. For example, digital competencies should be employed since planning new processes. Despite being well advertised, new technologies have details and possibilities, which only well-qualified professionals can in-depth enjoy. Similarly, lacks of company integration are another dimension of improvement islands: new technologies open new possibilities in terms of integration, connecting people using communication technologies, even informally, and company managers under new legal considerations can also exploit it. The same reasoning can be used concerning the collaboration issues, whether based on the consumer or the value chain's supplier side. Open-minded reasoning must base these new business models' design, even under new legal considerations [58]. For Barbalho and Dantas [58], although WMG Model [8] was chosen as the best to be applied in action research (as a free internet-based solution developed by Warwick University in England), the

Acatech Model [7] (developed by the German Academy of Science and Engineering) was the leader in some criteria in their studies.

In the same way, CMMs generally consist of sets with Goals and Practices. There are two categories of goals and practices: generic and specific. "Specific goals and practices" are specific to a particular process area, whereas "generic goals and practices" are a part of every process area and address the degree to which the process has been institutionalized. A process area is satisfied when organizational processes cover all the generic and specific goals and practices for that domain. The intention is to develop a simplified model which identifies the key characteristics or behaviors that might be expected of an organization at each stage of a digital investigation. Therefore, it is appropriate to consider the various processes typically involved in carrying out digital investigations and the consensus regarding best practices for those processes [56].

Since their emergence in the '70s, MMs have been published with regularity in a wide variety of fields. Given the existence of an increasing number of MMs, users must find ways to identify the strongest or most reliable models for their purposes [3].

Around 2010, MM's design became more structured with a MM project procedure model that describes possible organizational improvements by naming activities for all maturity levels. A set of maturity levels is applied to a relevant set of application area constructs, often represented in a tabular format, for maturity measurement [61].

According to Felch and Asdecker [29], MMs are an established means to support requirements such as assessing the current situation, determining the desired situation, and obtaining possible evolution paths to a specific process or company. MM is positioned as a tool to compare the current level of an organization or process to the desired level in terms of maturity [6], being used regularly for benchmarking and continuous improvement. Thus, the concept of maturity can be used for descriptive, prescriptive, and/or comparative purposes [22].

Due to its quality, applicability, and holistic comprehension, and considering that it is based on more than 150 interviews and discussions with experts from Germany, China, Japan, South Korea, the UK, and the USA, our studies were mainly based on Acatech Methodology [7] for introducing I4.0 (see Figure 11). In this case, the input includes "organizational" and "technological" enablers (in CUBE-4.0 there is a third input enabler considering the "processes maturity", explained later), while the methodological analysis focuses on the missing capabilities and the final output is a digital guiding roadmap.

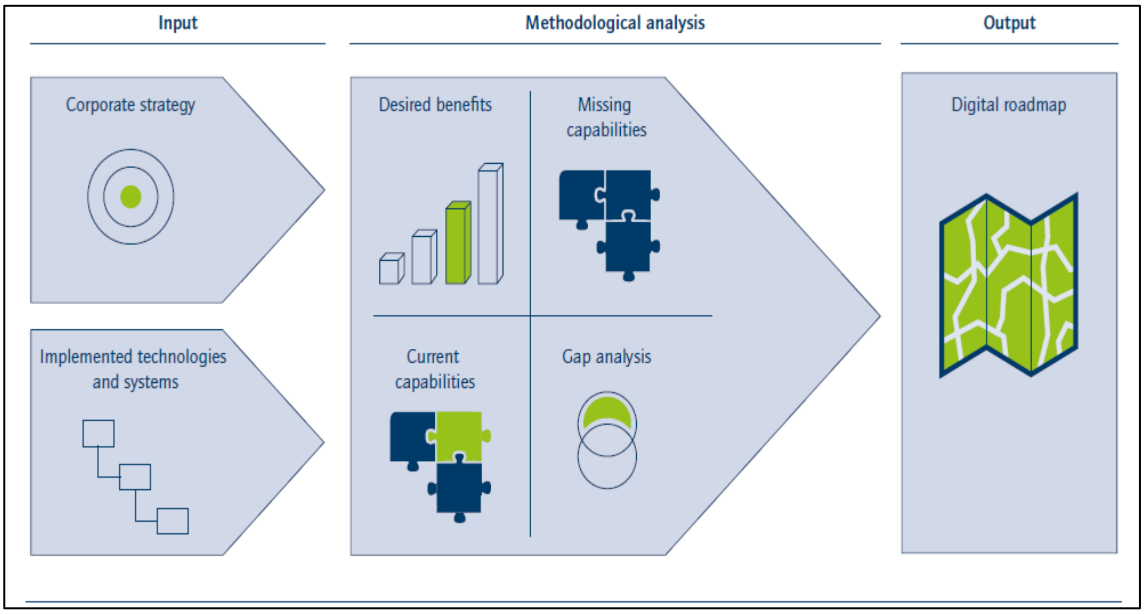


Figure 11: Acatech methodology for introducing I4.0 (Source: Schuh et al. [7]).

Therefore, a Maturity Model Roadmap represents a bottom-up approach, in which the specialists from the corresponding fields analyze the actual state as well as independently define the present maturity as a part of the company's strategy. The roadmap methodology is at the same time basis for self-assessment and a guide for implementing the I4.0 strategy. For instance, the Institute of Industrial Management at FH Joanneum University of Applied Sciences developed together with an internationally renowned industrial company, a Roadmap for the I4.0 implementation in an applied research project [62].

So, MMs are commonly used to conceptualize and measure the maturity of an organization or a process regarding some specific target state [6]. For Büyüközkan and Güler [44], in the DT context, some authors call MMs like "Digital Maturity Model (DMM)".

Thus, there is a need for an analytical tool to evaluate the significance of the factors in the DMM and to rank the companies according to their digital maturity. It is a multi-criteria decision-making problem with multiple factors under vagueness and impreciseness [44]. That is why there are some MM common properties: (i) maturity levels; (ii) "descriptor" with the name of each level (iii) generic description of each level; (iv) dimensions; (v) activities for each dimension; and (vi) description of each activity, for each maturity level [63].

A company has to fulfill certain activities to be considered more or less mature. According to Pirola et al. [14], maturity has to be improved in stages, that is "if a company wants to improve as a whole – maturity X-1 to maturity X – it must do …". This approach is thought to avoid "performance islands" [13] but will be time-consuming and will generate resistance and unknown consequences. Managers from more mature areas are interested in maintaining the improvements engine of their areas, while the less mature areas can feel depreciated, and people from areas assigned as "less mature" can also resist absenteeism or resign from their jobs [14]. This improvement path is described by a model component called a maturity level [5]. In general, it is easier to improve an area with an already existing momentum. Creating momentum in other organizational silos is time-consuming because personal resistance is commonly in place. Furthermore, researchers have found it difficult to analyze maturity levels for SMEs, because some basic technological enablers are missing (without them it is very difficult to understand and apply the SME maturity model), such as data and processes integration, mainly between the production floor and other company areas [14].

Our CUBE-4.0 also uses an Acatech and CMMI development path philosophy (see Figure 12), considering six levels, but differing from them by considering the scale from “not started” to “self-optimized” (more details in the topic 5.5.1), while Acatech goes from “computerization” to “adaptability” and CMMI goes from “incomplete” to “optimized”.

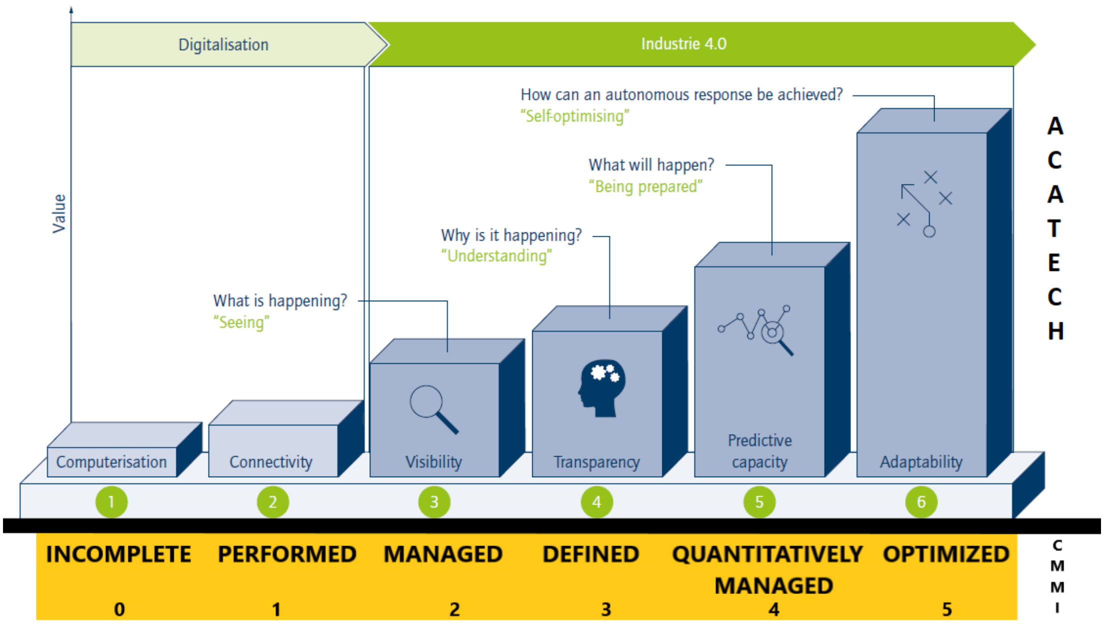


Figure 12: Comparison between Maturity Levels (Acatech) and Capability (CMMI), (Source: Author, based on Chrissis et al. [5] and Schuh et al. [7]).

The maturity model is an outstanding example of cooperation between academia and industry because it is recommendable for an interdisciplinary consortium of research institutions in different fields with partners from industry across every part of the industrial value chain to develop a methodology for establishing manufacturing companies’ current I4.0 maturity stage and identifying areas where further action is required. So, these systematic weaknesses and opportunity identification provide the basis for formulating an implementation strategy, offering manufacturing companies practical guidance for developing an individual I4.0 implementation strategy that is aligned with their business strategy [7].

Despite some important criticisms, MMs have been a favored tool for organizations and are an evergreen research topic in digital government and information systems [3].

Once the main bibliographic references discuss “maturity” and “capability”, it is important to distinguish between “maturity” and “readiness” concepts because they are confused in the scientific literature. For Basl [48], the readiness models are mostly MMs in many cases. Although they are labelled synonymously, there are some differences between them, detailed below:

- Schumacher et al. [6] express the difference between these two concepts, putting the readiness before starting the maturation process, that is, readiness assessment takes place before engaging in the maturing process, whereas maturity assessment aims for capturing the as-it-is state whilst the maturing process. For them, while readiness shows if the organization is ready to start a development process, maturity demonstrates the organization’s level about the analyzed process. So, readiness is the “state of being ready to do something”, while maturity is “a maturing state” (maturation). Or, indeed, readiness is “willingness or a state of being prepared for something” and maturity is “a very advanced or developed form or state”;
- For Pacchini et al. [46], readiness is the state in which an entity is to accomplish something, and maturity is the level of evolution that an entity is concerned with something;
- Carolis et al. [15], say that the terms “readiness” and “maturity” are relative and related, but not the same; and
- For Mittal et al. [23] and Akdil et al. [64], MMs aim to demonstrate the maturity level of an individual or entity, and help them to reach a more sophisticated maturity level after a step-by-step process of continuous improvement. On the other hand, readiness assessments are evaluation tools to analyze and determine the level of preparedness, attitudes, and resources, at all levels of a system,

where readiness models clarify whether the organization is ready to start the development process or not.

2.3.2 Future Trends and Clusters Analysis

According to the methodology described in Chapter 3, for choosing the threshold, there were 2,680 terms, with 51 terms fulfilling the threshold and 10 minimum occurrences. The irrelevant and duplicate keywords were deleted, such as “paper”, “set”, “context”, “regard”, “opportunity”, “order”, “term”, “need”, “process”, “country”, “data”, “research”, “approach”, “analysis” and “study”, resulting in 36 terms with 996 total occurrences and 4 clusters (see Figure 13).

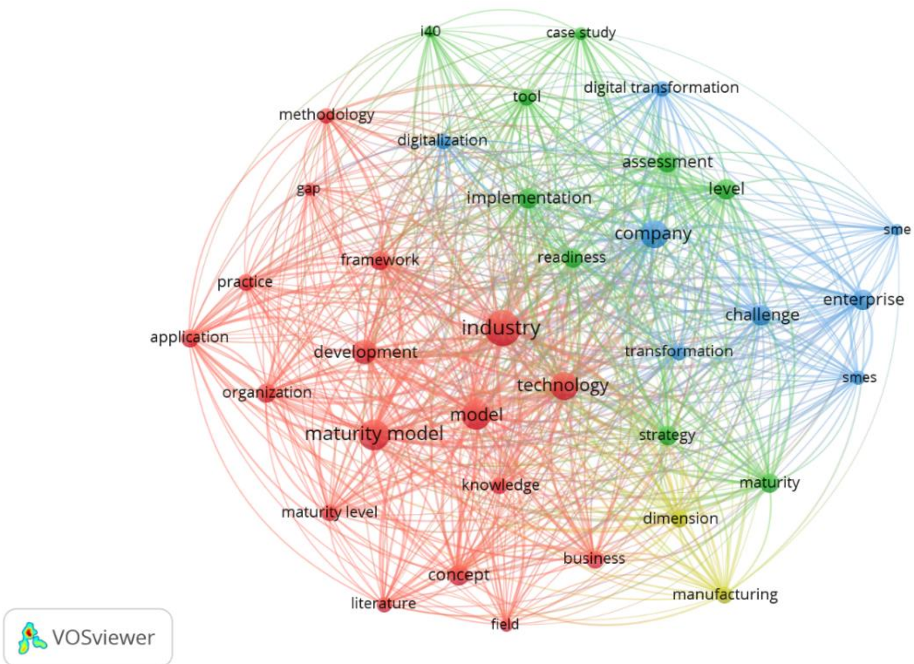


Figure 13: Keywords Clusters per Relevance (Source: Vos Viewer).

The “Maturity” term still appears more than “Readiness”, as well as “company” is more used than “enterprise”, as detected by the Bibliographic Synonyms Test (see Appendix A). “Industry” is the center of the research on this theme, followed by “Technology”. So, for the “red” cluster, “Industry” is the more relevant term, while in the blue cluster is “company”. In the yellow and green clusters, no relevant unit term was found highlighted.

As previously detected, the main contributions of this theme occurred in 2019, with the term "Readiness" being newer than "Maturity", and "I4.0" and "Digital Transformation" appearing only in late 2019 (see Figure 14).

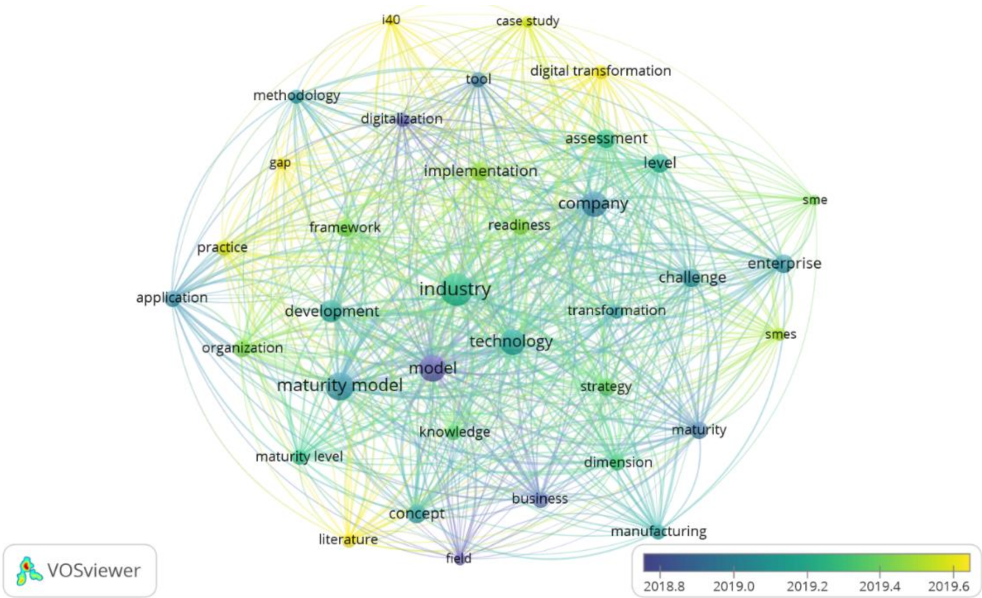


Figure 14: Keywords Clusters per Year (Source: Vos Viewer).

It was considered 25 as the maximum number of authors per document and two as the minimum number of papers by one author. Then 376 different authors were found, with 25 meeting the threshold. Besides, there were found 10 clusters, and the authors with the higher number of studies (total of 4) were Leyh et al. [18] (with SIMMI 4.0 Maturity Model).

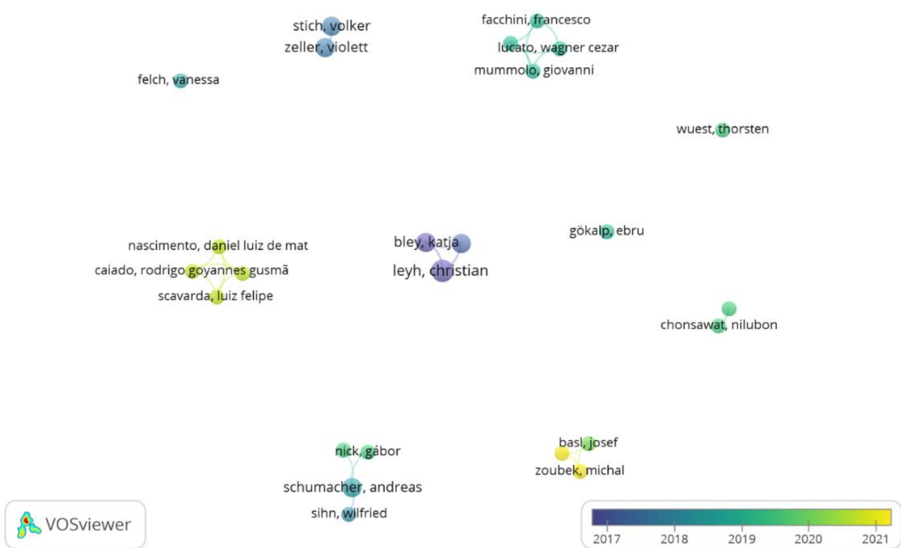


Figure 15: Authors Clusters (Source: Vos Viewer).

Although no direct relationship has been found between the 10 clusters, this graph (Figure 15) is important to verify that several research groups are studying this theme, with the most recent cluster (2021) represented by Zoubek and Simon [27], and Basl [48].

2.3.3 Analysis of the 63 Models found in Literature

After the quanti-qualitative analysis (see items 2.2, 2.3.1, and 2.3.2), 63 models were found, including maturity and readiness models, published between 1973 and 2021, last checked in June/2021, which the main authors coincide with the previous Vos Viewer analysis. Thus, Figure 16 presents an overview of these analyzed models.

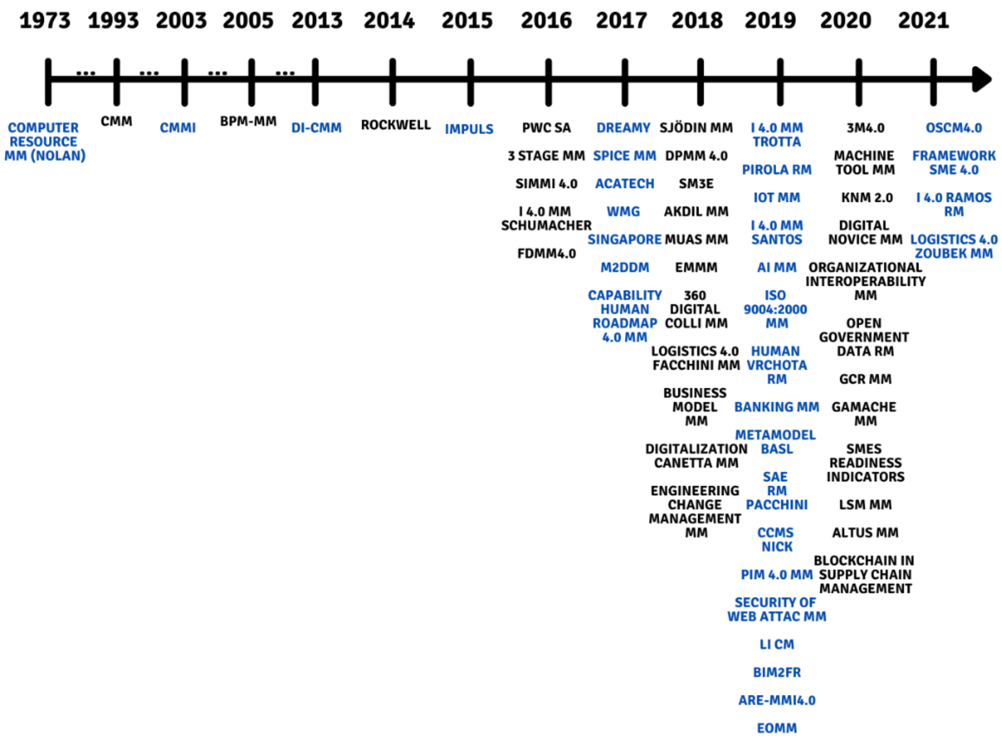


Figure 16: Timeframe of the 63 Maturity and Readiness Models analyzed (Source: Author).

As shown in Figure 16, from 2016 to 2020, 52 up to 63 MMs have been proposed. Only the year 2019 concentrates 17 models. There were mainly consultancy models at the beginning of this period, and in the last years, mostly scientific publications. Confirming the Vos Viewer analysis, “Maturity” still appears more than “Readiness”.

The qualitative analysis of these 63 models was also based on systematic bibliographic reviews by some of their authors, such as Zoubek and Simon [27], Silva et al.

[65], Basl [48], Pirola et al. [14], and Caiado et al. [63]. Then, the analyzed models were described and compared in Appendix B, whose main conclusions were summarized below.

It can be seen that the most cited models are the oldest and that Germany is the country that published the most on this subject and has the largest number of models created so far. Moreover, in recent years there has been an increase in the number of European countries producing scientific content on this subject.

Although 63 models can be considered a large number, some MMs just repeat the same concepts from existing maturity and readiness models, being just an extension and presenting the same limitations. For example, Santos and Martinho [66] was adapted from three existing maturity models [7], [86], and [6]; while Elnagar et al. [67] was adapted from [68] and Wagire et al. [69] was based on [46].

Besides, some models like Rübel et al. [70], Odważny et al. [71], Joblot et al. [72], Trotta and Garengo [73], Unny and Lal [74], Tobola et al. [75], Gaur and Ramakrishnan [76], and Puchan et al. [77], are preliminary works lacking important elements to allow an effective company analysis. Ifenthaler and Egloffstein [78], Nick et al. [79], Azevedo and Santiago [80], Basl [48], Osorio-Sanabria et al. [81], Merkus et al. [61], and Amaral and Peças [19], do not have information about output levels. Rojas et al. [28] is just applicable for web security and does not have input dimensions. Pacchini et al. [46] and Zoubek and Simon [27] present a tailored model for logistics processes. Mittal et al. [23] present only one (digital) capability: "data-driven decision-making". In Jin et al. [82], there are no standardized EM (Energy Management) tools, although the first-stage standardization is moving forward. In agreement with the work presented by De Bruin and Rosemann [68], the BiM2FR Model will be tested at a larger scale, as a way to adjust the first version. Elnagar et al. [67] presented the first version of the ARE-MMI4.0 Model, which is currently in an initial phase (called "populate"). As in Leyh et al. [22], 3M4.0 Model development is not yet complete. Further efforts on

Wagire et al. [69] can be directed at measuring the organization's readiness for DT. There is still a gap between a theoretical conception and a realistic view in Ramos Model [30].

Some models, like Nolan [54] and Chrissis et al. [5], were important for later models but they have old templates and are not feasible for a web-based application. Sanchez-Segura et al. [2] discuss the tools that support the ALTUS Model (excel sheet and interview templates), pretending to improve them as a web application in future work.

Traditional models, like CMM and its variations, were built only for well-established processes, such as software or product development. However, the outcomes of the new industrial revolution are still uncertain, especially when the processes involved are not known. So, the CMM is not a silver bullet and does not address all the important issues for successful projects [55]. For example, it does not currently address expertise in particular application domains, advocate specific software technologies, or suggest how to select, hire, motivate, and retain competent people, although these issues are crucial to a project's success.

Besides, models like CMM and Acatech tend to generate "performance islands", according to Barbalho and Dantas [58] and Vernadat [13]. In other models, like CMMI, there are two types of output levels: one for "continuous representation", and the other for "staged representation" capability levels, difficulting their uses in the company.

Some models, such as Schumacher et al. [6], Trotta and Garengo [73], Nick et al. [79], Azevedo and Santiago [80], Akdil et al. [64], Rojas et al. [28], Basl [48], Ifenthaler and Egloffstein [78], Osorio-Sanabria et al. [81], Merkus et al. [61], Amaral and Peças [19], Ramos et al. [30], Chrissis et al. [5], Geissbauer et al. [83], Schuh et al. [7], Rockwell [84], Agca et al. [8], Gökalp et al. [41], Canetta et al. [10], Colli et al. [85], Pessl et al. [62], Bandara et al. [40], Sjödin et al. [57], and Zoubek and Simon [27] – see Appendix B, present difficulties for being used by the companies, because of missing scientific documentation and transparent methodology for practical application, with much complexity and no explicit assessment approach. For example, Rafael et al. [86] present a model that approaches a more scientific and rigorous method for weighing the dimensions. In general, these models do not present essential information about their framework (dimensions, sub-dimensions, elements, levels, graphic type, calculation, and/or data collection method), so most of them only provide a general description for each stage and have difficulty having their clauses mapped synergistically [3]. Acatech Model presented by Schuh et al. [7], despite its well-integrated concepts and the detailed information regarding its model structure, lacks clarity in the evaluation, with few and incomplete examples provided. So, if a variable is too generic, an accurate assessment is difficult, and if a level is poorly described, a clear distinction between the dimension levels is missing. In some cases, like Singapore Model [87], because of its large elements set compared to the other models, these presented difficulties to be implemented, especially in small enterprises. In Maier et al. [88], a more intensive investigation of the "Business & Service Strategy" category is needed.

It is important to highlight that many of these models even have difficulty distinguishing concepts related to maturity, readiness, and I4.0. In Hsieh et al. [89], further research may focus on analyzing data collected from their model to reveal the difference in maturity status across the production/service in large/small-medium companies. In addition, the relationship among KM (Knowledge Management) culture, process, technology, and performance is worthy of being observed, as also the interplay between knowledge and intelligent application. Considering it was proposed in 2016 when the effort to propose maturity models was starting, some maturity levels and dimensions of Geissbauer et al. [83] lack synergy. Sometimes the maturity model, like Chrissis et al. [5], is so complex that it needs professional judgment to interpret the results after application in enterprises.

Some models such as Gökalp et al. [41], Pessl et al. [62], Akdil et al. [64], Margariti et al. [25], Osorio-Sanabria et al. [81], Merkus et al. [61], Rafael et al. [86], and

Agca et al. [8] have only theoretical development (only based on Literature Review), not been intensively validated in real-life application, or even tested, generating a gap between a theoretical conception and a practical view. And other models like Kerrigan [56] and Chonsawat and Sopadang [90] (which has tested only a simple example), need to be tested against more organizations to assess their usefulness fully as a benchmarking tool.

Another important problem is that models, like Rockwell [84] and Leyh et al. [18], focus only on the facets of the existing IT network and inadequately address the organizational and operations-related dimensions. And still, models like IMPULS [26], which focus on technological enablers, do not consider a few key technologies such as AI (Artificial Intelligence), AR (Augmented Reality), VR (Virtual Reality), smart glasses, and Blockchain Technology. Besides, they have a vague description of how the technologies can be used for integration and the inter-relations among them. In addition, most models like Pacchini et al. [46] rely on only a few enabling technologies, have few prerequisites, and have wrongly the same impact for each technology as far as I4.0 implementation. This demonstrates a measurement lack about the real impact of the technological tools on the companies' digital performance. In many cases, digital competencies and technologies outside the IT field are not discussed. Indeed, models like Schuh et al. [7], lack technology considerations for the proposed process analysis, being difficult to comprehend the differences between the maturity analysis for I4.0 and a generic improvement analysis for increasing something in the company's performance. On the other hand, De Carolis et al. [15] did not explore the technological enablers of its interconnectivity dimension. Besides, Ifenthaler and Egloffstein [78] present practical concerns about organizational culture, where "digital leadership" (i.e., leadership that is in line with the affordances of DT) is likely to play a crucial role.

Considering the model application, models such as Felch and Asdecker [29], Leyh et al. [18], and Schumacher et al. [6], cannot be applied to every type, size, and economic sector of the enterprise, depending on the company's country (regional bias), the specific size (for SME or large companies) and/or specific product provided (like regulatory bodies, criminal investigations, logistics, web security, IT, manufacturing, automotive, energy, business model, banking and others), limiting the validity of their findings. Another example is the DI-CMM Model [56], which has been developed with the needs of regulatory bodies and criminal investigations in mind, not applicable to various other sectors. In the same way, in the Acatech Model [7] is also missing the perspectives concerning SMEs, and Singapore [87] is a well-done research that intended to analyze only manufacturing sites. Pacchini et al. [46] is tested and validated only in a Brazilian auto-parts manufacturing organization. In Tavčar et al. [91], the ECM (Engineering Change Management) maturity assessment tool was tested and validated at eight automotive suppliers of different sizes; however, there is a strong emphasis only on a reliable supply of automotive enterprises. In Jin et al. [82], the main limitation of their model is that it presents difficult to apply to the SMEs in China, whose EM practices were seldom summarized or even raised. Indeed, a pilot test of Santos and Martinho [66] was performed in two Brazilian companies, both from the automotive industry. On the other hand, Colli et al. [85] has been tested only in large companies, not in SMEs. Caiado et al. [63] have a well-done and complete maturity model with a fuzzy rule-based I4.0. However, it focuses only on operations and supply-chain management. For future work, this research suggests conducting a longitudinal survey and evaluating maturity at different times by applying a roadmap with periodic goals. Other supply-chain MMs, as Schumacher et al. [6], lack a process view connecting the whole value chain.

Some models do not have a methodology to apply their surveys, like Geissbauer et al. [83] and Agca et al. [8], which is a consulting-based model, not an applied scientific effort. Others, such as Ganzarain and Errasti [42], Gökalp et al. [41], Rübel et al. [70], and Weber et al. [92], do not even have any questionnaire to make the surveys. And others, like

Akdil et al. [64], do not present a traditional questionnaire, just some complex architecture with an index to translate answers to a specific maturity level. Felch and Asdecker [29] demonstrated a MM validated through expert opinions and judgments, but also do not have a validated questionnaire, just a verified architecture.

In some models, such as Lichtblau et al. [26], Rockwell [84], De Carolis et al. [15], Akdil et al. [64], and Canetta et al. [10], filling out the survey questionnaire is difficult because it is not transparent and does not follow the output levels number, neither dimension logical, presenting a juxtaposition of dimensions. For example, among smart factories and smart operations, respondents could have questions regarding the clarity of each dimension and their queries to answer. Besides, some models' questionnaires emphasize the process view without tracking the common company functions; however, most companies are structured in these functional units. Therefore, it can be difficult to identify the right person in a company to answer the queries.

About the target audience of respondents, models like Singapore [87] do not consider employees from different departments to fill out the questionnaire and/or only examine manufacturing sites (not including executives and senior managers). Others, such as Santos and Martinho [66], use a small number of industry professionals to participate in the validation phase. Similarly, some models, like Vrchota et al. [93], use delayed data from enterprises, so they are no longer up-to-date. On the other hand, Pessl et al. [62] present a well-described model, where people from different divisions should ideally be included in the maturity assessment process; however, it is too complex for practical use.

About the final results report, many models, like Schumacher et al. [6], Leyh et al. [18], Schuh et al. [7], Gökalp et al. [41], De Carolis et al. [15], Agca et al. [8], Pessl et al. [62], Sjödin et al. [57] and Gajsek et al. [60], have just general diagnostics and recommendations, but not detailed planning or development steps analytics at the process level, without a clear definition of the action plan to implement I4.0 improvements. With general recommendations without action steps to drive the transition from the current to desired maturity level, as Pirola et al. [14], any existing model has a complete readiness roadmap with guidance strategies, using engineering concepts. Schumacher et al. [6] also did not identify improvement opportunities or a roadmap for further developments and Schuh et al. [7] suggested improvements are area-specific. Consequently, this model suggests only capability improvements, not activities for enabling maturity stage transition, which can strengthen differences in silo-areas.

About the monitoring process, no model presented indicators to manage the performance of the implemented model and to follow the continuous improvements deployed in the company, missing multi-criteria decision-making for I4.0-related problems. Besides, any model has an expert strategy system for addressing maturity gaps (between current and expected states), combined with the organization's Business Intelligence (BI), and displaying the results in a dashboard for real-time management of the organization. Gamache et al. [50] present a solid study, but it needs a more comprehensive SMEs' tools assessment to target those that offer the most benefits. A longitudinal study with the sample would also be interesting to validate the approach impact, the number of projects and the projects progress that have been implemented, and the gains made by the digital tools deployed.

Also, based on Renteria et al. [3], most existing MMs are uni-dimensional, which means that the stages of conceptualization and description treat the organization as a single unit, rather than decomposing it into organizational dimensions.

Finally, based on the presented models' shortcomings, is evident the need for a model which addresses the limitations found, geared to the readiness of a company in the DT context.

3. Methodology

In this chapter, is addressed the scientific methodology for this research. In Topic 3.1 is treated the research classification, while in Topic 3.2 is presented the activities carried out throughout the work.

3.1 Methodology Classification

Based on Silva and Menezes [94], the scientific methodology classification chosen for this thesis can be visualized in Figure 17 below, highlighted in yellow:

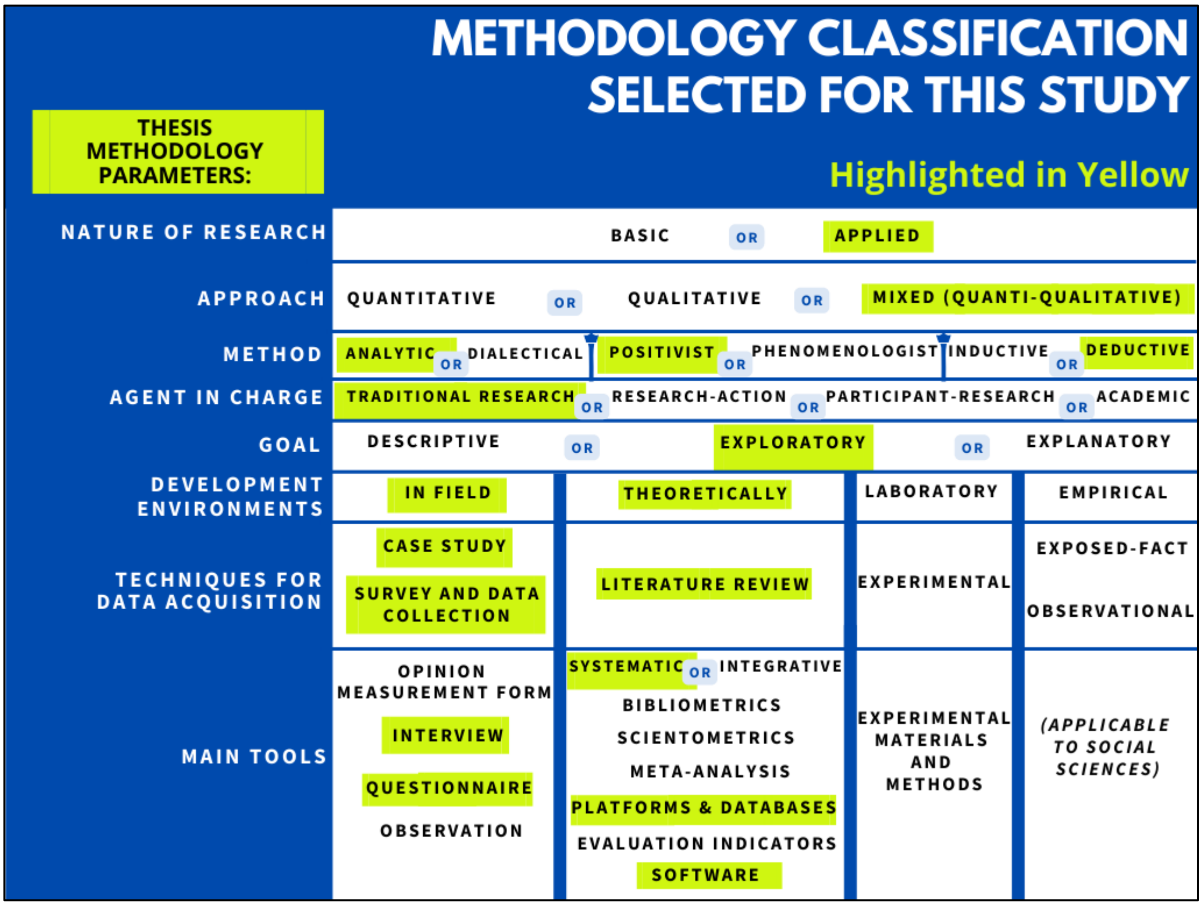


Figure 17: Methodology classification (Source: Author, based on Silva and Menezes [94]).

Based on Silva and Menezes' concepts [94], the main reasons for choosing this scientific methodology were as follows: it is **Applied** - this investigation aimed to generate knowledge for practical application to solve a specific problem; **Mixed (quanti-qualitative)** - a large part of the research can be quantifiable, that is, some of its theories, opinions, and information were translated into numbers, to classify and analyze them, besides including statistical resources and techniques. In addition, this study includes steps that cannot be quantified, as they represent an inseparable link between the objective world and the subjectivity of the subject. So, there was the first phase of quantitative data collection and analysis, followed by qualitative analysis. Therefore, it is a sequential mixed (quanti-qualitative) exploratory approach; **Analytic** - the research exposed constitutive aspects, with the separate study of the parts; **Positivist** - it included measurable mathematical expressions, to analyze data obtained with questionnaires; **Deductive** - the investigation was based on applicable generalizations, to generate particular empiric experience; **Traditional Research** - scientific research is "[...] the formal and systematic process of developing the scientific method. The fundamental objective of the research is to discover answers to problems using scientific procedures" [94]. The population is merely research "passive object". It is not researched to serve only an academic discipline. It is nonideological and does not engage with the population, the people, and the facts being researched. The research results were based on the empirical data obtained therein; **Exploratory** - this study aimed to provide greater familiarity with the problem, to make it explicit, and generate some hypotheses for the solution, through a bibliographic review, survey (interviews), and analysis of examples (case studies) that stimulate understanding. Although the problem has been widely studied in recent years, the scientific literature does not have a final prescription for the question of "what a company must do to transition from its current situation to I4.0"; **In the field** - observed facts and phenomena in the way they occur in the reality from a faithful cut of the studied public. To do this, data was collected about the examined elements. Later, this information was analyzed and interpreted on a solid theoretical basis; **Theoretically -** it considered the theories raised about maturity and readiness models, through a systematic bibliographic review method. Researchers using this method have no obligation to refute a theory, but to contribute to knowledge; **Survey and Data Collection** - the research involved the direct questioning of people whose behavior one wishes to know, questioning the object effect in this population, and collecting phenomena that occurred in the researched place; **Literature Review** - the study was elaborated from books, journals, and conference papers; and **Case Study** – it was selected based on Eisenhardt [95], who states that case studies usually combine data collection methods such as files, interviews, questionnaires, and observations. The evidence can be qualitative (e.g., words), quantitative (e.g., numbers), or both. Case studies can be used to accomplish several goals: to provide a description, test theory, or generate theory. The interest of this thesis, lies in the latter goal, theory generation from case study evidence, having important strengths such as novelty, testability, and empirical validity, which arise from the close connection with empirical evidence.

About the research tools, was used **Interview (face-to-face and/or online)** because it includes direct questions for people who have had practical experiences or who need the problem researched solution); and **Questionnaire**, because it includes open, closed, and multiple-choice questions. Regarding the **systematic bibliographic review, software (metadata programs), platforms,** and **databases** details, they will be discussed later.

3.2 Methodology Steps

For a better understanding of the methodology, based on Barbalho [97], each step is explained in this Chapter, as detailed in the following Figure 18.

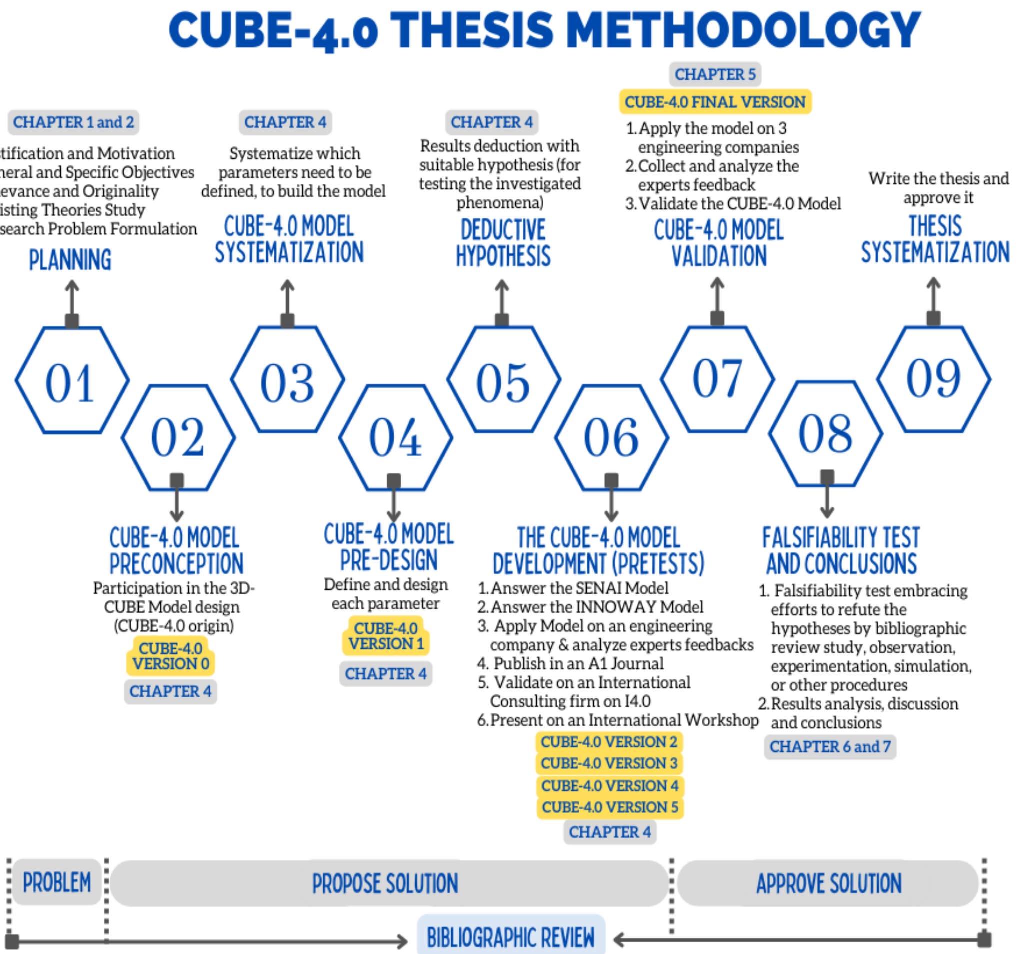
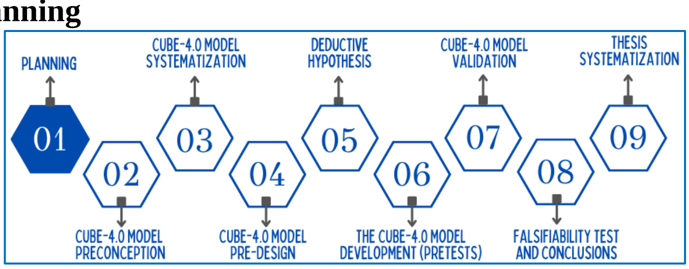


Figure 18: Methodology selected (Source: Author, based on Barbalho [97]).

This research used a hypothetical-deductive approach [97], that includes:

3.2.1 Planning



It was the initial planning stage, before starting the thesis, which included the following steps:

(a) Justification and Motivation

(b) General and Specifics Objectives

(c) Relevance and Originality

(d) Existing Theories Study

(e) Main Research Problem Formulation

About the research **(a) Justification and Motivation**, **(b) General and Specifics Objectives**, and **(c) Relevance and Originality**, they have been discussed in Chapter 1.

In **(d) Existing Theories Study**, the methodology used to investigate the previous theories follows the protocols for bibliographic analysis [96].

The scientific data compilation on a theme has been practiced for a long time, highlighting that one of the first recorded reviews dates to 1753, and was done by Sir James Lind on the prevention and treatment of scurvy, in the health area [98]. In addition, according to studies developed by Sidone et al. [99] and Maricato and Martins [100], the health area in Brazil is the one that generates more scientific research, than other areas of coverage.

According to information available on the CAPES website, the independent international database that gathers and summarizes the best and most reliable information in the health field, including the highest quality scientific evidence available worldwide, is known as the Cochrane Library (from Wiley publishing house).

Since the literature review improvement had a great contribution coming from the health area and one of its main scientific research networks is Cochrane, the steps used for this systematic bibliographic review elaboration were designed based on Cochrane's guidance, as detailed in Figure 19.

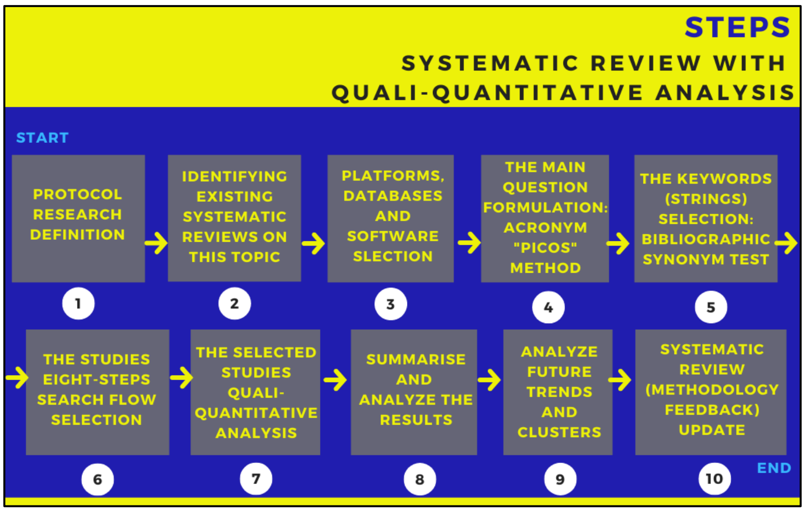


Figure 19: Bibliographic review performed. (Source: Author, based on Cochrane methodology).

The Cochrane and Kitchenham Bibliographic Review Methods [31] are very similar, and the second one only adapted the first one to be used in Software Engineering, considering its benefits and results. Therefore, using the same logic and benefits, this thesis applied, in an unprecedented way, the famous Cochrane method for Mechatronic Engineering.

Each step of Figure 19 is described as follows:

3.2.1.1 Protocol Research Definition

To define the literature review protocol for this research, the advantages and disadvantages of conducting a systematic or integrative literature review were studied, according to Kitchenham concepts [31] [32] [33], generating the results in Chapter 2.

3.2.1.2 Identifying Systematic Reviews on the theme

By using the previous keywords (see abstract), searches were carried out in the main existing databases in order to find studies that could already contemplate possible bibliographic reviews on the subject. Thus, the existing bibliographic reviews were identified and analyzed, generating the results detailed in Chapter 2.

3.2.1.3 Platform, databases, and software Selection

As the theme of this study is considered relevant, however recent, it was necessary to carry out extensive systematic research about the platform and databases to be used.

There are numerous national and international databases available, with open or restricted access, in all areas of knowledge. The two best-known databases in Brazil for international scientific research are Scopus and Web of Science (WoS). However, according to Maricato and Martins [100], currently, these two bases, although paid (restricted), are the most used because their platform and software have higher technical quality (for example they allow the export of metadata for analysis of publications, citations, and bibliometrics, can calculate bibliometric indicators, plot graphs and generate tables), and not necessarily because they have the best scientific studies. Therefore, with the objective to develop this study with the highest level and quality of information possible, and due to the very incipient and globally applicable theme, rigor was maintained in the selection of the platform, databases, publications, and studies. This decision generated the need to conduct a study of the feasibility to include other databases in this project, in addition to these two.

Thus, although the choice of platform and databases may be influenced by their coverage (temporal, documentary, and geographic), technical limitations, objectives, and biases, the following inclusion criteria, considering a priority for high-level scientific research, were used: a multidisciplinary approach, international scope, satisfactory number of studies, and link to technological innovation. The criteria met the UnB and Aachen universities guidelines, in addition to providing recent, relevant, and reliable content, peer review, and bibliometric indicators application. The platform and databases selected were detailed in Chapter 2.

To choose the software used to simplify the reference management workflow, the following features were considered [101]: free; stores, organizes, and searches all references in a single library; inserts references and bibliographies into documents; keeps all thoughts across multiple documents in one place; and collaborates with others by sharing references and ideas. The selected software was detailed in Chapter 2.

And, to select the software used to build and represent bibliometric maps, as well as to identify clusters and future trends, it was considered these following functionalities [102]: free; focuses on the bibliometric networks visualization; supports of high-precision text mining algorithms; relatively easy to use and more complete (items and links); and one that has grown the most in several studies and impacts within the main databases. The software selected was detailed in Chapter 2.

3.2.1.4 Main Question Formulation

Based on the recognized Cochrane method, the Acronym "**PICOS** - **P**articipants, **I**ntervention, **C**ontrol, **O**utcome and **S**tudy Design" methodology created for the health area was applied in this context for mechatronic engineering, to find the research question. The results were detailed on topic 3.2.1.

3.2.1.5 Main Keywords (strings) Selection

To start the bibliographic study and find the state of the art on this topic, a search of existing studies was conducted, with the descriptors definition, Boolean operators, keywords, and uniform strategies.

However, to address some problems of the traditional search method, optimize bibliographic searches, and improve the final results, an innovative method created by the Author, called the "**BST** - **B**ibliographic **S**ynonyms **T**est", was used in this study for the first time (see Appendix A). It is important to highlight that Kitchenham [31] also suggests testing synonyms, but randomly and by "trial and error", without a systematized methodology as proposed in this thesis. So based on the PICOS Diagram Method, which provides the most used terms (also called strings or synonyms) for each keyword, the purpose of the Bibliographic Synonyms Test is to select a maximum of eight main strings for each different database, considering the most relevant synonyms for each keyword.

This methodology and results were detailed in Appendix A.

3.2.1.6 Studies Selection

To select and review the studies found with Bibliographic Synonyms Test, it was necessary to establish some predetermined inclusion and exclusion criteria to obtain relevant scientific material and identify patterns. Thus, a systematic literature review was performed with a specific 8-Steps Search Flow, by reading mainly the title, abstract, and keywords of all studies found with BST.

From Search Flow - Stage 1, five exclusion criteria were applied: (1) not article/paper/chapter, (2) not English/Spanish/Portuguese, (3) study is not available, (4) published before 2016 (5 years from 2021) and (5) multiple publications (the same study that was found in more than one database is considered just once; so, for the final quantity of studies for each database, duplicate studies were concentrated in Scopus, the best-known international database).

From Search Flow - Stage 2, two exclusion criteria (not applicable in companies and not related to the research question) and one inclusion criterion (studies that are not articles/papers/chapters but contain important MMs) were applied.

All results were detailed in Chapter 2.

3.2.1.7 Quanti-qualitative analysis of the selected studies

A critical, careful, and reproducible quanti-qualitative analysis was performed on the selected papers, based on the number and type of studies, total citations per study, year published, country of origin, sort of access, and content.

All results were detailed in Chapter 2.

3.2.1.8 Summarize and analyze the results

Based on Ercole et al. [35], the studies were read, analyzed, classified, and summarized in Appendix B, based on the following parameters: enterprise characteristics considered in the study, model type, input dimensions, outputs, critical analysis, output levels, country origin, possible shortcomings, if the model had been tested, and the creation year.

All results were detailed in Chapter 2.

3.2.1.9 Analyze future trends and clusters

The analysis of future trends and clusters in this theme was performed using Vos Viewer and Mendeley softwares, through a scientific map elaboration with visualization of scientometrics networks [90].

To begin the qualitative analysis of these studies, it was important to evaluate the relation of their abstracts, keywords, and author clusters. Then, all studies were organized by database, in Mendeley Software, and exported all together to the Vos Viewer for proper reviews and comparisons.

The occurrences number and the relevance score were shown by Van Eck and Waltman [102]. In “network visualization” mapping, aspects are represented by circle labels (the bigger the circle, the greater the relevance), while the cluster and its links determine each aspect by color. In “Overlay Visualization” mapping, aspects are also represented by circle labels, and the colors indicate the average year of the published studies (i.e., the date obtained after averaging the publication dates of all studies by each author).

Thus, in Vos Viewer, two analysis types were developed: “Title / Abstracts / Keywords analysis” and “Author analysis”. For the first one, a map based on text data was created, for reading Mendeley's RIS data with the binary counting method. For the second, a map based on bibliographic data was created, for reading the Mendeley RIS data with the co-authorship and full count method.

Results were detailed in Chapter 2.

3.2.1.10 Systematic Bibliographic Review Update

Once this doctoral thesis is published, the bibliographic review will receive suggestions and criticisms, which should be incorporated into subsequent editions, characterizing a dynamic publication that should be updated each time new studies on the subject arise.

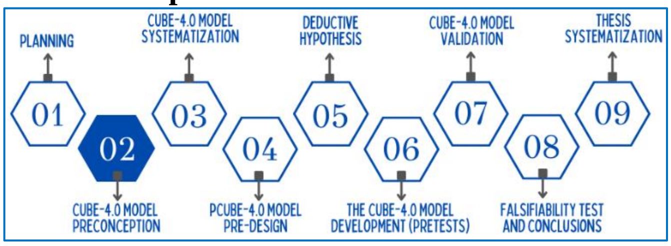
About **(e) Main research problem formulation**, this step was based on the PICOS Methodology (see details on topic 3.2.1.4) and the results can be seen in Table 4.

Table 4 - PICOS analysis (Source: Author, based on the Cochrane Method).

PICOS	IDEAS	KEYWORD ORIGIN	KEYWORD STRINGS	MAIN SUBJECT
PPARTICIPANTS (study population)	Engineering company (industry) of any size and economic sector	COMPANY	COMPANY CORPORATE ENTERPRISE BUSINESS	**READINESS TO DIGITAL TRANSFORMATION: THE CUBE-4.0 READINESS MODEL FOR DIAGNOSIS AND IMPROVEMENTS PROPOSAL**
IINTERNVENTION (interest in this study)	Roadmap with: - company's readiness current level (status) - strategies for readiness' improvement	ROADMAP	ROADMAP	
CCONTROL (characteristic to be controlled)	Readiness	READINESS	READINESS	
OOUTCOME (main expected product)	New Readiness Model, efficient and easy to apply in practice	MODEL	"MATURITY MODEL" "READINESS MODEL" "CAPABILITY MODEL"	
SSTUDY DESIGN (context)	Digital Transformation context	"CONTEXT 4.0"	"DIGITAL TRANSFORMATION" "INDUSTRY 4.0"	
Main Research Question: HOW TO ANALYZE AND IMPROVE AN ENGINEERING COMPANY READINESS THROUGH DIGITAL TRANSFORMATION CONTEXT?				

Therefore, this research aimed to answer the following research question, obtained with the PICOS methodology: *HOW TO ANALYZE AND IMPROVE AN ENGINEERING COMPANY READINESS THROUGH DIGITAL TRANSFORMATION CONTEXT?*

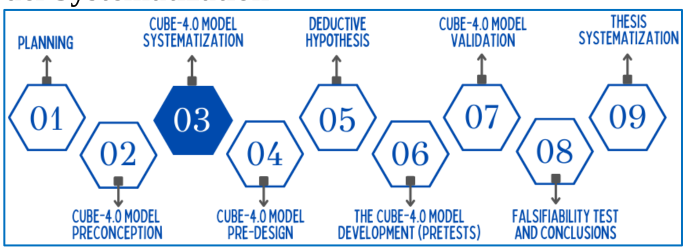
3.2.2 Model Preconception



In this phase, the Author participated in the development of the predecessor model (called 3D-CUBE), to learn the model construction methodology, as well as get acquainted with the main concepts related to the theme.

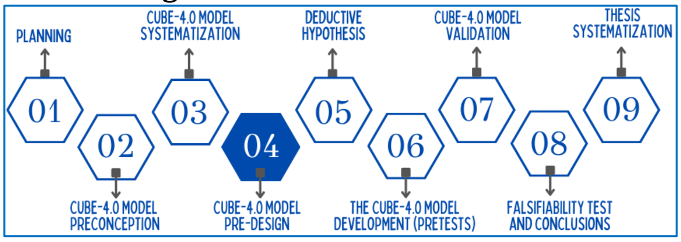
Results were detailed on topic 4.1.

3.2.3 Model Systematization



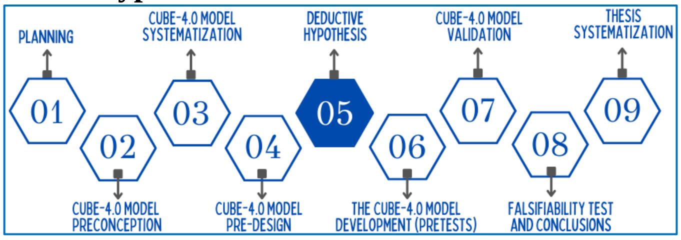
Based on the literature review, were selected which parameters needed to be defined, to build a readiness model. For more details, refer to Chapter 4.

3.2.4 Model Pre-design



In the hypothetical-deductive method, this step proposes solutions consisting of existing models, for each parameter selected in Topic 3.2.3.

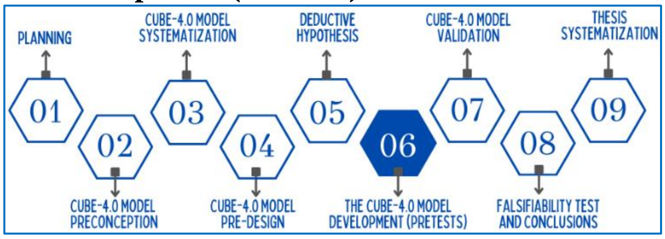
3.2.5 Deductive hypothesis



This step was the consequences deduction in the form of hypotheses suitable for testing the investigated phenomena. Due to the Model's complexity and wide scope, this step was discussed with theoretical implications for the most likely business profiles in terms of its readiness (that our Model could diagnose), and the main possible results.

Results were detailed on topic 4.4.

3.2.6 Model Development (Pretests)



After an extensive systematic literature review and the Author's experience in a participant-research (described in items 3.2.6.1 and 3.2.6.2), the CUBE-4.0 Model "Version 0" has been modified and generated "Version 1", which was used to start the pretest in the "Company A" (see item 3.2.6.3). So, using AlBar and Hoque [103] methodology, the expert panel review, the pretesting, and the pilot study were utilized to refine and validate the CUBE-4.0 Framework, Questionnaire, and Roadmap.

By testing and validating the CUBE-4.0 Questionnaire and CUBE-4.0 Roadmap, the entire CUBE-4.0 Model was indirectly tested and validated, including its levels, dimensions, sub-dimensions, elements, score calculation, radar graphic, and data collection/survey methodology.

Therefore, the CUBE-4.0 method development was subdivided into six pretests:

- answer the Maturity Model Questionnaire provided for one of the most recognized maturity models in Brazil (SENAI Model [16]);
- answer the Maturity Model Questionnaire provided for INNOWAY Model [104];
- apply the CUBE-4.0 Questionnaire (Version 1) and CUBE-4.0 Roadmap (Version 1) in a Brazilian Engineering Enterprise ("Company A");
- publish in an A1 Journal;
- analyze the CUBE-4.0 Questionnaire and Roadmap with a recognized international consulting firm on I4.0; and
- present the CUBE-4.0 Model at an International Workshop.

Then, the feedback from these Questionnaire and Roadmap pretests was used to adjust and improve the whole CUBE-4.0 Model, generating the version which will later be applied to engineering firms.

3.2.6.1 Pretest 1: Answering SENAI Questionnaire

The goal of this first pretest was to put the Author-self in the respondent's place, empathizing with their feelings when filling out this type of questionnaire, as well as compare with the CUBE-4.0 Model and, if appropriate, adjust the model proposed in this thesis with some relevant information from the SENAI [16] method.

At this point, it is important to highlight that the MM proposed by the Brazilian National Industrial Learning Service - SENAI [16] is one of the most used in Brazil, which is based on the Acatech Model [7]. SENAI [16] has partnered with the German engineer's academy that created the Acatech Model and is applying it to Brazilian companies as a tool to propose lacks for I4.0 implementation. Acatech was deployed in question and used as an online tool to be applied in this way.

In order to improve the CUBE-4.0 Model development stage, the Author participated as an observer-participant and focal point in a survey conducted by a large Brazilian company in the electric sector, responding to the SENAI [16] questionnaire applied to all its departments, in order to assess the maturity of this company about I4.0 and its innovation culture.

In addition, a meeting was held with those responsible for the SENAI [16] maturity model, during the XXVI SNPTEE (National Seminar on Electricity Production and Transmission), in order to better understand the SENAI [16] Questionnaire and verify its benefits and shortcomings.

3.2.6.2 Pretest 2: Answering INNOWAY Questionnaire

Because the results obtained by the SENAI [16] method were not considered satisfactory by this Brazilian company, it hired another consulting company, called INNOWAY [104], to perform the same type of questionnaire again. So, the purpose of this stage was to put the Author-self again in the respondent’s place, as an observer-participant in a survey conducted by the same Brazilian company.

3.2.6.3 Pretest 3: Applying the CUBE-4.0 Questionnaire (Version 1) and CUBE-4.0 Roadmap (Version 1) in the “Company A”

In order to evaluate and validate the CUBE-4.0 Questionnaire and Roadmap, these were applied, in face-to-face and online interviews, with a Brazilian engineering company (that produces metallic components for civil construction), called “Company A”. All the necessary interviews were conducted, with updates to the model according to the feedback from the company's specialists, until its acceptance by them.

It must note that the in-person technical visits in “Company A” were very important, both for motivating the teams at “Company A” to contribute to the design of this readiness model, as for the Author's learning throughout the process.

3.2.6.4 Pretest 4: Publishing in an A1 Journal

Although the CUBE-4.0 previous “Version 0” (the 3D-CUBE created by Silva et al. [39]) has already been published at the 26th EurOMA Conference in June/2019 [39] and in DYNA Colombian Journal in June/2021 [65], for the first time this new version was published in a recognized A1 Journal: “Production & Manufacturing Research”, by Francis and Taylor Group. The idea was to improve and adjust the CUBE-4.0 Model, during the revisions requested by this recognized Editorial Team, to approve the paper.

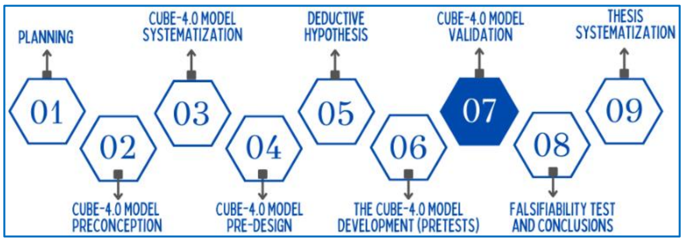
3.2.6.5 Pretest 5: Analyzing the CUBE-4.0 Questionnaire and Roadmap with a recognized international consulting firm on I4.0

To collect relevant information and feedbacks for the Model, the CUBE-4.0 Questionnaire and Roadmap were submitted to a DT consulting global company analysis through interviews, which is recognized in the market for 35 years, in 41 countries, with more than 30,000 employees, being among the top-100 IT companies in the world.

3.2.6.6 Pretest 6: Presenting the CUBE-4.0 Readiness Model in an International Workshop

Finally, the Author presented the CUBE-4.0 Model at the 35th Ordinary General Assembly, promoted by the International Transportation Industry Chamber (CIT), which operates in more than 30 countries around the world, in the development, modernization, and interconnectivity between transport modes. The Chamber’s affiliates and partners include companies, technical institutes, and education and research centers, among others.

3.2.7 Model Validation



As well as the MM of Wagire et al. [69], CUBE-4.0 validation is supported by:

- deduction from prior literature;
- expert consultation (judgment and opinion); and
- case study.

According to Eisenhardt's study [95], to build a theory from a Case Study, an extension of this tactic is to group cases into three or four for comparison. In other words, for a case study, three interviews are sufficient to obtain satisfactory results.

For the companies' selection that participated in the CUBE-4.0 project and to comply with the experts' suggestion for this doctoral thesis, the support of the Brazilian National Industry Confederation (CNI) was requested to recommend the most suitable industries for this type of research. CNI indicated seven companies in different economic sectors, considering that they would already have a satisfactory level of preparation regarding I4.0, have an interest in DT projects, and could contribute to this research. For selecting three within the seven companies suggested by CNI, e-mails were sent to the companies, with the questionnaire attached, requesting a brief initial meeting to address the issue. Two of them never answered us. Thus, we did the initial interview (Launching) with the other five companies indicated. Although very well recognized in the market, two of them were discarded for not presenting the minimum requirements to fill out the questionnaire, that is, they are not industries, but consulting companies. Therefore, this step was ended and the CUBE-4.0 was not applied in these two companies, taking advantage of only conceptual feedback about DT and reinforcing the CUBE-4.0 methodology. Thus, the other three companies were selected, among which one of them was also selected to analyze and test our model previously ("Company A").

Besides, according to the criteria established by IBGE (Brazilian National Institute of Geography and Statistics), ANVISA (Brazilian National Health Surveillance Agency), and BNDES (Brazilian National Bank of Economic and Social Development), an industry is considered a microenterprise with up to 19 employees, small if it has 20 to 99 employees, medium if it has 100 to 499 employees and large if it has more than 500 employees.

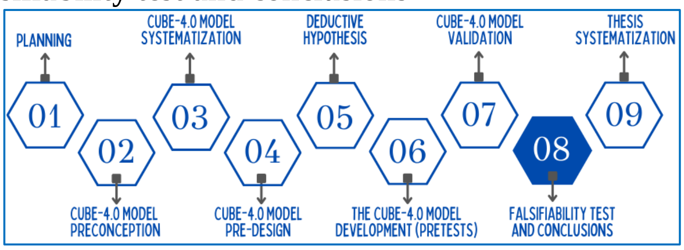
Therefore, this thesis applied three case studies with the three selected companies: **(1)** for a small/medium enterprise ("Company A"), **(2)** for a medium enterprise ("Company B"), and **(3)** for a large enterprise ("Company C").

Li et al. [20] say that "previous research requires company managers to possess a certain amount of knowledge about Industry 4.0", so the application of this Model was focused on the manager of the company's main processes.

It is also important to highlight that by validating the CUBE-4.0 Questionnaire and Roadmap, automatically the Model's Framework is also being validated.

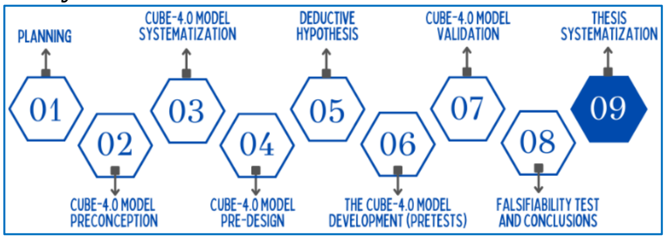
Finally, to apply the questionnaire to the three selected companies (see Chapter 5), only virtual meetings were held without inconvenience.

3.2.8 Falsifiability test and conclusions



This step refers to falsifiability testing which encompassed efforts to disprove the previous deductive hypotheses, as well as to analyze the results and summarize the main conclusions of this thesis. For more details, see Chapters 6 and 7.

3.2.9 Thesis Systematization



Finally, all the content referring to the previous topics was written up in this thesis and presented for its approval to an examining board, composed of 2 external professors and 2 renowned internal professors who are experts on the subject.

4. CUBE-4.0 Model Development

The CUBE-4.0 Model development main results were detailed below.

4.1 Model Preconception

It is noteworthy that the CUBE-4.0 Model is an evolution of the initial model called 3D-CUBE, which was elaborated in June/2019 (EurOMA, [39]) by Ambrosio, Barbalho, Heine, Adam, and Schmitt, and later detailed in June/2021 (DYNA, [65]). Specially for the DYNA publication, the Author participated in some definitions and updates. This 3D-CUBE was considered as “Version 0” for CUBE-4.0.

Importantly, the name “3D-CUBE” was changed to “CUBE-4.0” because each cube has three dimensions, and the “3D” information would be duplicated. Also, since the Model’s idea was to prepare engineering companies for I4.0, it was decided that the name CUBE-4.0 would be more appropriate.

4.2 Model Systematization

Thus, based on the literature review, especially in Caiado et al. [22], it was determined that a satisfactory readiness model should contain at least the following information, in as much detail as possible:

- Scope (in which company it could be applied);
- Dimensions / Sub-dimensions / Elements;
- Readiness Levels;
- Data Collection Methodology;
- Calculation and Evaluation Methodology;
- Questionnaire; and
- Roadmap (for delivering to the company its results with graphics and recommendations).

Therefore, the expression CUBE-4.0 Model encompassed all these parameters: the Framework (scope, dimensions, sub-dimensions, elements, levels, data collection, and calculation methodology), Questionnaire, and Roadmap.

Then, in the next topic, each parameter was pre-defined and generally explained.

4.3 Model Pre-design

The CUBE-4.0 gives a tri-dimensional view of readiness, which facilitates the company's understanding of its real situation through DT. So, as a result of the evaluation process, there is a readiness vector R= (X, Y, Z), where "X" is the organizational enabler, "Y" is the technological enabler, and "Z" is the process maturity enabler. When diagnosed, a company has different readiness levels in each dimension, with sub-dimensions and a third granularity named "elements" (Figure 20). Some authors, such as Schuldt et al. [105], call these elements KPIs. However, we understand KPIs as performance indicators used to assess whether certain actions are reaching the stipulated goal.

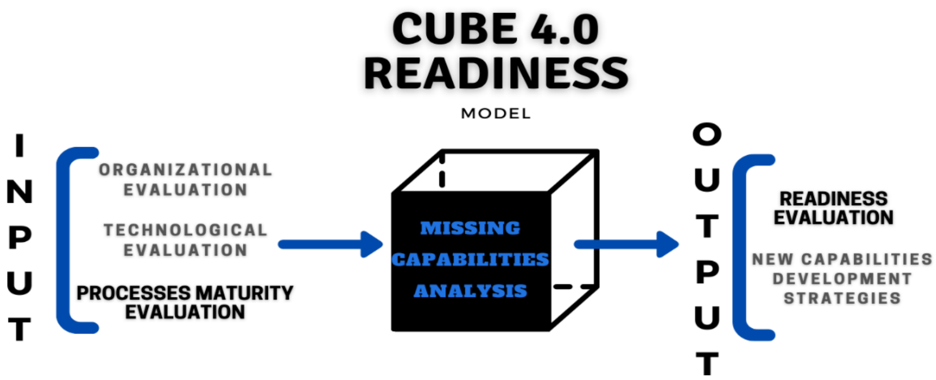


Figure 20: Framework of the proposed CUBE-4.0 Readiness Model (Source: Author).

The proposed "CUBE-4.0 Model" reflects how ready any kind/size of an engineering company is to engage in an I4.0 environment. Considering that our Model focuses on numerically assessing a company's readiness level for DT, it can also be called a "CUBE-4.0 Readiness Model".

The CUBE-4.0 Readiness Model considers the dimensions of organizational enablers, technological enablers, and, for the first time in literature, the maturity of the firm's operation processes (basically Product-Service Development and Order Fulfillment) as input. For this unprecedented dimension of process maturity, our Model can quant-qualify maturity more completely and at various levels. So, the main difference between our proposed Model and the other 63 models is that the CUBE-4.0 is the only one that considers "maturity" as an INPUT process, while all other models understand "maturity" as an OUTPUT. Besides, in our Model, the relationship between "maturity" and "readiness" is clearly defined. Most existing MMs today use the same CMMI maturity concept, others have no well-defined concepts, and others use "readiness" and "maturity" almost synonymously. Therefore, in CUBE-4.0 Model, the readiness can be measured more objectively, that is, using a tri-dimensional vector score indicating whether the company is ready or not for DT.

4.3.1 CUBE-4.0 Readiness Levels

Based on the CMMI maturity levels [5] and incorporating elements from Schuh et al. [7], readiness levels were initially pre-defined in the previous 3D-CUBE as follows: Initial, Managed, Defined, Optimized, and Self-adapted, with values ranging between 1 and 5, respectively. This first proposal has similarities with previous I4.0 MMs, mainly to the DREAMY Model [15], which is also based on the CMMI approach and its capability and maturity levels assessment. However, while the DREAMY Model focuses only on process improvements, the 3D-CUBE Model considers organizational and technological enablers as well. The only novelty would be the 5^{th} level (Self-adapted), which is based on Schuh et al. [7], following the adaptability concept, where continuous adaptation allows a company to delegate certain decisions to IT systems so that it can adapt to a changing business environment as quickly as possible. Thus, the enterprise has a set of adaptable technologies and processes that enable self-optimization.

However, after further studies on CMMI Model, it was suggested to insert an initial step to the 3D-CUBE (generating the CUBE-4.0 Version 1) to comply with the CMMI maturity level lack. According to Chrissis et al. [5], the CMMI Model suggests two different kinds of levels: one for "continuous improvement" - capability levels (which has Level 0 – Incomplete), and one for "staged improvement" - maturity levels (which has no Level 0). It is important to note that the CMMI Model only mentions and studies maturity and capability levels and does not consider readiness in its analyses. A company could improve separate areas with different capability levels in place. To implement this concept, the CMMI Model inserted an additional level of analysis when evaluating capability, the null level, or "zero", an underperformed process. Besides, many Brazilian companies are at level 0 nowadays, so this is very important to add this possibility to the CUBE-4.0 Model. Finally, for level 1, it was seen that "initiated" has a more optimistic perception than "initial", which is why this change was made. Then, it was decided that to better differentiate between levels 0 and 1, the first one would be called "not initiated" and the other one "initiated", because "incomplete", "initial", and "initiated" terms could be interpreted as the same level.

Thus, the predefined CUBE-4.0 Readiness Levels were: 0 - Not Initiated, 1 - Initiated, 2 - Managed, 3 - Defined, 4 - Optimized, and 5 - Self-adapted.

4.3.2 CUBE-4.0 Dimensions, Sub-dimensions, and Elements

So, based on previous studies, CUBE-4.0 was pre-designed with 3 dimensions (1 – Organizational, 2 – Technological and 3 – Process maturity enablers), 7 sub-dimensions (1_1 - Organizational Culture, 1_2 - Business Model, 1_3 - Human Resources, 2_1 - Production Technology, 2_2 - Information Technology, 3_1 - Product-Service Development, 3_2 - Order Fulfillment), and 22 elements (1_{11} - Top-down support for Industry 4.0, 1_{12} – Agility, 1_{13} - Willingness to change, 1_{21} - IT/cloud-based business models, 1_{22} - Service-based business models, 1_{23} - Spin-offs-based business models, 1_{24} - Partners-based business models, 1_{31} - Vertical and parallel communication, 1_{32} – Training, 1_{33} - Newness in contractual relations, 2_{11} - Anthropomorphic support systems, 2_{12} - Cognitive support systems, 2_{13} - Managerial support systems, 2_{14} - Driving network production, 2_{21} - Interconnected company data, 2_{22} - Information transparency, 2_{23} - Decentralized Decisions, 3_{11} - Customer-based new product development, 3_{12} - Cross-company engineering and development, 3_{21} - Customized-based production system, 3_{22} - Supply-chain integration and 3_{23} - Sales & Operations planning).

All these elements will be explained later in Chapter 5.

4.3.3 CUBE-4.0 Readiness vector score calculation

The company's readiness evaluation can be a self-assessment or by interview, always preferentially the second way initially, and after being more "mature" in this process, the enterprise could do a self-assessment as a strategy to gather data. It can help the analyst to build propositions for the most suitable improvements.

In our CUBE-4.0 Model, the survey and the firm evaluation focus firstly on each element. Each sub-dimension receives the same score as its respective element that has scored the lowest, i.e., the scores of all elements in a specific sub-dimension will be compared and the lowest score found will be the sub-dimension score. The same logic applies from the sub-dimension to the respective dimension score. That is why the enterprise should not focus and invest only in one element, as the other unenriched elements will prevent the company's readiness for DT. Therefore:

$$R^{\rightarrow} = \text{READINESS} = (\boldsymbol{O}, \boldsymbol{T}, \boldsymbol{M})$$

$\boldsymbol{O}$: organizational enabler

$\boldsymbol{T}$: technological enabler

$\boldsymbol{M}$: process maturity enabler

According to the final tri-dimensional vector score $R^{\rightarrow}$, it is possible to define if the company's readiness is at level 0, 1, 2, 3, 4, or 5, for each dimension, in order to improve its processes and management assertively.

4.3.4 CUBE-4.0 Data Collection and Survey

In order to deepen the CUBE-4.0 Data Collection step details, according to Rajnai and István [106], elaborating a methodology based on international best practices makes the process faster and helps avoid risks. However, having similar questions and methodology does not make the results of online surveys comparable. The information obtained by the Hungarian Survey confirmed this experience [106].

According to Ifenthaler and Egloffstein [78], there are five steps to developing a survey: (1) Launching, (2) Self-diagnosis, (3) Interviews, (4) Recommendations and Planning, and (5) Accompaniment. Similarly, the evaluation of the company's digital performance in Gamache et al. [50] study consisted of five steps: (1) Project launch, (2) self-diagnosis, (3) face-to-face interviews, (4) planning, and (5) coaching.

The Accompaniment/Coaching step (also called "Deploy and Maintain"), which is the last step of the Ifenthaler and Egloffstein [78] and Gamache et al. [50] methodologies, includes motivating and coaching the firm, and was not part of this thesis. For Ifenthaler and Egloffstein [78], the purpose of this whole process is to get the company to act, so on the closing day of the project, resources should be presented to acquire more information about the solutions to be implemented, on the available funding, and the possibilities of accompaniment during the implementation projects.

Thus, the following Data Collection methodology for the CUBE-4.0 was pre-defined, which includes five different steps, with a total duration of approximately 30 days for execution: (1) Launch (half a day, where there are defined: number of respondents - at least 30% of the workforce such as SENAI Model [16], and interviewees name), (2) Interview (one or more days, which can be individual or in teams, and one interview or as many as necessary), (3) Self-diagnosis (this is another interview with the respondents, which lasts one or more days; otherwise, the questionnaire can be answered individually at any time with a deadline for completion), (4) Tabulation (seven days, to analyze the results), and (5) Recommendations and Planning (seven days, to write up and present the results to the company).

Each step will be better described later in Chapter 5.

4.3.5 CUBE-4.0 Questionnaire

For this Survey process, a questionnaire was pre-designed with 22 questions (one for each element), and a few questions about the respondent and company data.

4.3.6 CUBE-4.0 Roadmap

The Roadmap is shown in Appendix D.

4.4 Deductive hypothesis

As can be seen in Figure 21, there are some deductive hypotheses about the possible CUBE-4.0 evaluation outcomes. In this example, there are four graphs: in the first one, the company only focuses on the “technological” enabler, not investing in the other two. This also happens for radar charts 2 and 3, in which the enterprise focuses, on “organizational” and “process maturity” enablers, respectively. In the last graphic, it could be seen a typical evaluation, where many companies fit in, considering investments in several areas, with different levels of readiness among them. Probably, this last graphic depicts the most common empirical situation when applying the Model in real cases, possibly with a higher technological enabler.

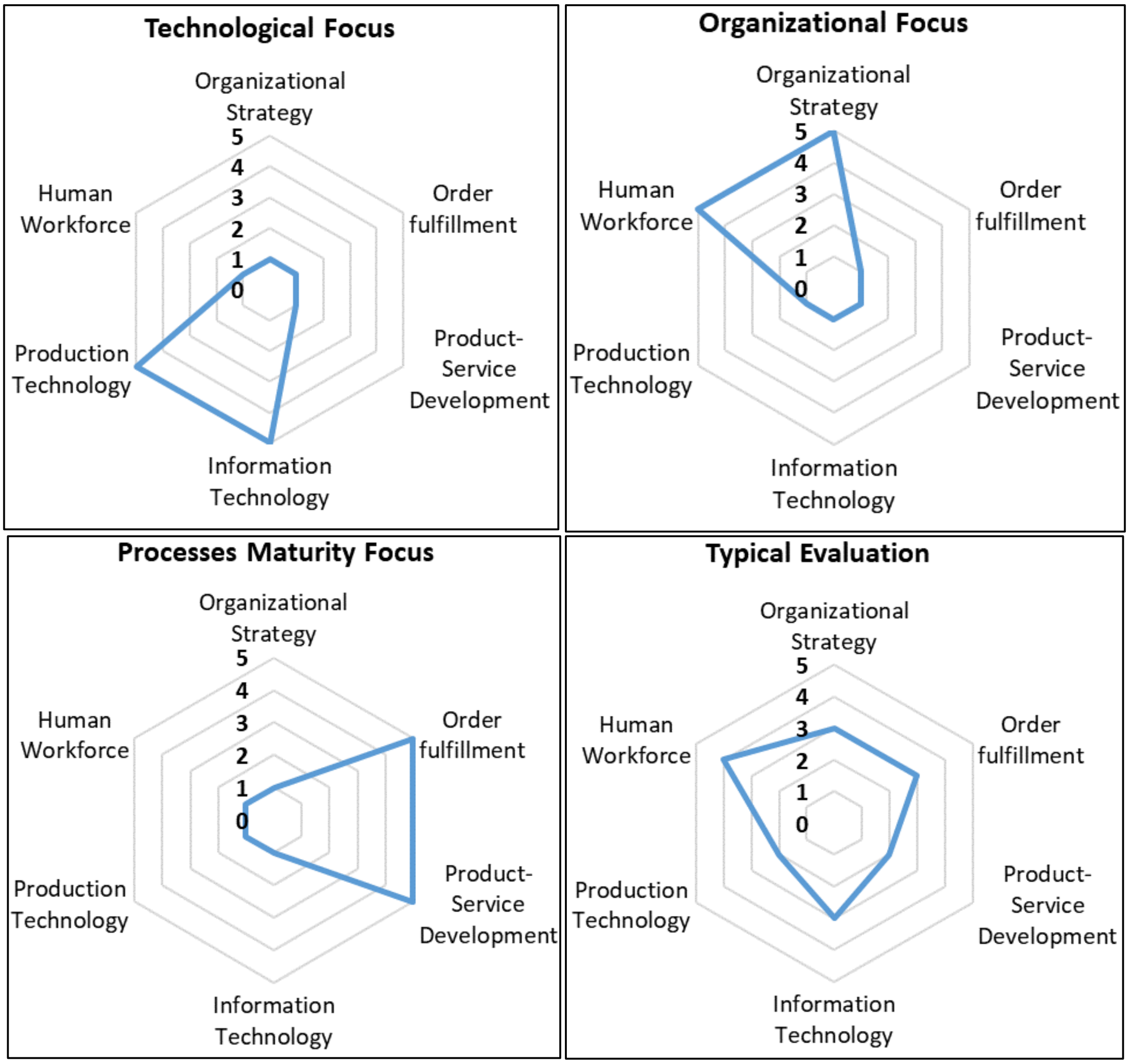


Figure 21: Typical evaluation using a CUBE-4.0 Radar Chart (Source: Author).

Then, at this point, three main hypotheses can be verified for the theoretical limits of an engineering company results, according to the CUBE-4.0 Model:

- The theoretical limits of the CUBE-4.0 Model for “organizational” enabler (when the readiness vector is (x, 0, 0), where x = 1, 2, 3, 4, or 5) present a situation where a company focuses on organizational enablers but invests in few technologies and does not have sufficient process maturity to realize I4.0 potentials.
- The CUBE-4.0 Model theoretical limits for “technological” enabler (when the readiness vector is (0, y, 0), where y = 1, 2, 3, 4, or 5) characterize a

situation in which a company focuses exclusively on implementing new technologies in some areas, but does not yet leverage the full technology potential. For instance, in Brazil, companies seek to connect to I4.0 through technological facilities. They want to introduce technology to reduce costs, especially labor costs. It turns out that the focus on technology often provides underutilized solutions. The enterprise has, for example, an ERP SAP system with all possible modules, but people are not trained, do not know how to use the system, or have difficulty understanding the unfolding of the work in other areas. Organizational and process maturity enablers are low, so the technology is underutilized. Therefore, its technology aspirations are not supported by its organizational and/or process maturity enablers, which are displayed in the CUBE-4.0 Model.

- The theoretical limits of the CUBE-4.0 Model for process maturity enabler (when the readiness vector is (0, 0, z), where z = 1, 2, 3, 4, or 5) is also a hypothetical case in which a company has more emphasis on process maturity than on organizational or technological enablers. It works effectively with partners along the supply-chain, its order fulfillment is integrated, its NPD involves customers and takes place across all departments in a firm, and its sales and operations interfaces work harmoniously. However, it lacks top management support for an I4.0 transformation and its members are averse to change, for example, besides no investments are made in new technology.

4.5 Model Pretests

The analysis of existing models (during the bibliographic review) and these six pretests were the main inputs to the CUBE-4.0 Model development.

4.5.1 SENAI Questionnaire

The SENAI [16] questionnaire was filled out by this Author on October/2021, who verified that the SENAI's method was divided into 8 dimensions (Strategy, Leadership, Culture, Relationship, Process, People, Structure, and Resources), and evaluated by five levels. It has 33 different types of questions and was filled out for different employees: with distinct positions (including directors and operational technicians), different lengths of time in the company (divided into 1 to 10 years, 11 to 20, 21 to 30, and above 30 years working in the company), and various locations covered by the company (11 different Brazilian states).

Considering SENAI's methodology [16], the objective was to get at least 30% of the workforce to fill out the questionnaire. However, because the company only used the methodology of delivering the questionnaire online with a deadline for completion, without conducting any interviews with the teams that would answer it, this goal was not achieved, as only approximately 20% of employees filled in, which may have impacted the results effectiveness and reliability.

The entire process of applying the SENAI [16] questionnaire and analyzing the results, lasted approximately two months. This process ended with the final report delivery (with 17 pages), during a meeting with the team responsible for this process in the enterprise under evaluation.

The application result of the SENAI [16] questionnaire in the company was a grade of 3.71, highlighting the dimensions "Leadership" and "Strategy" as strengths of its DT.

The final report was considered poor, with only one page containing suggestions for improvement paths, which focused on training, R&D, and other innovation strategies.

But for this thesis, the most important is to focus on the SENAI [16] questionnaire applicability, which presented the main limitations below:

- it is adaptable for 15 specific economic segments, whose ratings are confusing and repetitive;
- the questionnaire does not include all kinds of engineering companies and important area sectors, such as logistics, energy, robotics, and others;
- although I4.0 covers several technologies, it focuses only on these resources: the Internet of Things, Big Data, and autonomous robotics;
- focuses only on Brazilian companies, not including international ones;
- in the levels' categorization, it goes from 1 to 5, and does not include level 0 ("none"), where many Brazilian companies are nowadays;
- the questions in the questionnaire have different types and quantities of responses, as well as different measurement metrics, and are not homogeneous or comparable among themselves, which causes difficulty in the questionnaire application, tabulation of the evaluation, and conclusion. For instance, in the same question, some answers are not part of the graded readiness scale;
- some questions focus on techniques, equipment, technologies, and specific tools, which do not apply to all types of engineering companies, may soon become obsolete, and/or do not encompass all those that exist in the world, having difficulty to define a firm's level of readiness;
- some questions are complex, subjective, and difficult to answer. For example, "*what qualifications will your employees need in the future?*";
- although it has 33 questions, it is very superficial and generic, and does not explore each of the proposed dimensions;

- its methodology includes only the application of the questionnaire written individually, with a deadline for completion, not including the possibility of interviews (which can greatly optimize the survey results). This methodology proved to be inefficient because few people answered the questionnaire, and the goal of 30% of the workforce was not reached;
- although the results' presentation is extensive (with 17 pages), it was tiring, limited, and its suggestions for improvement hardly add value; and
- it is available on the platform in Portuguese only.

Besides, a meeting was held with the responsible for SENAI's maturity model, during the XXVI SNPTEE (National Seminar on Electricity Production and Transmission), held on 05/18/2022, and many of these shortcomings were discussed and confirmed.

4.5.2 INNOWAY Questionnaire

The INNOWAY Model [104] questionnaire was filled out by this Author in March/2022. Its platform presented a good interaction with the users, allowing them to save and return, when necessary, as well as guaranteeing anonymity and confidentiality (via QR CODE). However, it presented the main limitations below:

- a very extensive questionnaire, with 142 questions answered, whose amount may increase or decrease, depending on previous responses;
- the questionnaire answered is focused on business enterprises (marketing, communication, people management, and others), not including industries;
- presents only questions related to the organizational dimension, focusing on entrepreneurship, adaptability, innovation, people, culture, strategies, leadership, intelligence, ideation, development, and management;
- although I4.0 covers several agile methodologies, it focuses only on SCRUM, LEAN, KANBAN, and FDD (Feature-Driven Development);

- the questions in the survey have different types and quantities of responses, as well as different measurement metrics, and are complex, not homogeneous, and not comparable among themselves. This causes difficulty in applying the questionnaire, answering, tabulating the evaluation, and concluding. For instance, many questions include the answers “Totally Disagree”, “Partially Disagree”, “No, I don't agree”, “Yes, I agree”, “Totally agree”, and “Don't know”, which are all too subjective options;
- it is exclusive for consulting INNOWAY Model [104], which charges very expensive for its application; and
- it is available on the platform only in Portuguese.

On the other hand, it presented a good result regarding the application methodology, which includes several meetings, one for each company’s department, starting with a brief explanation of the survey's objective by the interviewer. Soon after, the questionnaire was made available via link so that respondents could answer it individually, while interviewers remained in the room for any questions or needs.

The only problem is that an adequate selection of interviewees was not made, besides carrying out this process with the entire company (more than 1,000 employees). Difficulties were presented in the results tabulation and the answers’ reliability because many interviewees made it mandatory, not knowing how to respond to most of the questions.

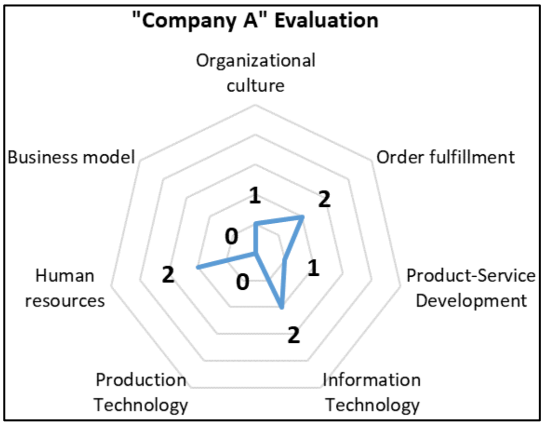
4.5.3 Application of CUBE-4.0 Questionnaire (Version 1) and CUBE-4.0 Roadmap (Version 1) in “Company A”

Step 1 (CUBE-4.0 Questionnaire and Roadmap Version 1): The first CUBE-4.0 Questionnaire (Version 1) was conducted on 09/06/2021, with the head of the Rolled Steel Department of “Company A”, whose result was satisfactory and was also summarized in this topic. It is important to highlight that the data collection methodology here was different in relation to Steps 2 through 4 of this topic 4.5.3. In Step 1, after a visit to the "Company A" website (see Figure 22), the interviewer was asking each question, with explanations to the respondent, and the interviewer herself was filling out the online questionnaire with the company's answers. As this methodology was not satisfactory, for the other steps, the INNOWAY methodology [104] was used, that is, a meeting was held for the selected interviewees to individually fill out the online questionnaire, while the interviewer was in the room waiting for the conclusion. In this Step 1, a manager well-familiarized with I4.0 concepts answered the entire questionnaire and was asked to provide feedback regarding her perception of the whole Model. After tabulating the results, the CUBE-4.0 Roadmap (Version 1) was sent by e-mail to "Company A". Thus, in order to evaluate and validate the CUBE-4.0 Roadmap, it was applied using the results obtained in the previous stage with CUBE-4.0 Questionnaire (Version 1).

In general, this application brought changes in the CUBE-4.0 Framework and Questionnaire.

Figure 22: In-person interview at "Company A" – Step 1 (Source: Author).

It should be noted in Figure 23 that the "Company A" had the best results in process maturity enabler, compared with technological and organizational criteria.

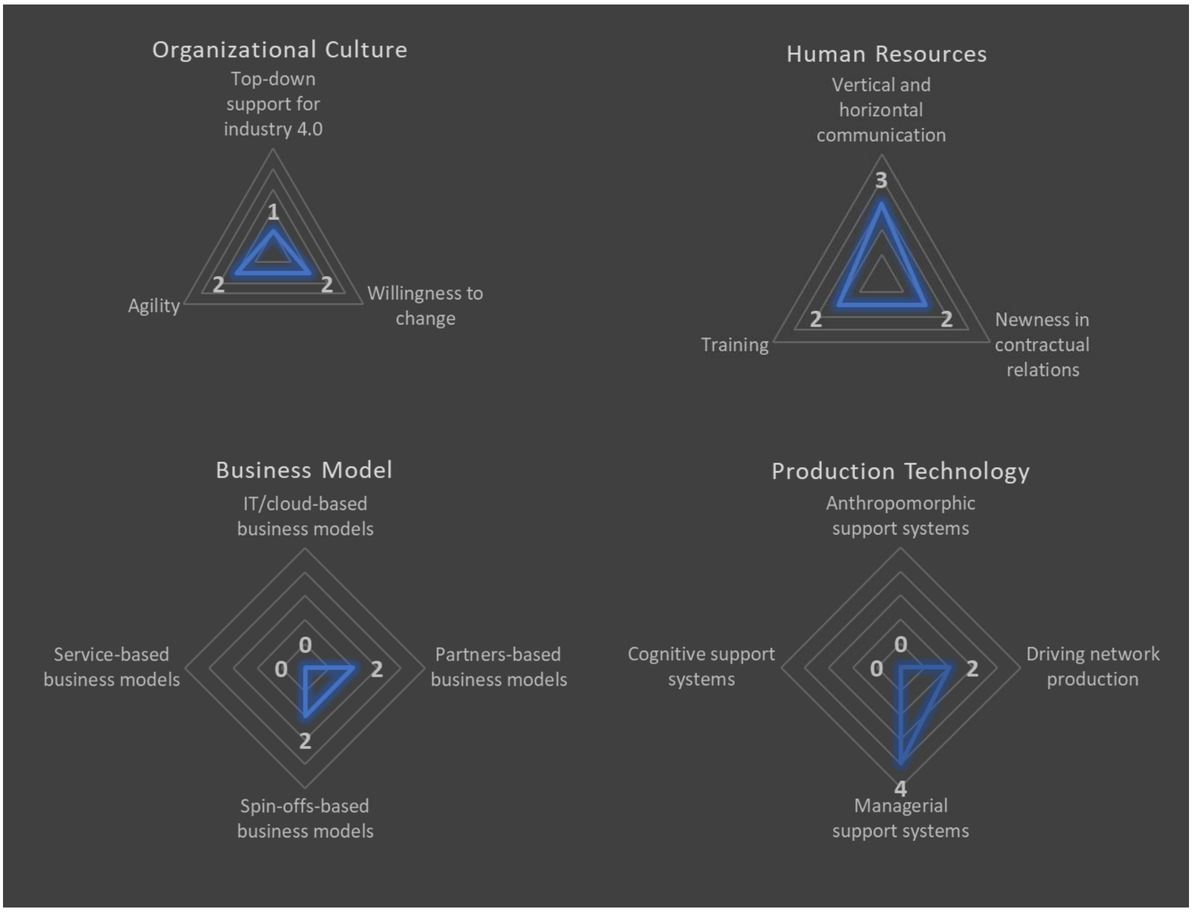


STEP 1

ORGANIZATIONAL ENABLER	Organizational culture	1	**0**
	Business model	0	
	Human resources	2	
TECHNOLOGICAL ENABLER	Production Technology	0	**0**
	Information Technology	2	
PROCESS MATURITY	Product-Service Development	1	**1**
	Order fulfillment	2	
READINESS (0, 0, 1)			

Figure 23: “Company A” Results – Step 1 (Source: Author).

Considering Figure 24, although presenting a good evolution regarding Technological Information, Product Development, Order Fulfillment, Organizational Culture, and Human Resources, the company is still in an incipient stage regarding its Business Models and Technological Production, the reason why the “R” vector ended up reducing its values.



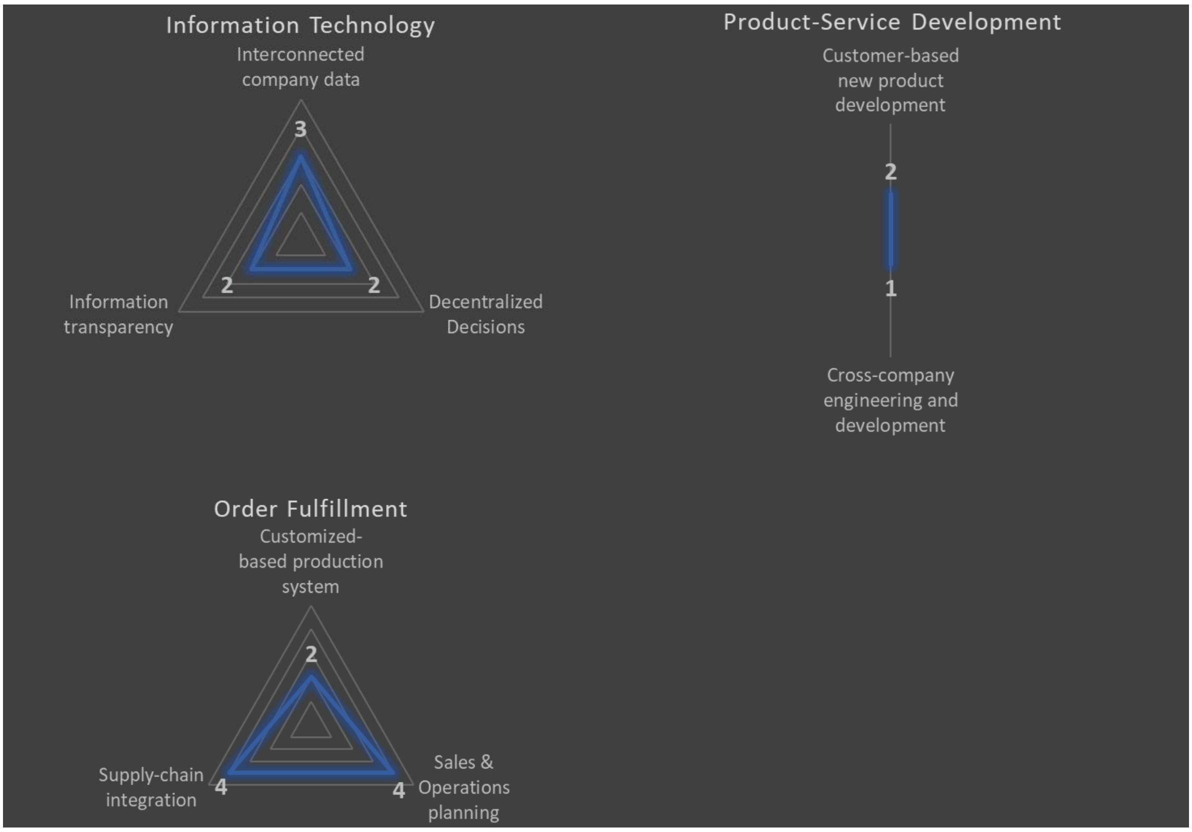


Figure 24: Scores for each Element – Step 1 (Source: Author).

Besides, it was realized the need to increase the number of analyzed elements to the "Product-Service Development" sub-dimension, so the radar chart graphic would no longer be a straight graph, as this kind of chart would not aid in analysis and decision-making.

Some questions were mutually exclusive, generating "0" in some answers, greatly impairing the analysis of the company's readiness, because, with the smallest 1 element zeroed, the entire dimension ends up with the score 0. In fact, this happened with this large reputable company, for which a higher score than the vector found was expected.

Moreover, as feedback, "Company A" said it found the result very low, which discouraged a bit of participation in this DT process. In addition, the respondent found the process of filling out the questionnaire very time-consuming, as well as mentioning that she had no contact with the online questionnaire for previous reading and initial preparation.

Therefore, it was possible to revise the wording, format, content, sequence, layout, simplicity, and clarity of the survey instrument. Then, based on this CUBE-4.0 method pilot application, besides reducing the number of questions, grouping similar topics together, and correcting some spelling errors, the following improvements were made to the questionnaire (see Table 5).

Table 5 - Questionnaire improvements after "Company A" feedback – Step 1 (Source: Author).

Section/ Question	QUESTIONNAIRE (Version 1)	QUESTIONNAIRE (Version 2)	JUSTIFICATION
INITIAL INFORMATION	Instead of asking about the "respondent's training area"	Ask about "the company's economic sector"	It is most relevant to the study and helps more with the results
ADD FIRST QUESTION	---	"How would you describe the I4.0 implementation status in your company?"	To get an idea of the respondent's perception of the company's situation regarding I4.0
SECTION 1: ORGANIZATIONAL	Instead of "organizational culture"	Add "organizational strategy"	Because it is more comprehensive and reliable for the questionnaire's organizational elements
SECTION 1: ORGANIZATIONAL QUESTION 2	---	Add the question: "How is the ORGANIZATIONAL STRUCTURE adaptation process to I4.0?"	Because it is an important organizational element and was missing from the questionnaire
SECTION 1: ORGANIZATIONAL QUESTION 3	Instead of four questions (one for each business model based on: IT/CLOUD, SERVICES, PARTNERSHIP, or SPIN-Offs)	It has chosen to join these four questions in just one: "How is the BUSINESS MODEL conforming to I4.0?"	Whereas a company can opt for only one of the four suggested business models, so that its grade does not get zeroed undermining the final evaluation
SECTION 1: ORGANIZATIONAL QUESTION 4	---	Add the question: "How are CONTRACTUAL LABOR RELATIONS [with the workforce], in relation to I4.0?"	Because it is an important organizational element and was missing from the questionnaire
SECTION 1: ORGANIZATIONAL QUESTION 5	---	Add the question: "How is your company's LEADERSHIP preparation for I4.0?"	Because it is an important organizational element and was missing in the questionnaire
SECTION 1: ORGANIZATIONAL QUESTION 6	About the expression "COMMUNICATION"	Add the explanation "INTERNAL COMMUNICATION"	To facilitate respondent's understanding
SECTION 1: ORGANIZATIONAL QUESTION 7	About the expression "TRAINING"	Add "How is the team's TRAINING "on I4.0" and "the I4.0 technologies use in its realization""?"	To facilitate respondent's understanding
SECTION 1: ORGANIZATIONAL QUESTION 8	Instead of two questions (one for "agility" and one for "willing to change")	It has chosen to join these two questions in just one: "How is the INNOVATION CULTURE being managed?"	Because both questions deal with the innovation culture, it was decided to simplify the questionnaire as much as possible
SECTION 2: TECHNOLOGICAL QUESTION 13	Instead of asking only "How data is interconnected?"	Ask: "How is the DATA TRANSPARENCY AND INTERCONNECTIVITY, in real time [automatically by sensors], with security and guarantee that it has a single source?"	It is more complete and will help more in the analysis of results
SECTION 2: TECHNOLOGICAL QUESTION 14	Instead of asking "How is the transparency of information?"	Ask: "How is INFORMATION SECURITY in your company?"	Transparency has already been evaluated in other questions and information security is a very relevant item for company readiness

			(that was missing in the questionnaire)
SECTION 3: PROCESS MATURITY QUESTION 16	Instead of asking only about "engineering and development in the company"	Ask about "ENGINEERING, RESEARCH AND DEVELOPMENT integration with other companies"	Because "RESEARCH" is an important technological element, and it was missing in the questionnaire. Besides, it is important to evaluate not only these processes within the company, but also with partners
SECTION 3: PROCESS MATURITY QUESTION 20	Instead of asking about "sales planning and operations"	Ask about "the integration between SALES and OPERATIONS"	To facilitate respondent's understanding
SECTION 3: PROCESS MATURITY QUESTION 21	---	Add the question: "How is the QUALITY MANAGEMENT SYSTEM application, with multiple customer integration channels to after-sales services?"	Because it is an important process in a company and was missing in the questionnaire
ADD FINAL QUESTION		"How would you describe the I4.0 implementation status in your company?"	It is the same FIRST QUESTION repeated at the end, to assess how much this questionnaire impacted the respondent's perception
FEEDBACK QUESTIONS	---	Add these questions: "How would you rate this questionnaire? ( ) Difficult to fill out and not effective ( ) Difficult to fill out, but effective ( ) Easy to fill out, but not effective ( ) Easy to fill out and effective" "What can your company do to accelerate the processes, tools, skills, and attitudes needed for I4.0?" "Other Comments:"	Because this questionnaire can also be a good opportunity for the company to collect good ideas for innovation from its employees, being another benefit of the CUBE-4.0 Model. Besides, it is very important to know the company's opinion in relation to our questionnaire, in order to always be making continuous improvements and adaptations

Thus, the table above shows the 17 changes made to the questionnaire, with their respective justifications, which also helped in adjusting the CUBE-4.0 dimensions, sub-dimensions, and elements.

As feedback from "Company A", it was verified the difficulty of understanding some questions on the CUBE-4.0 Questionnaire (Version 1), demonstrating not to be so effective.

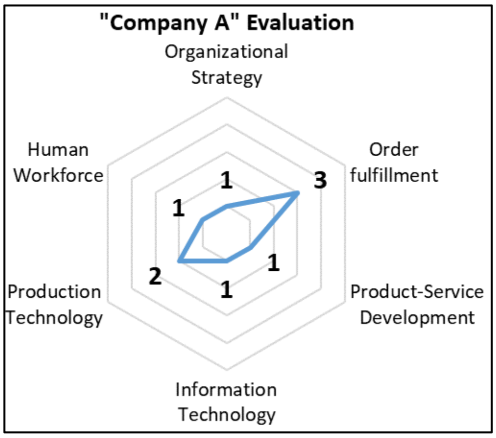
However, the questionnaire helped them think about what their company can do to accelerate the processes development, tools, skills, and attitudes required for I4.0, leading them to the completion of the need to “hire a consultancy”.

The CUBE-4.0 Roadmap (Version 1) was sent by e-mail with the results and some recommendations, being praised and without suggestions for improvement by “Company A”, which is why the initial roadmap version proposed was validated.

The only “Company A” suggestion to be adapted in future works for the “Deploy and Maintain” step, would be to add specific strategies to improve data collection regarding processes within the enterprise, because they do not know exactly how to do it yet.

Step 2 (CUBE-4.0 Questionnaire Version 2): These results and improvement suggestions from “Company A” were analyzed and the CUBE-4.0 Questionnaire was reviewed, generating a Version 2, which was applied again in the same company. This interview was conducted on 07/15/2022, with the head of the Rolled Steel Department, the head of the Production Department, and an engineering trainee, whose result was satisfactory and was also summarized in this topic.

It should be noted in Figure 25 that “Company A”, unlike Version 1, had the same results among the process maturity, technological, and organizational enablers R=(1, 1, 1). Although presenting better results regarding the Production Technology ($Version_1$ = 0, $Version_2$ = 2) and Order Fulfillment ($Version_1$ = 2, $Version_2$ = 3), the company presented lower scores for Human Workforce ($Version_1$ = 2, $Version_2$ = 1) and Information Technology ($Version_1$ = 2, $Version_2$ = 1).



STEP 2			
ORGANIZATIONAL ENABLER	Organizational Strategy	1	1
	Human Workforce	1	
TECHNOLOGICAL ENABLER	Production Technology	2	1
	Information Technology	1	
PROCESS MATURITY	Product-Service Development	1	1
	Order Fulfillment	3	
READINESS (1, 1, 1)			

Figure 25: "Company A" Results – Step 2 (Source: Author).

As an improvement over the presentation of radar graphics (see Figure 26), it was noted that the white background of the graphics showed greater acceptance from the respondents and thus became the formatting then adopted.

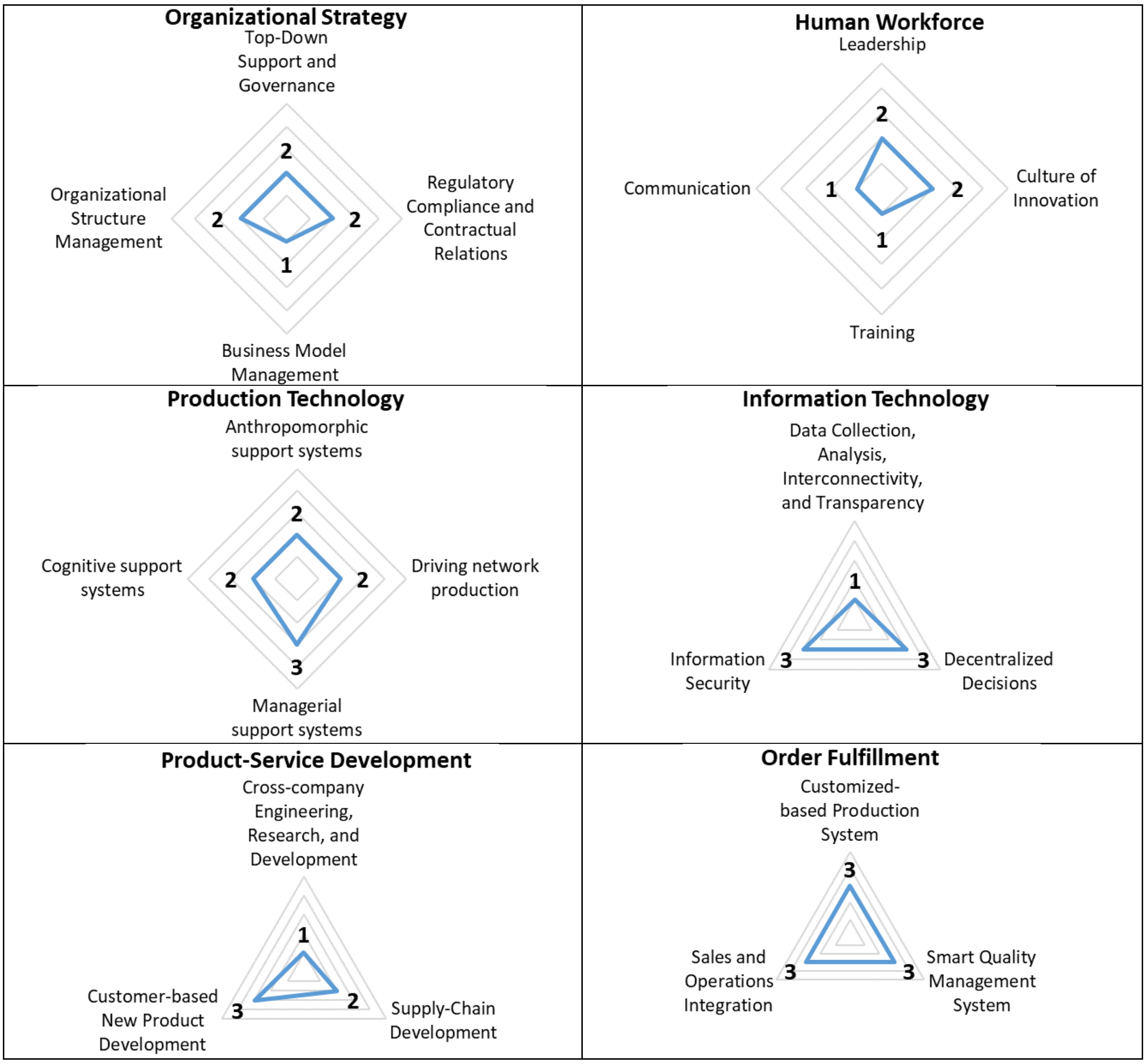


Figure 26: Scores for each Element – Step 2 (Source: Author).

Whereas, although the basic elements concepts have not changed substantially, it was apparent that some scores have changed greatly from Version 1 to Version 2. One possibility was that, in the meeting held to complete this questionnaire during Step 2, much focused on the methodology for calculating the vector “R”, highlighting that if any element had a score of 0, the entire dimension would receive this same score. What helped explain this conclusion was the fact that, in this Version 2, no element received a score of 0 from respondents. Therefore, in the following completion meetings (steps 3 and 4), no detail was given about this calculation methodology, just so as not to influence the respondents.

It was possible to again revise the wording, format, content, sequence, layout, simplicity, and clarity of the survey instrument. Therefore, the following improvements were made to the questionnaire (see Table 6).

Table 6 - Questionnaire improvements after “Company A” feedback – Step 2 (Source: Author).

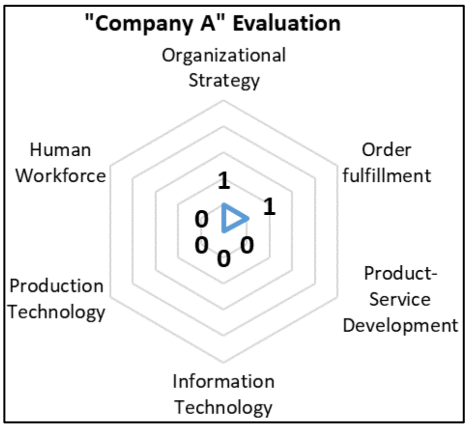
Section/ Question	QUESTIONNAIRE (Version 2)	QUESTIONNAIRE (Version 3)	JUSTIFICATION
GENERAL INFORMATION	In the first meeting (Launching step), focus on the vector calculation methodology	In the first meeting (Launching step), does not focus on the vector calculation methodology and focuses on the CUBE-4.0 dimensions	Not to influence the respondents about the possibility to have a score of 0 for the vector’s dimensions
GENERAL INFORMATION	With background music, while respondents answer the group survey	Take away background music while respondents answer the group survey	Because it was attracting the participants’ concentration and discussion
GENERAL INFORMATION	Excessively long and tiring answers	Shorter, objective, and with standardized answers	To facilitate respondent’s understanding and answering
GENERAL INFORMATION	Respondents can be from any hierarchical level in the company	Respondents must be the leaders or managers of the analyzed processes	Because this type of questionnaire is very specific and not all employees would easily fill it

As feedback from the “Company A”, the questionnaire was better than the Version 1, but still not as effective, because “the questionnaire could not be applied at the operational level, as it requires a certain analysis of the company's scenario as a whole”.

However, “Company A” was able to have some insights from the questionnaire, especially about the need to “invest in training, integrated information, data systems, and the R&D area”.

Step 3 (CUBE-4.0 Questionnaire Version 3): These results and improvement suggestions from "Company A" were analyzed and the CUBE-4.0 Questionnaire was reviewed again, generating a Version 3, which was applied again in the same company. This interview was conducted on 07/29/2022, with the Project Coordinator of Processes and Improvements, whose result was satisfactory and was also summarized in this topic.

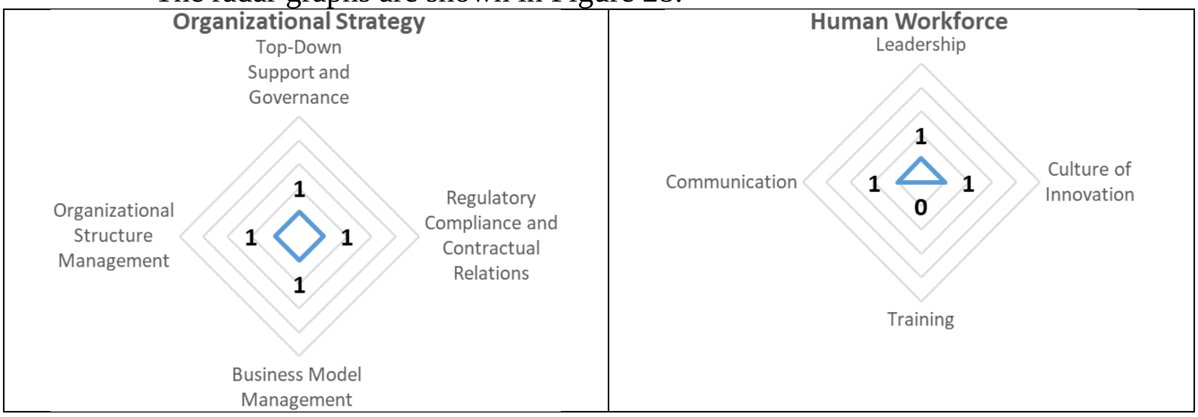
It should be noted in Figure 27 that "Company A" in the third step, unlike Version 1 and 2, had zero score for almost all results, excluding Organizational Strategy (Level 1) and Order Fulfillment (Level 1), generating a vector R=(0, 0, 0) and presenting all sub-dimensions with a lower score than Version 2.



STEP 3			
ORGANIZATIONAL ENABLER	Organizational Strategy	1	**0**
	Human Workforce	0	
TECHNOLOGICAL ENABLER	Production Technology	0	**0**
	Information Technology	0	
PROCESS MATURITY	Product-Service Development	0	**0**
	Order Fulfillment	1	
READINESS (0, 0, 0)			

Figure 27: "Company A" Results – Step 3 (Source: Author).

The radar graphs are shown in Figure 28:



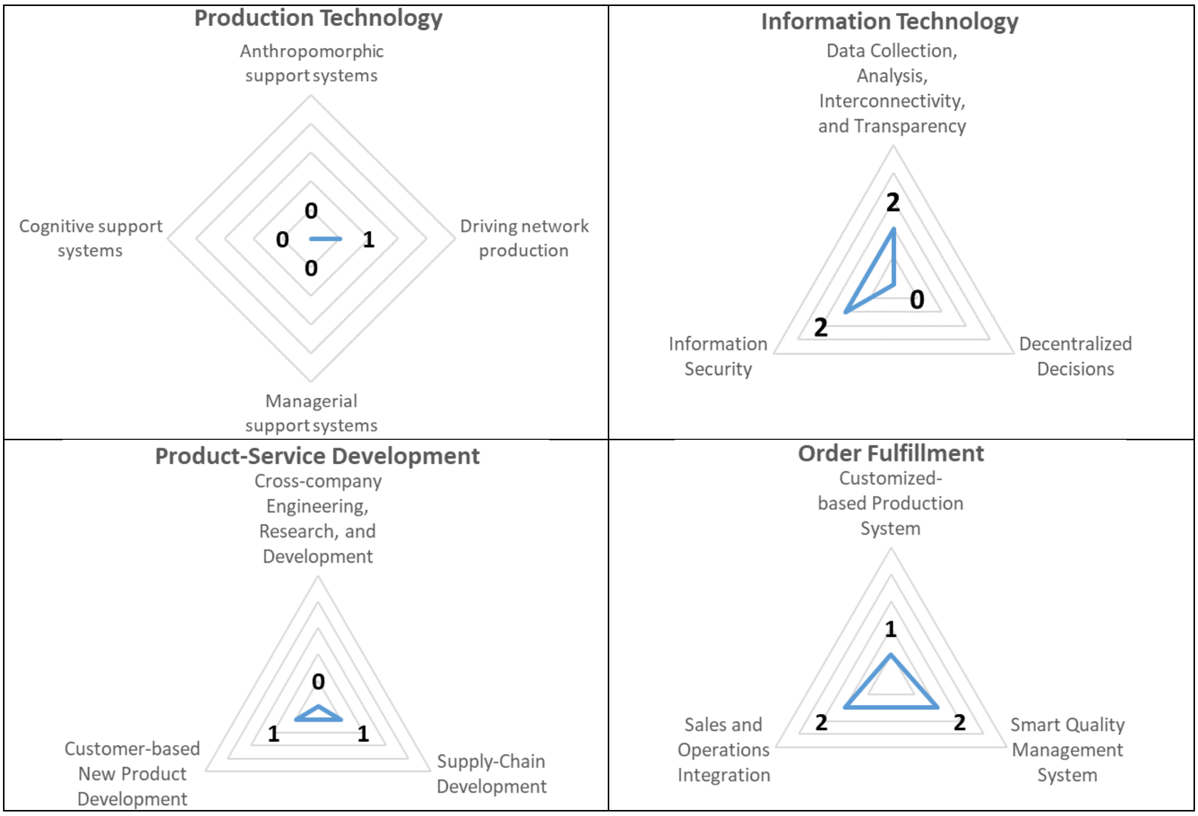


Figure 28: Scores for each Element – Step 3 (Source: Author).

The main hypothesis is justified by the fact that the Version 3 questionnaire was filled out by only one person from "Company A" - who had a judicious, perfectionist, and conservative profile, besides not having enough technical knowledge for all the questions. This reinforces the need for more than one respondent per company, in order to avoid bias and subjectivity.

It was possible to revise again the wording, format, content, sequence, layout, simplicity, and clarity of the survey instrument. Then, the following 10 improvements were made to the questionnaire (see Table 7).

Table 7 - Questionnaire improvements after "Company A" feedback – Step 3 (Source: Author).

Section/ Question	QUESTIONNAIRE (Version 3)	QUESTIONNAIRE (Version 4)	JUSTIFICATION
GENERAL SUGGESTION	---	Avoid one questionnaire per person and maintain one questionnaire per company (answered as a team)	To ensure reliability and avoid answering without technical knowledge
GENERAL SUGGESTION	Select respondents randomly from the company	Select respondents to have at least one representative (manager, if possible) from each macro-process in the company: **Organizational** [Management / Human	To ensure that all questions are answered reliably and with technical quality

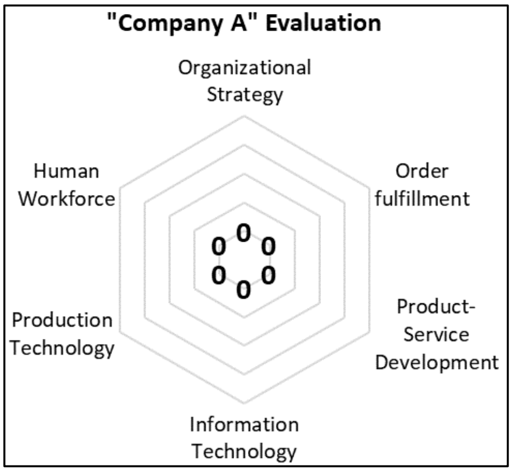
		Resources], **Technological** [IT / Production Technologies], and **Operational** processes [Engineering / R&D / Supply-chain / Production / Sales]. And add this explanation to the questionnaire introduction	
GENERAL SUGGESTION	---	Divide the questionnaire into sections, detailing for each one, what macro-process (dimension) it refers to	To help the respondent better understand the scope of the questions
GENERAL SUGGESTION	---	Write in the questionnaire introduction that: "If you work for a group of several companies, here you should fill in only one data that you intend to implement I4.0. If the goal is to deploy I4.0 in all companies in the group, you must select the one in the most incipient stage or make an average among the readiness of all units"	So that the questionnaire actually makes sense and helps the company make effective internal management decisions
GENERAL SUGGESTION	---	Always make a prior meeting (Launching step)	To optimize research understanding, participation and results
FOR EVERY QUESTION	**Level 0:** "My company still considers the implementation of I4.0 unnecessary."	**Level 0:** "My company values I4.0 but doesn't know how to implement it."	Because if the company is filling out a questionnaire regarding its readiness for DT, this obviously means that the company is interested in the subject and wants to perform a digital transformation. For example, the way the answer was given, the company might be forced to select the answer for Level 1, while in fact, it is still at Level 0
FOR EVERY QUESTION	---	Insert the option ( ) Do not know, as the last answer for each question	So that the respondent is not obliged to answer questions about which he has no knowledge and/or is not able to answer
INITIAL INFORMATION	---	Insert introduction before each section	To better separate the sections and set the respondent with the main concepts related to digital transformation
FOR EVERY QUESTION	---	Insert examples and better explain each question	Making them clearer and more objective, to help the respondent better understand the question and its answers, guiding and conceptually defining the specific focus of each of them
FOR EVERY QUESTION	---	Return with level "Takes random and incipient initiatives", but with a new name: EXPERIMENTED	Due to the importance of this level and the fact that many companies currently have exactly this level of readiness. Regarding the name changed to EXPERIMENTED, it occurred to meet the concept of I4.0, as explained later

As feedback from the “Company A”, it did not find it difficult to answer the questionnaire and felt the same pace (same kind of answers) in 80% of the questions, which it considered good and effective, besides helping in the process. “Company A” reported the improvements in the process, besides presenting an improvement in the organization’s reading and understanding, resulting in a less tiring questionnaire.

However, “Company A” confided that this low vector score can demotivate teams and generate doubts about the model’s reliability and its implementation by the company.

Step 4 (CUBE-4.0 Questionnaire Version 4): These results and improvement suggestions from “Company A” were analyzed and the CUBE-4.0 Questionnaire was reviewed again, generating a Version 4, which was applied again in the same company. This interview was held on 08/05/2022, with the head of the Rolled Steel Department, the head of the Production Department, and the Project Coordinator of Processes and Improvements, whose result was satisfactory and was also summarized in this topic.

It should be noted in Figure 29 that the “Company A” score in the fourth step, was even worst than in Version 3 and had a zero score for all the results, generating a vector R= (0, 0, 0) and presenting all sub-dimensions with a lower score than all the other versions.



STEP 4

ORGANIZATIONAL ENABLER	Organizational Strategy	0	**0**
	Human Workforce	0	
TECHNOLOGICAL ENABLER	Production Technology	0	**0**
	Information Technology	0	
PROCESS MATURITY	Product-Service Development	0	**0**
	Order Fulfillment	0	
READINESS (0, 0, 0)			

Figure 29: “Company A” Results – Step 4 (Source: Author).

The radar graph is shown in Figure 30:

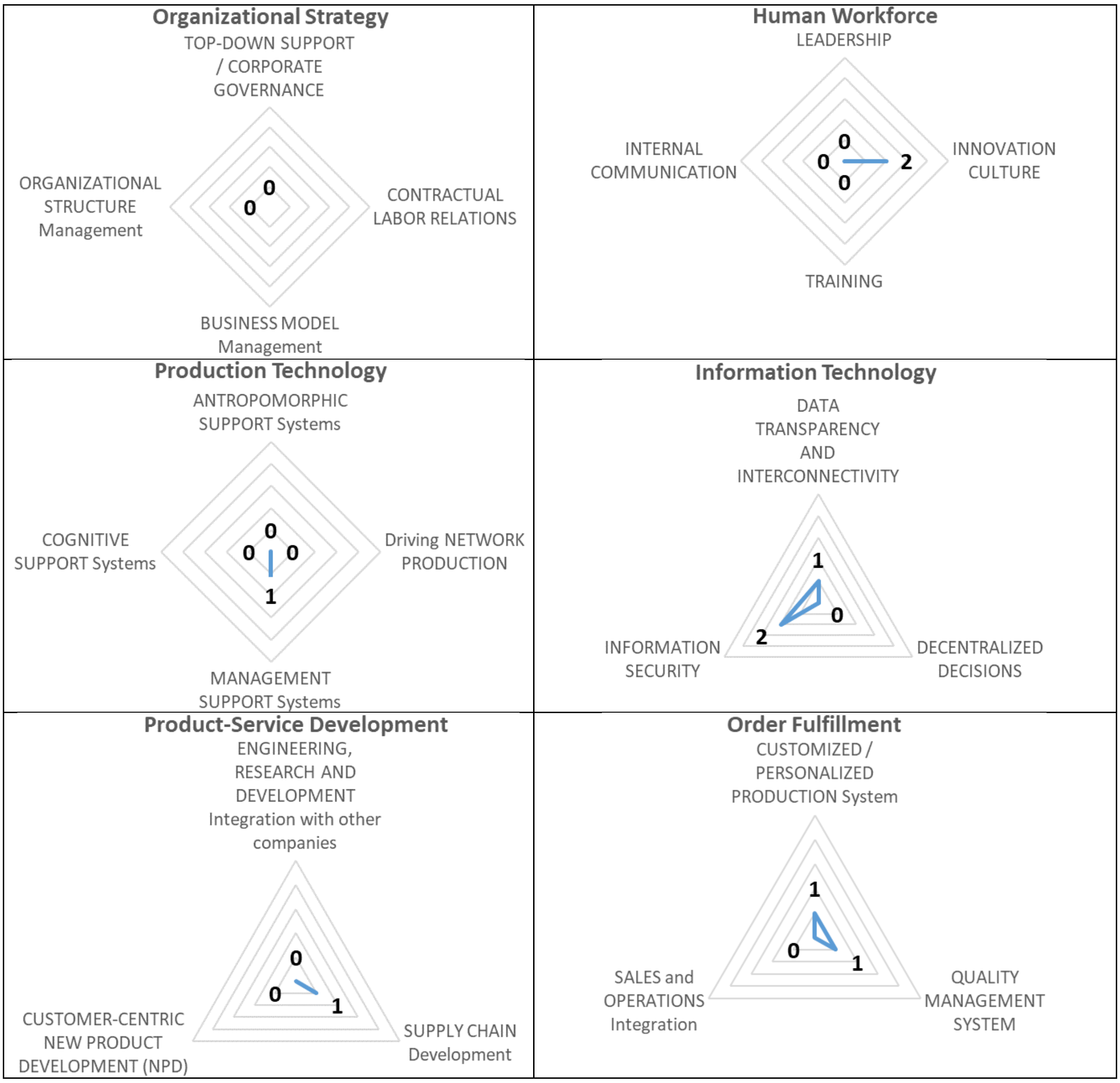


Figure 30: Scores for each Element – Step 4 (Source: Author).

In this step, two problems were observed, which were not repeated during the Model application (described in Chapter 5).

The first, was to consider a few interviewees from the company. In this case, besides being an engineer with a detailed and conservative profile, he confessed that in some cases he gave a dubious answer, because he did not have enough technical knowledge. The second, was the possibility of the answer “Do not know”, which impaired the tabulation, specially the organizational strategy sub-dimension, hindering the results analysis. Therefore, this option was again removed from the questionnaire (see Table 8).

Table 8 - Questionnaire improvements after “Company A” feedback – Step 4 (Source: Author).

Section/ Question	QUESTIONNAIRE (Version 4)	QUESTIONNAIRE (Version 5)	JUSTIFICATION
FOR EVERY QUESTION	( ) Do not know	Remove this multiple-choice option	Not impairing the results analysis
COMPANY SIZE	( ) 1 to 5 employees ( ) From 6 to 10 employees ( ) From 11 to 49 employees ( ) From 50 to 249 employees ( ) More than 250 employees	( ) 1 to 5 employees ( ) From 6 to 19 employees ( ) From 20 to 99 employees ( ) From 100 to 499 employees ( ) More than 500 employees	To follow the guidance of ANVISA, BNDES, and IBGE on industries classification by a number of employees

These results and improvement suggestions from “Company A” were analyzed and the CUBE-4.0 Questionnaire was reviewed again, generating a Version 5, which was used for the next validation steps.

As feedback, “Company A” reported that after the rectifications, the questionnaire became more effective and easier to fill out, besides reporting some insights that occurred during the process, such as: “hire a person exclusively for this [digital transformation] and not divert it to other activities” and that “the world full of technology needs an increasingly qualified team for cybersecurity”.

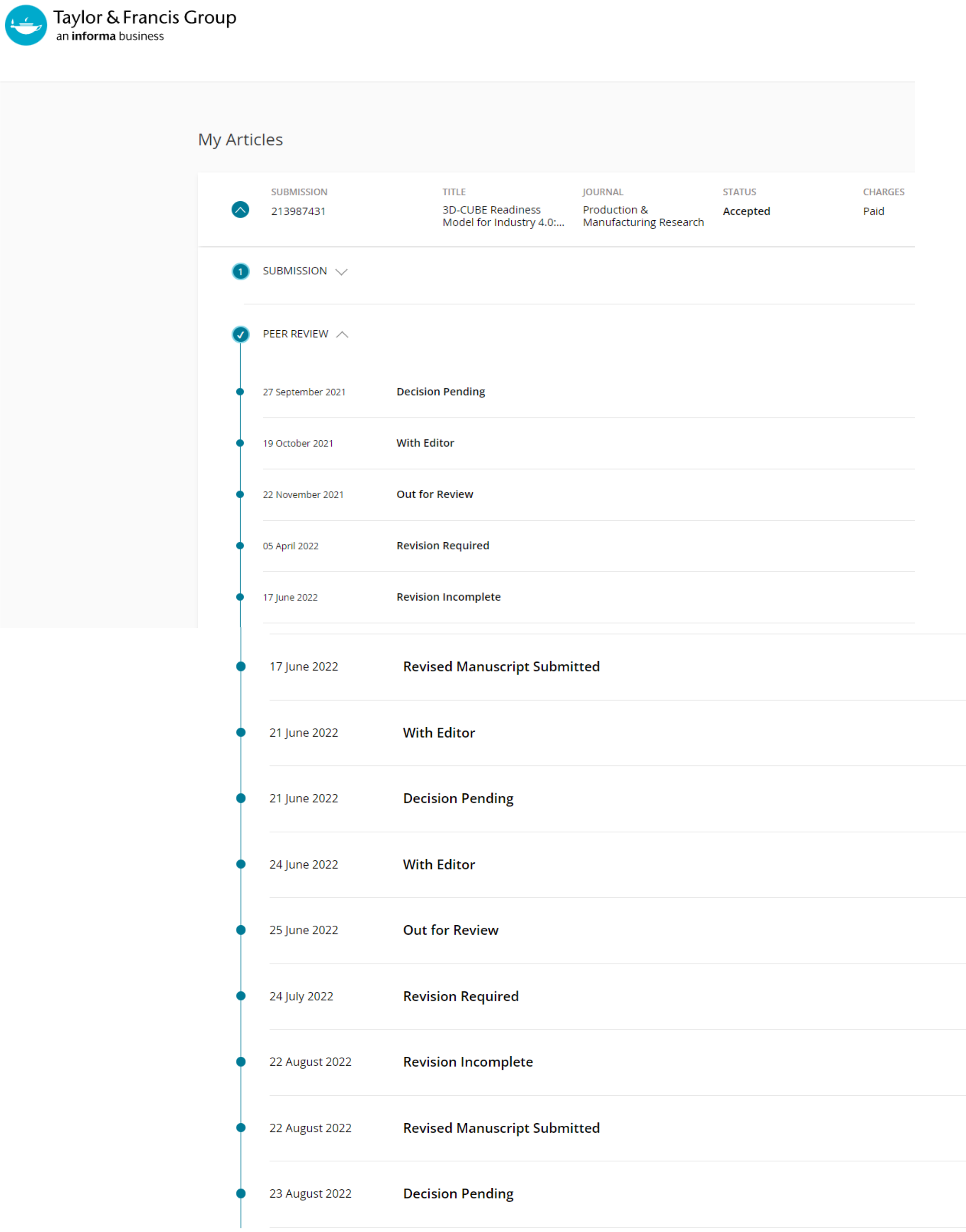
However, at this point, there was found a problem: the CUBE-4.0 Model was satisfactory but with a low final vector score. Then, it was realized that the solution was to modify the approach for presenting the results to the company, and no longer change the structure of the Model. This idea came up during a meeting with the board examiners of this research. Then, this solution was ratified on the pretest 5 (see item 4.5.5) and detailed in topic 5.5.3.2.

4.5.4 Publication in an A1 Journal

The CUBE-4.0 article was accepted on October 6^{th}, 2022, by the “Production & Manufacturing Research” Journal, by Taylor and Francis Group.

Publishing the paper “3D-CUBE Readiness Model for Industry 4.0: technological, organizational and process maturity enablers” in this Journal, was crucial for the CUBE-4.0

development. The first article's version was submitted to this Journal on September 27th, 2021, followed by four required revisions (see Figure 31).


Taylor & Francis Group
an informa business

My Articles

SUBMISSION	TITLE	JOURNAL	STATUS	CHARGES
213987431	3D-CUBE Readiness Model for Industry 4.0:...	Production & Manufacturing Research	Accepted	Paid

SUBMISSION

PEER REVIEW

27 September 2021	Decision Pending
19 October 2021	With Editor
22 November 2021	Out for Review
05 April 2022	Revision Required
17 June 2022	Revision Incomplete
17 June 2022	Revised Manuscript Submitted
21 June 2022	With Editor
21 June 2022	Decision Pending
24 June 2022	With Editor
25 June 2022	Out for Review
24 July 2022	Revision Required
22 August 2022	Revision Incomplete
22 August 2022	Revised Manuscript Submitted
23 August 2022	Decision Pending

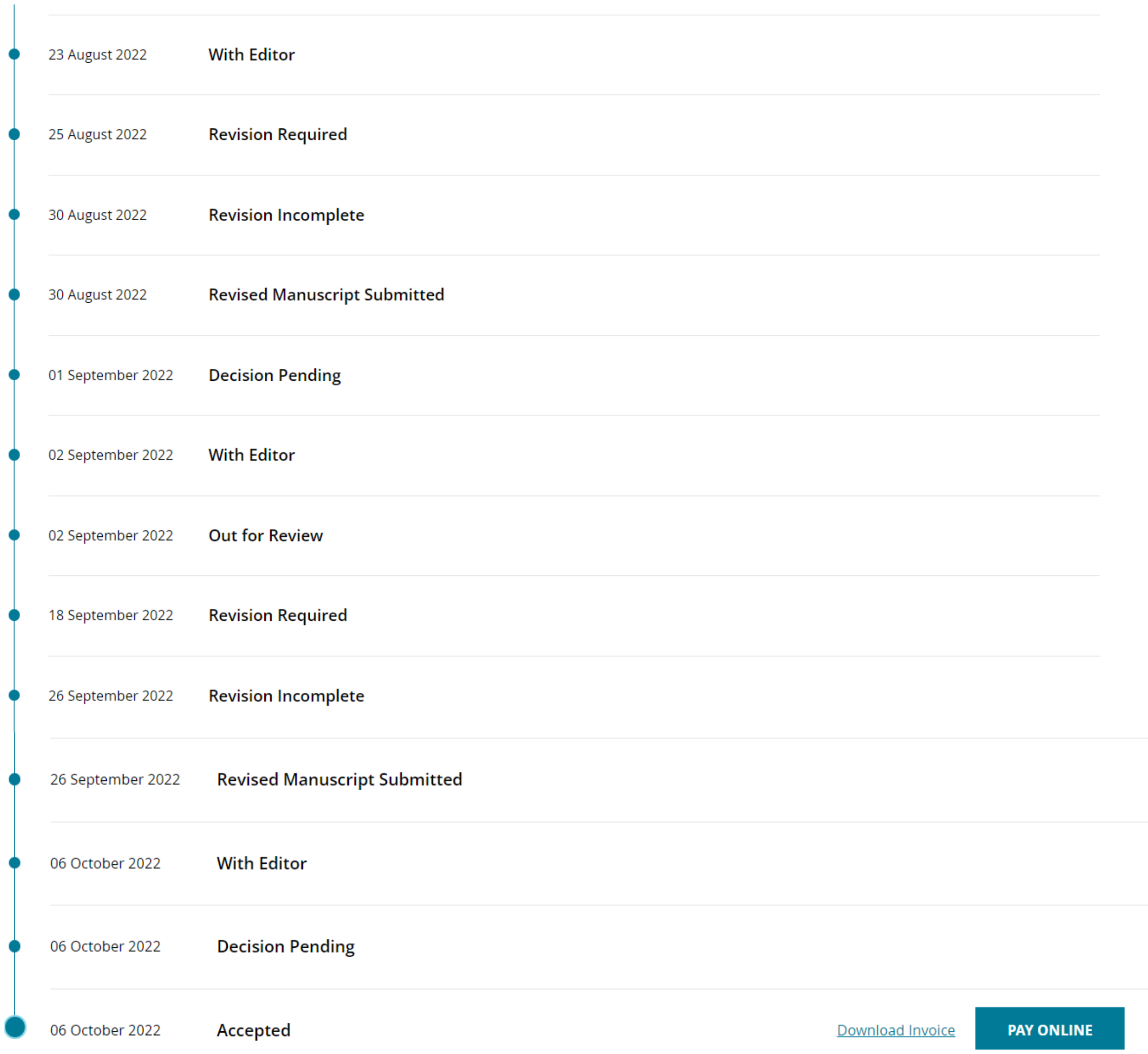


Figure 31: Acceptance of CUBE-4.0 by Production & Manufacturing Research Journal (Source: Taylor and Francis Online).

In the publication process in this prestigious Journal, 52 suggestions for improvement were made by its editor and reviewers, contributing greatly to the maturation of the CUBE-4.0 Model. The main contributions are shown in Table 9:

Table 9 – Main suggestions for CUBE-4.0 from Taylor & Francis Editors and Reviewers (Source: Author).

Comments from Editors and Reviewers:	**Changes made in CUBE-4.0 Model:**
"Concerning the methodology; why the authors chose a bibliometric analysis approach instead of a systematic literature review? Bibliometric analysis seems a bit odd, as the authors have not analyzed their findings from this perspective; where the authors come from, what institutes they represent and so… Instead, the analysis is more a literature review stylish."	The review of the literature was done using a **systematic bibliographic review**, including searching on ten databases, based on PRISMA concepts [157].
"Again, reasoning missing, why M, T, and O and where do the Dimensions come from?"	Ok, these "M", "T", and "O" axes were replaced for **(X, Y, Z)**, and the dimensions' source was explained.

"Important aspects like Human factors, Safety, and Ergonomics are missing in the model. I would propose the authors to familiarize themselves for instance with publications by Patrick W. Neumann or Adel Badri in this matter (and just to make sure, I'm not any of those, nor I do not belong to their research groups)".	Ok, **human factors, safety, and ergonomics were included (as a sub-dimension)** in the Model, especially with Patrick W. Neumann [149] and Adel Badri [148] contributions.
"Your manuscript is much better now."	"Thank you very much for your professional job and support. The reviewers that you assigned to our article really contributed to our results. Their suggestions, and your comments as editor, really help us to improve our own research. Thank you".

Therefore, according to the table above, it was noticed that the main contribution of this Journal was to alert us about the need to add more elements aimed at the human factor, giving further solidity to CUBE-4.0.

4.5.5 Validation of CUBE-4.0 Questionnaire and Roadmap with a recognized international I4.0 consultancy

In a meeting held on October/2022, this recognized international consulting firm on I4.0 analyzed the CUBE-4.0 Model and offered a robust selection of information about DT. The main contributions were as follows:

- clarified, with scientific arguments, fundamental concepts about the difference between "I4.0", "Digital Transformation" and "4th Industrial Revolution", which are still very confused worldwide;
- enjoyed the model and congratulated for efficiency, systematic bibliographic review, and credibility;
- agreed with the three selected dimensions and correlated them with concepts widely used in his consulting practice: "back office" (CUBE-4.0 technological enabler), "meddle office" (CUBE-4.0 organizational enabler), and "front office" (CUBE-4.0 process maturity enabler);
- congratulated readiness level being dimensioned by a three-dimensional vector, confirming that it makes a lot of sense, which helps the company to

understand its opportunities for improvement, and that he never had seen such a methodology;

- found the CUBE-4.0 explanation of the difference between "maturity" and "readiness" to be fanciful, and stated that from that moment on, he would only use the more appropriate terminology: "readiness", ratifying the CUBE-4.0 concepts; and
- reported that today, in the world, most companies are still in Industry 3.0. Therefore, CUBE-4.0 should create some mechanism when presenting the roadmap so that companies do not be discouraged in the DT process due to low scores.

This last feedback was the most important and generated a change in the vector score calculation, which will be detailed in topic 5.5.3.2.

At the end of the interview, he asked to follow closely this CUBE-4.0 project, because he said he was sure that it will contribute greatly to the DT of industries worldwide.

4.5.6 Presenting the CUBE-4.0 Readiness Model in an International Workshop

During this workshop in Costa Rica (see Figure 32), on 15th and 16th November 2022, it was possible to disclose the CUBE-4.0 Model to more than 100 people linked to the logistics and transportation industry, representing 14 countries (Argentina, Brazil, Canada, Colombia, Costa Rica, El Salvador, Ecuador, Guatemala, Mexico, Nicaragua, Panama, Peru, Uruguay, and Venezuela), who really appreciated the project and asked to have access to this thesis.

Figure 32: Presentation of the CUBE-4.0 Model for the International Transportation Industry Chamber members – CIT (Source: CIT Online).

It can be concluded that these six development steps were satisfactory and important for this study. All the justifications detailed in Chapter 4 help to conclude the CUBE-4.0 necessity and importance, as a new proposed readiness model to assess the engineering companies' status about DT.

Then, after performing all the small adjustments from steps 4.5.4, 4.5.5, and 4.5.6, the CUBE-4.0 Questionnaire (Final Version) was pre-validated, which focuses on the departments managers and has 21 questions, one for each CUBE-4.0 element. It can be evaluated in its entirety in Appendix C.

Also, the CUBE-4.0 Roadmap (Final Version) was pre-validated and can be seen in Appendix D.

Therefore, this final CUBE-4.0 Model was applied in three engineering companies (see Chapter 5).

5. CUBE-4.0 Validation

The CUBE-4.0 validation in this thesis was based on the case study method, which was developed with three engineering companies, called “A”, “B” and “C”, respectively. Even, “Company C” is a famous multinational, which signed a non-disclosure agreement with this CUBE-4.0 project.

5.1 Small/Medium Enterprise (“Company A” - 187 employees)

This interview with “Company A” was conducted on 09/19/2022 (4:00 to 4:46 pm) and the CUBE-4.0 Questionnaire (Final Version) was answered by the head of the Production Department, Project Coordinator of Processes and Improvements, Supply Manager, Buyer, Quality Technician, Quality Supervisor, Controller (IT), IT Supervisor, and Human Factor Analyst, the result of which was satisfactory and is summarized below.

The questionnaire results were verified in loco by face-to-face evidence and observation (technical visit by sampling), generating reliability to the process and the CUBE-4.0 methodology (see Figure 33).

Figure 33: In-person interview at “Company A” (Source: Author).

It is important to highlight that the respondents completed the questionnaire considering the entire company (187 employees).

The main results can be seen in the Roadmap “A” below (see Figure 34).

CUBE-4.0 ROADMAP: "Company A"

HOW TO IMPROVE THE READINESS OF YOUR COMPANY THROUGH THE DIGITAL TRANSFORMATION CONTEXT?

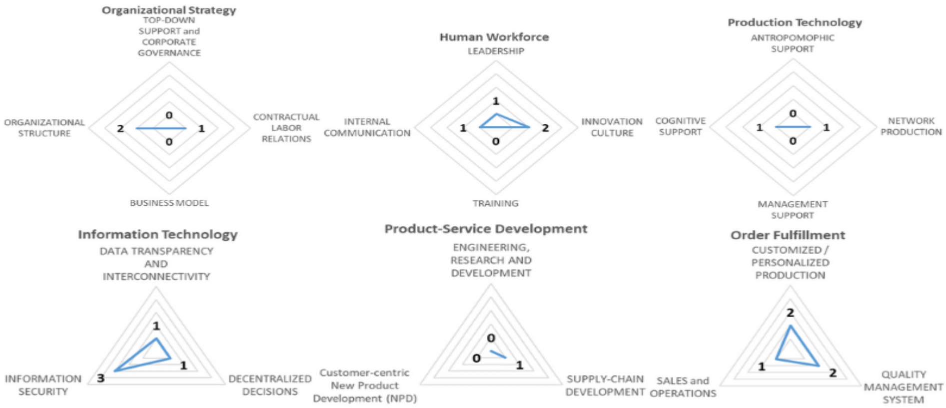
1. FILLING IN "CUBE-4.0 QUESTIONNAIRE":

On 19th September 2022, the questionnaire was filled in by the head of the Production Department, Project Coordinator (Processes and Improvements), Supply Manager, Buyer, Quality Technician, Quality Supervisor, Controller (IT), IT Supervisor, and Human Factor Analyst.

2. ANALYZING THE QUESTIONNAIRE'S RESULTS:

		Value min	Value max	Vector Rmin	Vector Rmax
ORGANIZATIONAL ENABLER	Organizational Strategy	0	2	0	2
	Human Workforce	0	2		
TECHNOLOGICAL ENABLER	Production Technology	0	1	0	3
	Information Technology	1	3		
PROCESS MATURITY	Product-Service	0	1	0	2
	Order Fulfillment	1	2		

READINESS$_{MAX}$ is R = (2,3,2)
"Company A" reaches Level: 3



3. RECOMMENDATIONS FOR ELEMENTS WITH SCORE < 3:

CUBE-4.0 ELEMENTS (< 3)	GENERAL RECOMMENDATIONS FOR "COMPANY A" IN THE NEXT 6 MONTHS
TOP-DOWN SUPPORT and CORPORATE GOVERNANCE	Top management takes random and incipient initiatives.
ORGANIZATIONAL STRUCTURE	Complete the deployment in a unified, company-wide manner and monitor it.
BUSINESS MODEL	Take random and incipient initiatives.
CONTRACTUAL LABOR RELATIONS [with the workforce]	Establish planning and begin to implement individual solutions for just a few processes.
LEADERSHIP	Establish planning and start preparing the leadership for just a few processes.
INTERNAL COMMUNICATION	Establish planning and start to implement individual solutions for just a few processes.
TRAINING	Take random and incipient initiatives.
INNOVATION CULTURE	Complete the implementation in a unified manner throughout the company and monitor it.
ANTROPOMORPHIC SUPPORT	Take random and incipient initiatives.
COGNITIVE SUPPORT	Establish planning and start to implement them.
MANAGEMENT SUPPORT	Take random and incipient initiatives.
NETWORK PRODUCTION	Establish planning and start deploying individual solutions for only a few processes.
DATA TRANSPARENCY AND INTERCONNECTIVITY	Interconnect data using I4.0 technologies, only within each department.
DECENTRALIZED DECISIONS	Establish plans and begin to implement them for only a few processes.
ENGINEERING, RESEARCH AND DEVELOPMENT	Take random and incipient initiatives.
CUSTOMER-CENTRIC NEW PRODUCT DEVELOPMENT (NPD)	Take random and incipient initiatives.
SUPPLY-CHAIN DEVELOPMENT	Enable some sectors of the supply chain to supply on demand.
CUSTOMIZED / PERSONALIZED PRODUCTION	Set up the entire production system (such as machining, assembly, warehousing, picking, and/or transportation) for "single lot" but still without data-driven optimization.
SALES and OPERATIONS	Establish planning and start to implement this integration for only a few operations.
QUALITY MANAGEMENT SYSTEM	Complete implementation in a unified manner for all after-sales services, and monitor.

4. FILLING IN "CUBE-4.0 QUESTIONNAIRE" AGAIN:

The expected date for filling in "CUBE-4.0 Questionnaire" again and compare the results is 19th March 2023.

References

PhD Tesis: PROPOSAL OF THE CUBE-4.0 READINESS MODEL FOR ENGINEERING COMPANIES THROUGH DIGITAL TRANSFORMATION CONTEXT

ANY QUESTIONS, PLEASE CONTACT:
brunafelippes@gmail.com

Figure 34: Roadmap for "Company A" (Source: Author).

It should be noted in Figure 34 that “Company A” had the best results in technological enabler ($Level_{max}$ 3), in comparison with organizational ($Level_{max}$ 2) and process maturity ($Level_{max}$ 2) criteria.

It is possible to realize that, according to the CUBE-4.0 methodology, this company would have its vector R=(0, 0, 0) – Level 0, that is, for the three dimensions there are elements for which the “Company A” still did not know how to implement I4.0, such as top-down support and corporate governance, business model, training, anthropomorphic support, management support, engineering, research and development, and Customer-Centric New Product Development (NPD).

On the other hand, there were elements whose level of readiness allowed the company to reach the R=(2, 3, 2) – Level 3, such as organizational structure, innovation culture, information security, customized/personalized production, and quality management system.

The element with the highest level of readiness (3) was information security, with all others needing improvement actions to balance the “Company A” level of readiness.

About Organizational Strategy, it was recommended to start assessing the possibility of top-down governance to invest more in the companies’ DT, besides investing in the development of new business model strategies.

Regarding Human Workforce, it was recommended to start reviewing its plans, strategies, and resources for training employees.

About Production Technology (which has the lowest readiness), it was advised some investments in anthropomorphic (as Robots in the production line) and management (as Big Data) supports, and then in cognitive support (as Artificial Intelligence) and network production (as Additive Manufacturing).

Regarding Information Technology, although the company presented good information security, it was recommended that the information transparency and interconnectivity tools be optimized, as well as the decision-making practices in a more decentralized way (i.e., with decision-making tools).

About Product-Service Development (which also has the lowest readiness), it is expected that the company can start investing more in engineering, research, and development integration with partner companies and in Customer-Centric New Product Development (NPD) strategies, and then in supply-chain integration.

Regarding Order Fulfillment, although the company has better readiness about customized/personalized production and quality management system, it is expected that the company can start investing more in sales and operations integration.

After answering the CUBE-4.0 Questionnaire, the "Company A" had the following feedbacks:

- they were motivated due to the scope of the questions and its applicability to their company;
- during the meeting to answer the questionnaire, they had insights (such as: in the training area, they were already able to implement certain improvements);
- only felt easy to fill out the questionnaire because there were representatives from various departments, specially managers. If it was supported individually, they would certainly have doubts and might respond inappropriately, damaging the final results. They suggested keep using this methodology to involve several departments in completing the questionnaire;

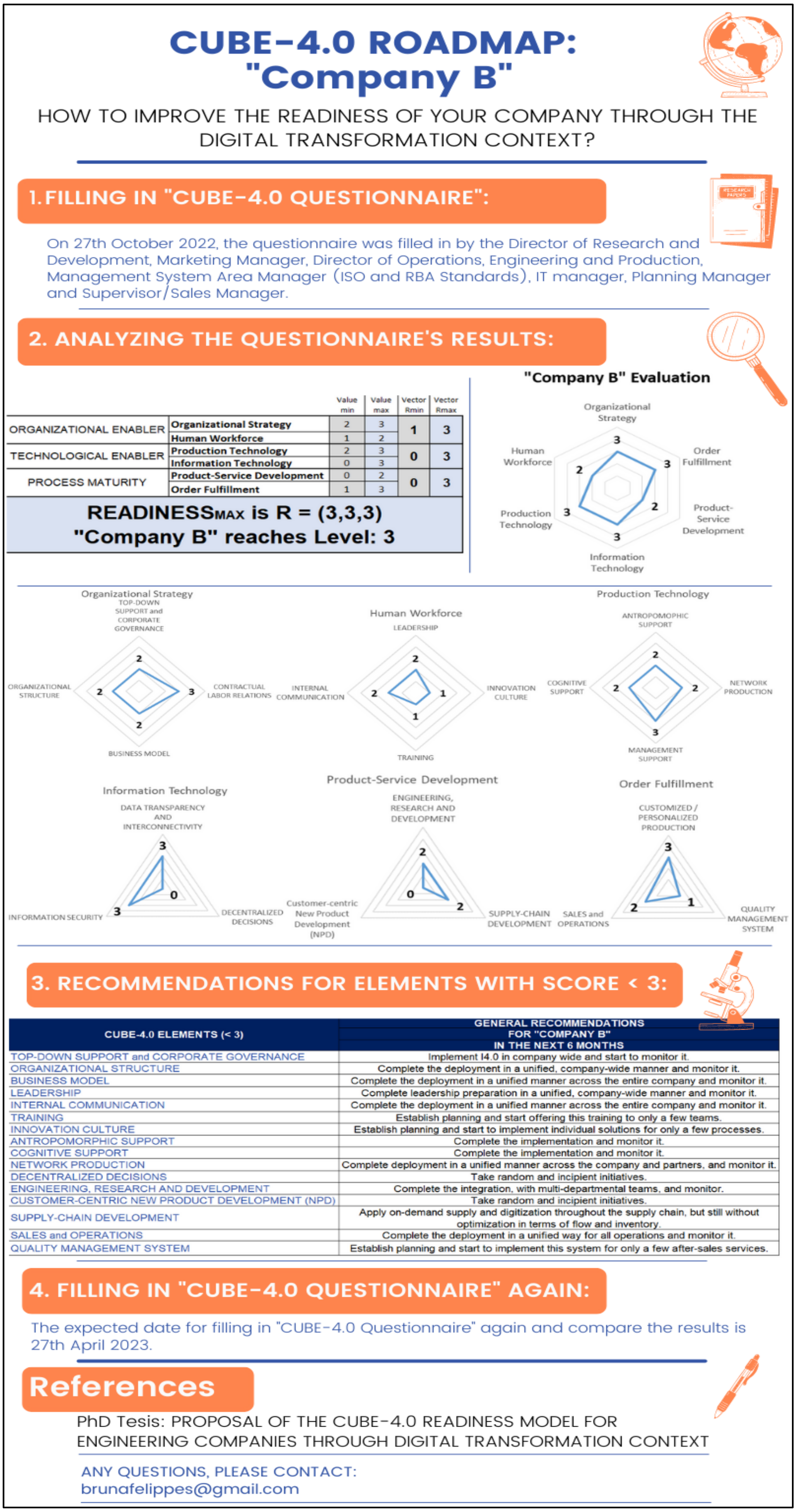
- they liked the questionnaire and the methodology of application in the company: easy and quickly; and
- this CUBE-4.0 Model presented a great opportunity to share information about I4.0 between the company's departments and teams.

5.2 Medium Enterprise ("Company B" - 440 employees)

This interview with "Company B" was conducted on 10/27/2022 (4:00 to 4:41 pm) and the CUBE-4.0 Questionnaire (Final Version) was answered by the Director of Research and Development, Marketing Manager, Director of Operations, Engineering and Production, Management System Area Manager (ISO and RBA Standards), IT Manager, Planning Manager and Supervisor/Sales Manager, the result of which was satisfactory and is summarized below.

Although "Company B" had several units, the focus of this research was only one of them, located in São Paulo/Brazil (440 employees).

The main results can be seen in the Roadmap "B" below (see Figure 35).



CUBE-4.0 ROADMAP: "Company B"

HOW TO IMPROVE THE READINESS OF YOUR COMPANY THROUGH THE DIGITAL TRANSFORMATION CONTEXT?

1. FILLING IN "CUBE-4.0 QUESTIONNAIRE":

On 27th October 2022, the questionnaire was filled in by the Director of Research and Development, Marketing Manager, Director of Operations, Engineering and Production, Management System Area Manager (ISO and RBA Standards), IT manager, Planning Manager and Supervisor/Sales Manager.

2. ANALYZING THE QUESTIONNAIRE'S RESULTS:

		Value min	Value max	Vector Rmin	Vector Rmax
ORGANIZATIONAL ENABLER	Organizational Strategy	2	3	1	3
	Human Workforce	1	2		
TECHNOLOGICAL ENABLER	Production Technology	2	3	0	3
	Information Technology	0	3		
PROCESS MATURITY	Product-Service Development	0	2	0	3
	Order Fulfillment	1	3		

READINESS$_{MAX}$ is R = (3,3,3)
"Company B" reaches Level: 3

3. RECOMMENDATIONS FOR ELEMENTS WITH SCORE < 3:

CUBE-4.0 ELEMENTS (< 3)	GENERAL RECOMMENDATIONS FOR "COMPANY B" IN THE NEXT 6 MONTHS
TOP-DOWN SUPPORT and CORPORATE GOVERNANCE	Implement I4.0 in company wide and start to monitor it.
ORGANIZATIONAL STRUCTURE	Complete the deployment in a unified, company-wide manner and monitor it.
BUSINESS MODEL	Complete the deployment in a unified manner across the entire company and monitor it.
LEADERSHIP	Complete leadership preparation in a unified, company-wide manner and monitor it.
INTERNAL COMMUNICATION	Complete the deployment in a unified manner across the entire company and monitor it.
TRAINING	Establish planning and start offering this training to only a few teams.
INNOVATION CULTURE	Establish planning and start to implement individual solutions for only a few processes.
ANTROPOMORPHIC SUPPORT	Complete the implementation and monitor it.
COGNITIVE SUPPORT	Complete the implementation and monitor it.
NETWORK PRODUCTION	Complete deployment in a unified manner across the company and partners, and monitor it.
DECENTRALIZED DECISIONS	Take random and incipient initiatives.
ENGINEERING, RESEARCH AND DEVELOPMENT	Complete the integration, with multi-departmental teams, and monitor.
CUSTOMER-CENTRIC NEW PRODUCT DEVELOPMENT (NPD)	Take random and incipient initiatives.
SUPPLY-CHAIN DEVELOPMENT	Apply on-demand supply and digitization throughout the supply chain, but still without optimization in terms of flow and inventory.
SALES and OPERATIONS	Complete the deployment in a unified way for all operations and monitor it.
QUALITY MANAGEMENT SYSTEM	Establish planning and start to implement this system for only a few after-sales services.

4. FILLING IN "CUBE-4.0 QUESTIONNAIRE" AGAIN:

The expected date for filling in "CUBE-4.0 Questionnaire" again and compare the results is 27th April 2023.

References

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ANY QUESTIONS, PLEASE CONTACT:
brunafelippes@gmail.com

Figure 35: Roadmap for "Company B" (Source: Author).

It should be noted in Figure 35 that the “Company B” had the best results evenly among the organizational ($Level_{max}$ 3), technological ($Level_{max}$ 3), and process maturity ($Level_{max}$ 3) enablers, demonstrating a balance between the readiness of the three dimensions.

It is possible to realize that, according to the CUBE-4.0 methodology, this company would have its vector R=(1, 0, 0) – Level 0, that is, for the technological and process maturity dimensions there are elements for which “Company B” still did not know how to implement I4.0, such as in decentralized decisions and in Customer-Centric New Product Development (NPD).

On the other hand, there were elements whose level of readiness allowed the company to reach the R=(3, 3, 3) – Level 3, such as in contractual labor relations, management support, data transparency and interconnectivity, information security, and customized/ personalized production. All other elements needed improvement actions to balance the “Company B” level of readiness.

About Organizational Strategy, while it showed a good readiness for contractual working relationships, it was recommended to start evaluating the possibility of top-down governance to invest more in the company’s DT, besides investing in developing the organizational structure and new business model strategies.

Regarding Human Workforce, it was recommended to start reviewing its plans, strategies, and resources for employee training and promoting an innovation culture.

About Production Technology, although it showed a good readiness for management support, it was recommended some investments in anthropomorphic support (as Robots in the production line), cognitive support (as Artificial Intelligence), and network production (as Additive Manufacturing).

With respect to Information Technology (which had the lowest readiness), although the company presented good information security, transparency, and interconnectivity, it was recommended decision-making practices in a more decentralized way (i.e., with decision-making tools).

About Product-Service Development (that also had the lowest readiness), it was advised that the company start investing more in Customer-Centric New Product Development (NPD) strategies, and then in engineering, research and development, and in supply-chain integration.

Regarding Order Fulfillment, although the company has shown better readiness about customized/personalized production, it is expected that the company can start investing more in the quality management system, and then in sales and operations integration.

After answering the CUBE-4.0 Questionnaire, “Company B” had these feedbacks:

- they liked the questionnaire because it was short. They have already had the experience with large questionnaires with many questions and found them very poor, tiring, and not very effective;
- they really enjoyed the methodology of bringing people together in one room (even virtual) to respond to this questionnaire, because it allows feedbacks and provides time and space to level information between people from the same company. They also liked not including numerous respondents, because many employees had no idea what to answer, which could harm the results;
- they also praised the fact that we held a prior meeting with a “Company B” representative to explain the CUBE-4.0 methodology. And, only after this representative understood the process and selected the most appropriate respondents, it was scheduled a specific appointment just to answer the questionnaire. For “Company B”, this generates more reliable responses;
- they found the questionnaire excellent, which can be applied to any type of industry (including pharmaceutical, for example);

- said they were surprised by the questionnaire scope, as they thought that the focus of DT was, in fact, more linked to technological aspects. During the questionnaire completion, they realized that the organizational and process aspects are also important, agreeing with the CUBE-4.0 methodology;
- they were also positively surprised by the fact that the methodology considers the same level of importance and the same weight for the three dimensions, i.e., a cube with all sides of the same size. At that time, the importance of CUBE-4.0 being like this was explained by the interviewer, specially to avoid the formation of “performance islands”, as discussed in previous chapters;
- they were still attached to the old concept where the technological aspects should be the most important for I4.0. They also found it fantastic when we explained that one dimension standing out over the others may even help the company grow, but over time will not be able to maintain and progress on the DT path;
- they liked the fact that the questionnaire presented questions aligned to various departments, reinforcing the importance of maintaining this methodology to have several people from different departments answering the questionnaire at the same time;
- considering that the answers to the questions were very similar, they suggested improving the formatting to better separate them, preventing the respondents from getting confused. It was explained that this rhythm (repetition) in the answers was purposeful, to facilitate the process of completing the questionnaire, but its formatting would be improved soon;
- they realized that the completion of the questionnaire was an excellent opportunity. Not only for each one to contribute to the perception of their

respective area, but also to discover others' perceptions about their own department;

- they said that due to the excellent experience they had during the questionnaire, they were with high expectations regarding the Roadmap. They would even like to receive a detailed action plan (framework), including guidelines about how they can optimize their processes. It was even mentioned that they intend to define a specific team only to implement the improvements suggested by the CUBE-4.0 Model;
- during the meeting to answer the questionnaire, they had insights and realized that there are still many things that need to be implemented. Although the "Company B" had a more balanced score between dimensions, it wants to know what can be done to increase its readiness score in all 3 dimensions; and
- they asked to receive a copy of this final thesis.

5.3 Large Enterprise ("Company C" – more than 40,000 employees)

The interview with "Company C" was held on 10/27/2022 (2:00 to 2:49 pm) and the CUBE-4.0 Questionnaire (Final Version) was answered by the Manager of Technology Innovation Management, Head of the Institutional Relations Section, and Manager of Digital Solutions Development, whose result was satisfactory and is summarized below.

Respondents completed the questionnaire considering the almost 50 existing plants, in more than 10 countries, with more than 40,000 employees. Since there were units at different stages than others, they averaged to respond.

The main results can be seen in the Roadmap "C" thereafter (see Figure 36).

CUBE-4.0 ROADMAP: "Company C"

HOW TO IMPROVE THE READINESS OF YOUR COMPANY THROUGH THE DIGITAL TRANSFORMATION CONTEXT?

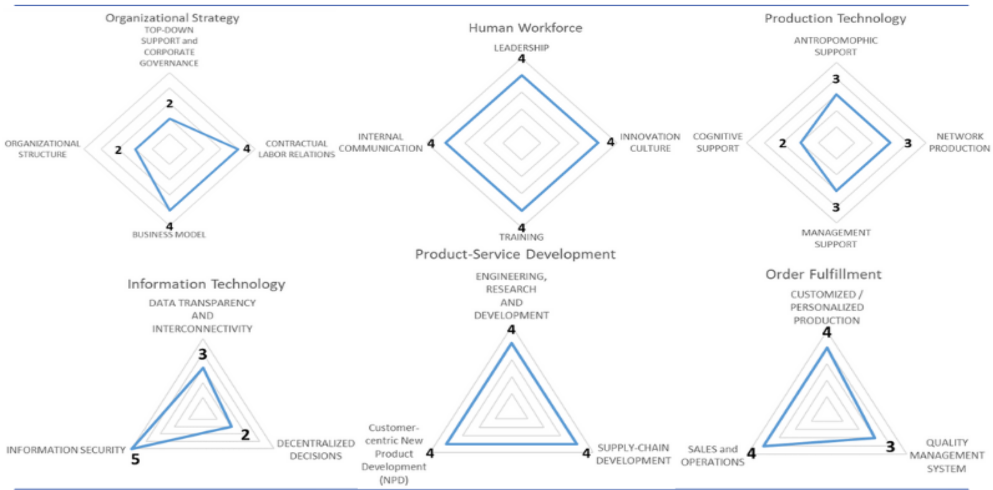
1. FILLING IN "CUBE-4.0 QUESTIONNAIRE":

On 27th October 2022, the questionnaire was filled in by the Manager of Technology Innovation Management, the Head of the Institutional Relations Section and the Development Manager of Digital Solutions.

2. ANALYZING THE QUESTIONNAIRE'S RESULTS:

		Value min	Value max	Vector Rmin	Vector Rmax
ORGANIZATIONAL ENABLER	Organizational Strategy	2	4	2	4
	Human Workforce	4	4		
TECHNOLOGICAL ENABLER	Production Technology	2	3	2	5
	Information Technology	2	5		
PROCESS MATURITY	Product-Service Development	4	4	3	4
	Order Fulfillment	3	4		

READINESS$_{MAX}$ is R = (4,5,4)
"Company C" reaches Level: 5



3. RECOMMENDATIONS FOR ELEMENTS WITH SCORE < 3:

CUBE-4.0 ELEMENTS (< 3)	GENERAL RECOMMENDATIONS FOR "COMPANY C" IN THE NEXT 6 MONTHS
TOP-DOWN SUPPORT and CORPORATE GOVERNANCE	Implement I4.0 in company wide and start to monitor it.
ORGANIZATIONAL STRUCTURE	Complete the deployment in a unified, company-wide manner and monitor it.
COGNITIVE SUPPORT	Complete the implementation and monitor it.
DECENTRALIZED DECISIONS	Complete the implementation in a unified manner throughout the company and monitor it.

4. FILLING IN "CUBE-4.0 QUESTIONNAIRE" AGAIN:

The expected date for filling in "CUBE-4.0 Questionnaire" again and compare the results is 27th April 2023.

References

PhD Tesis: PROPOSAL OF THE CUBE-4.0 READINESS MODEL FOR ENGINEERING COMPANIES THROUGH DIGITAL TRANSFORMATION CONTEXT

ANY QUESTIONS, PLEASE CONTACT:
brunafelippes@gmail.com

Figure 36: Roadmap for "Company C" (Source: Author).

It should be noted in Figure 36 that the Company "C" had the best results in technological enabler ($Level_{max}$ 5), in comparison with organizational ($Level_{max}$ 4) and process maturity ($Level_{max}$ 4) criteria.

It is possible to realize that, according to the CUBE-4.0 methodology, this company would have its vector R=(2, 2, 3) – Level 2. That is, for the organizational and technological dimensions there are still elements for which "Company C" has not yet completed the implementation in a unified manner throughout the company, such as top-down support and corporate governance, organizational structure, cognitive support, and decentralized decisions. All these elements need improvement actions to balance the readiness level of the "Company C".

On the other hand, there were elements whose level of readiness allowed the company to reach the R=(4, 5, 4) – Level 5, such as in contractual labor relations, business model, leadership, internal communication, training, innovation culture, information security, engineering, research and development, customer-centric new product development (NPD), supply-chain, customized/personalized production, and sales and operations.

About Organizational Strategy (which had the lowest readiness), although it had a good readiness for contractual labor relations and business models, it was recommended to start assessing the possibility of top-down governance to invest more in DT in the company, besides investing in the organizational structure development.

With regard to Human Workforce, all the four elements are regularly optimized, requiring only self-adaptation implementation (without prior approval).

About Production Technology (which also had the lowest readiness), although it had a good readiness for anthropomorphic support (as Robots in the production line), management support (as Big Data), and network production (as Additive Manufacturing), it was recommended some investments in cognitive support (as Artificial Intelligence).

Regarding Information Technology (which also had the lowest readiness), although the company presents Level 5 for information security and a good data transparency and interconnectivity, more decentralized decision-making practices (i.e. with decision-making tools) were recommended.

About Product-Service Development, all the three elements are regularly optimized, requiring only self-adaptation implementation (without prior approval).

Regarding Order Fulfillment, although the company had better readiness about customized/personalized production, and sales and operations integration, more investment in the quality management system is expected.

After answering the CUBE-4.0 Questionnaire, the “Company C” provided the following feedbacks:

- liked the questionnaire because it was short. They have already had experience with large questionnaires with many questions, being bad, tiring and not very effective;
- enjoyed the application methodology in the company: filled out by more than one person at the same time, avoiding subjectivity and partiality;
- suggested that, before starting to fill out the questionnaire, respondents should be advised to define whether the responses scope will be for the entire company or for only one or more units, depending on its necessity, especially for larger and/or multinational companies. Strategically, for the “Company C”, that is, for some units in some countries, it is not advantageous to invest in I4.0 at this time;
- in addition, if the company decides to answer the questionnaire for the company as a whole, considering all its units, the “Company C” suggests that an average of readiness be made to answer each question, specially for

larger companies. For example, the “Company C” considered the situation average of its 48 units spread across 13 different countries, each with its level of readiness;

- they suggested offering a gift to the survey respondents, to motivate them in this process. They reported that this is a very common routine for this type of research;
- they suggested assessing whether there is any particularity in some questions, for the company whose client is another enterprise, and not the final consumer, as is the “Company C” case; and
- suggested to add, for each question, fields for open writing by the respondent, if he/she wants to qualitatively justify the reason for such an answer.

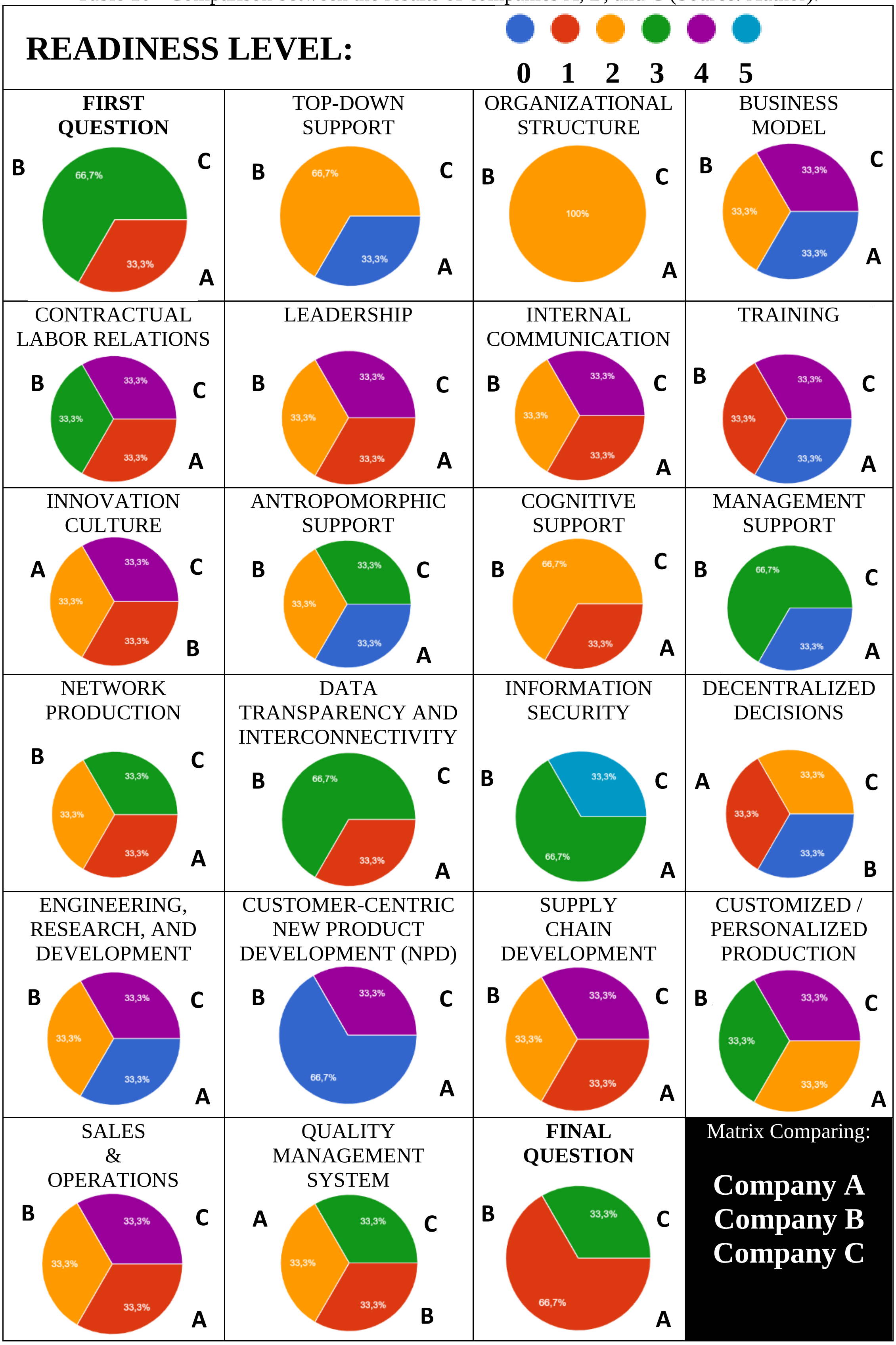
After applying the CUBE-4.0 Model in these three selected industries, a comparative results analysis was performed.

5.4 Results comparison after applying the CUBE-4.0 in three companies

Analyzing Table 10, it can be seen that the largest company (“Company C”) had better readiness results of its elements in relation, respectively, to companies “B” and “A”.

The same happens with “Company B” in relation to “Company A”. The only exception were the elements: Innovation Culture, Decentralized Decisions, and Quality Management System, which presented a higher readiness level in “Company A” compared to “Company B”.

Table 10 - Comparison between the results of companies A, B, and C (Source: Author).



Regarding the companies' readiness sense, it was observed that before filling out the questionnaire, respondents from “Company A” perceived their readiness at Level 1, while interviewees from Companies “B” and “C” indicated that they would be at Level 3. However, after completing the questionnaire, although the Companies “A” and “C” maintained the same score for their readiness, “Company B” lowered its grade from 3 to 1. This indicates that the questionnaire helped broaden “Company B's” understanding of I4.0, making them realize that there were still more actions to be taken for DT, in addition to those already detected.

With regard to organizational aspects, for Companies “A” and “C” the human workforce facets were at a higher readiness level, in relation to organizational strategy aspects, the opposite occurring for “Company B”.

It is interesting to note that for the element “Organizational Structure”, all companies have selected Level 2. Furthermore, regarding organizational enabler, only “Company A” presented level 0 (minimum value) for some elements, while only “Company C” obtained 4 (maximum value) for some elements.

The element that had a bigger level, considering the sum of all companies, was Contractual Labor Relations, while the lowest level was Top-down support and Training, respectively. Finally, only 25% of the elements had a coincidence answer between at least two companies: top-down support (B=C) and organizational structure (A=B=C). So, there were more similarities between Companies “B” and “C” for the organizational dimension.

With regard to technological aspects, for Companies “A” and “C” the information technology aspects were with a higher readiness level, in relation to production technology aspects, the opposite occurring for “Company B”.

It is interesting to note that, regarding technological enabler, only “Company A” had Level 0 (min value) for some elements, while only “Company C” had 5 (max value) for one element.

The element that had the highest level, considering the sum of all companies, was Information Security, while the lowest level was Decentralized Decisions. Finally, 57% of the elements had a coincident response between at least two companies: cognitive support (B=C), managerial support (B=C), transparency and data interconnection (B=C), and information security (A=B). Therefore, there were more similarities between Companies “B” and “C” in the technological dimension.

With regard to process maturity aspects, for Companies “A” and “B” the order fulfillment elements were with a higher readiness level, in relation to product-service development aspects, the opposite occurring for “Company C”.

It is interesting to note that, regarding to process maturity enabler, not only “Company A” had level 0 (minimum value) for some elements. This was the first time that “Company B” had level 0 for an element (customer-centric NPD), while only “Company C” had 4 (maximum value) for some elements.

The element that had the highest level, considering the sum of all companies, was customized/personalized production, while the lowest level was customer-centric NPD. Finally, only 17% of the elements had a coincident answer between at least two companies: customer-centric NPD (A=B). So, there were more similarities between Companies “A” and “B” for the process maturity dimension.

It can be concluded that Companies “B” and “C” have greater similarity among themselves in relation to “Company A”, especially concerning the technological dimension. Furthermore, it was observed that Companies “A” and “C” showed greater readiness in respect to the technological dimension, while “Company B” had a balance among the three dimensions.

5.5 CUBE-4.0 Validated Model (Final Version)

Firstly, it is important to highlight that after the CUBE-4.0 application in the three engineering companies, there was no need for any modification to the Model philosophy, proving its efficiency and validation.

The CUBE-4.0 Questionnaire, CUBE-4.0 Roadmap, readiness levels, elements, sub-dimensions, and dimensions, as well as the methodology for vector readiness calculation and data collection, were validated after concluding all steps described in Chapter 3. Once approved, the final version follows below.

5.5.1 CUBE-4.0 Readiness Levels (Final Version)

According to the improvements detailed in Chapters 4 and 5, the main changes were made, and the final CUBE-4.0 Readiness Levels can be seen in Figure 37:

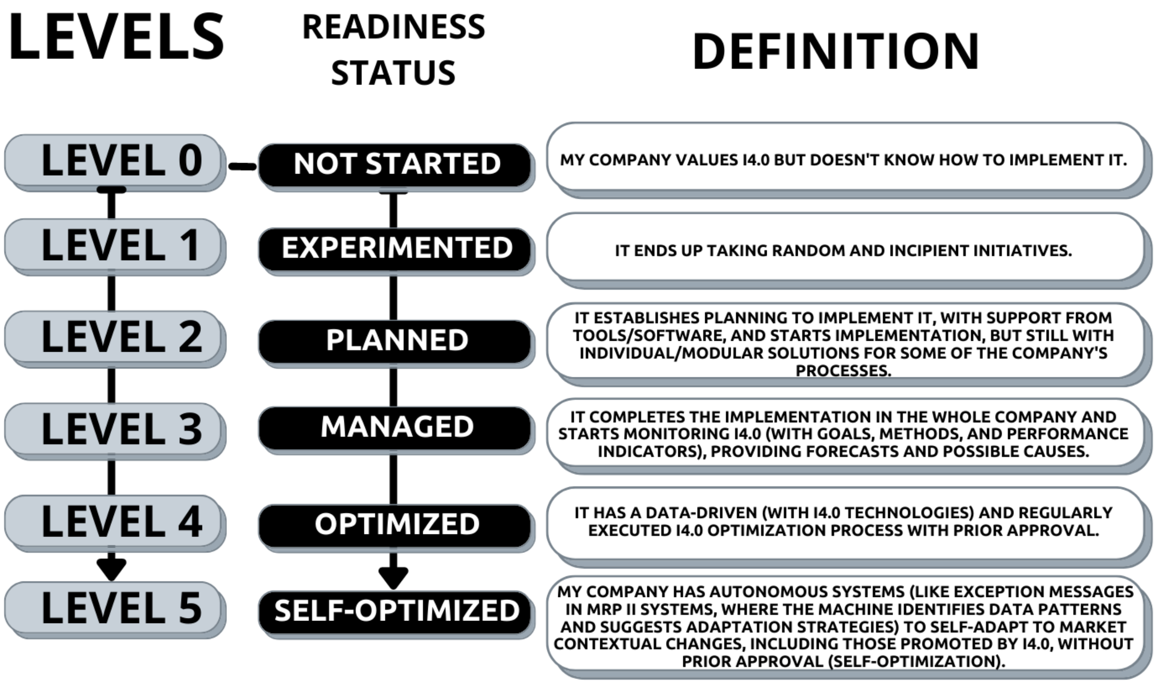


Figure 37: CUBE-4.0 Readiness Model Levels (Source: Author).

As well as for the dimensions, each sub-dimension and each element also range from Level 0 to 5 (six levels), which are now with different concepts:

- **Level 0:** In this stage, the company does not know how to start I4.0 implementation and has not made any move in that direction yet. It has come to be called “Not Started” just so that people do not link to the concept of “Not Initiated”, which is very well-known in CMMI methodology.

- **Level 1:** At this stage, the company ends up taking random and incipient initiatives. It has come to be called “Experimented”, because at this stage the company is still in the process of experimentation and risk analysis, not yet having a DT process planned, defined, and structurally initiated. And this is perhaps the most important step in this DT process. According to Chonsawat and Sopadang [90], “it is clear that the challenges and barriers as perceived by experts related to smart technology and systems are centered around (i) the perceived risk of novel technologies, (ii) the complexity of integration, and (iii) the consideration of human and organizational factors. […] Addressing these three challenges might strengthen the confidence in smart technologies, help decision makers to understand related risks, and support sustainable innovation”. Besides, agile processes provide autonomy and flexibility in smart factory implementation [57]. For example, the Minimum Viable Solutions (MVS), as a type of agile process, creates a continuous evaluation cycle that provides opportunities to continuously improve production processes in the face of changing demands, always based on experimentation to minimize risks. So, innovation is about taking risks and experimenting.

- **Level 2:** At this stage, the company establishes planning to implement it, with support from tools/software, and starts the implementation, but still with individual/modular solutions for some of the company's processes. It came to be called “Planned”, instead of “Managed”, because it was considered that at this stage the company is still in the process of planning the changes to be made, and does not yet have a defined and managed process of DT.

- **Level 3:** At this stage, the company completes the implementation in the whole company and starts monitoring I4.0 (with goals, methods, and performance indicators), providing forecasts and possible causes. It has been called “Managed”, instead of “Defined”, because this is a more complete and comprehensive concept: the process must first be defined, so that it can be fully managed.

- **Level 4:** At this stage, the company has a data-driven (with I4.0 technologies) and regularly runs the I4.0 optimization process with prior approval. It remained as “Optimized”, but with a different philosophy than the CMMI approach. It units the last two CMMI levels (i.e., “Quantitatively managed” and “Optimized”) into one concept. An autonomous process means that a piece of equipment can be guided by sensors and actuators autonomously during production, in real-time, and according to the conditions of the moment. Decision-making is done using algorithms that evaluate the performance and state of the production measurements, causing the equipment pieces to take action to meet the goals set by the algorithms [50].

- **Level 5:** At this stage, the company has autonomous systems (like exception messages in MRP II systems, where the machine identifies data patterns and suggests adaptation strategies) for self-adaptation to market contextual changes, including those promoted by I4.0, without prior approval (self-optimization). **“**Self-optimized” is used, instead of “Self-adapted”, only to utilize the same nomenclature in order to facilitate understanding of the evolutionary trend from Level 4 (“Optimized”) to 5 (“Self-Optimized”). So, if all CUBE-4.0 dimensions, sub-dimensions, and elements, have a maximum score of 5, it represents a company’s complete readiness for DT.

5.5.2 CUBE-4.0 Dimensions, Sub-dimensions, and Elements (Final Version)

According to the improvements detailed in Chapters 4 and 5, the final CUBE-4.0 Dimensions, Sub-dimensions and Elements can be seen in Figure 38:

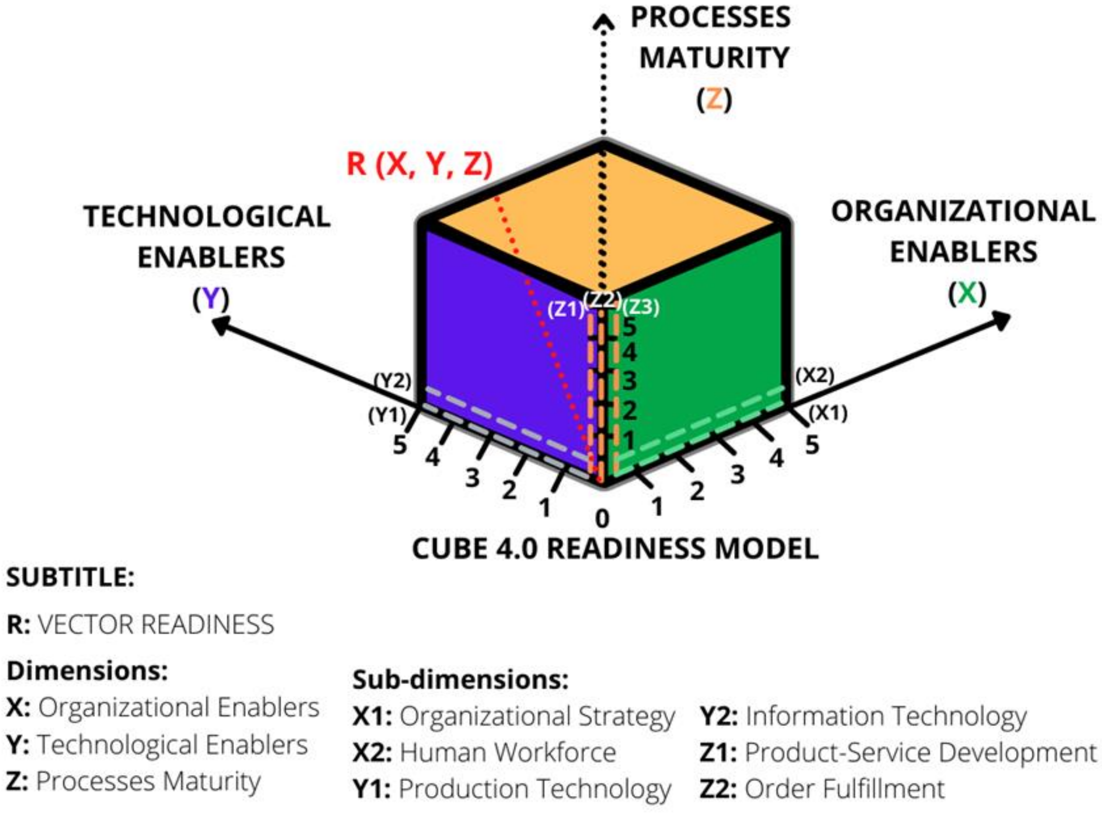


Figure 38: Final CUBE Readiness Model Proposal, after validation (Source: Author).

It is important to highlight that each CUBE-4.0 element was subjected to a literature review to determine how the authors usually evaluate it [50].

In Table 11, one can be seen that there are fewer elements than those referred to in Version 1, emphasizing that the organizational enabler had the highest changes. Therefore, this new proposal addresses all the limitations found in the previous model and is more complete, contemplating all the main processes existing in an engineering company.

Table 11 - CUBE-4.0 Dimensions, Sub-dimensions, and Elements (Source: Author).

DIMENSIONS	SUB-DIMENSIONS	ELEMENTS
ORGANIZATIONAL ENABLERS (X)	Organizational Strategy (X_1)	TOP-DOWN SUPPORT / CORPORATE GOVERNANCE (X_{11})
		ORGANIZATIONAL STRUCTURE Management (X_{12})
		BUSINESS MODEL Management (X_{13})
		CONTRACTUAL LABOR RELATIONS (X_{14})
	Human Workforce (X_2)	LEADERSHIP (X_{21})
		INTERNAL COMMUNICATION (X_{22})
		TRAINING (X_{23})
		INNOVATION CULTURE (X_{24})
TECHNOLOGICAL ENABLERS (Y)	Production Technology (Y_1)	ANTROPOMORPHIC SUPPORT Systems (Y_{11})
		COGNITIVE SUPPORT Systems (Y_{12})
		MANAGEMENT SUPPORT Systems (Y_{13})
		Driving NETWORK PRODUCTION (Y_{14})
	Information Technology (Y_2)	DATA TRANSPARENCY AND INTERCONNECTIVITY (Y_{21})
		INFORMATION SECURITY (Y_{22})
		DECENTRALIZED DECISIONS (Y_{23})
PROCESS MATURITY (Z)	Product-Service Development (Z_1)	ENGINEERING, RESEARCH, AND DEVELOPMENT Integration with other companies (Z_{11})
		CUSTOMER-CENTRIC NEW PRODUCT DEVELOPMENT-NPD (Z_{12})
		SUPPLY-CHAIN Development (Z_{13})
	Order Fulfillment (Z_2)	CUSTOMIZED / PERSONALIZED PRODUCTION System (Z_{21})
		SALES and OPERATIONS Integration (Z_{22})
		QUALITY MANAGEMENT SYSTEM (Z_{23})

Next, each element will be explained, starting with the organizational enablers, then the technological enablers, and finally the unedited process maturity enablers.

5.5.2.1 Organizational Enablers

Organizational enablers for readiness are differentiated into two sub-dimensions, following Schumacher et al. [6] and De Carolis et al. [15]:

- Organizational Strategy
- Human Workforce

5.5.2.1.1 Organizational Strategy

Organizational strategy is about the necessary support and philosophy that a company must have to enable organizational change. Organizational strategy requires top managers to show interest in I4.0 solutions, demonstrating that the organization itself is open to new ideas and concepts regarding its structure and processes. A digital strategy represents the improvement of products and processes through digital technologies and the opportunity to develop a brand-new business model. A good digital strategy must incorporate a long-term vision, a business model review, and a digital plan to achieve business objectives [43]. Thus, the Organizational Strategy sub-dimension is the adaptive organization that a company encompasses in response to or anticipating changes in its external environment [61]. This sub-dimension includes the elements: "top-down support and corporate governance", "organizational structure management", "Business Model (BM) management", and "contractual labor relations".

a) Top-down Support and Corporate Governance

First, a "Top-down support for I4.0" is needed to start the I4.0 initiatives and projects; once a company is trying to implement I4.0, the comfort zones are forced to be exceeded [107] [4]. Only strong support from senior managers with a strict mindset [23] can sponsor the changes needed for the transformation process. Senior management's support is necessary for bottom-up (several small initiatives begin without this support, but if it exists, they are enhanced) and, mainly, top-down efforts (initiatives and projects defined by senior managers). Top-down support includes governance, which is a "mechanism for managing complex projects and changing initiatives" [61].

b) Organizational Structure Management

Organizational structure management considers the analysis of impacts from the investments in the I4.0 technologies, innovation management, and use of technologies [66].

Organizational structure englobes “practices, actions, business process, the flexibility, working rules, collaborations and communications, and procedures that complement and accommodate activities within and between organizations” [61].

c) Business Model Management

BMs are simplified and aggregated representations of the relevant activities in a company, consisting of its strategy, customer/market perspective, and value constellation [109]. I4.0 BMs can be demonstrated by integrating connectivity and other I4.0 technologies into their operation. New digital technologies can improve one's offer and relationship with the customer [43]. I4.0 enables companies to associate the obstacles of BMs in one sector they operate, with solutions or obstacles in another sector. Flawed operational decisions can lead to a downward spiral if not interrupted by warning systems, such as a decrease in profit. BM is subdivided into: “IT/cloud-based BMs”, “Service-based BMs”, “Spin-offs-based BMs”, and “Partners-based BMs”:

- IT/ cloud-based BMs: based on the result of technological enablers in I4.0, which can directly connect customers to a company [137]. Knowledge creation and management are essential issues here [138], as well as the use of Big Data [147], and cloud computing [139];
- Service-based BMs: based on product-service systems, that is, the servitization of BMs that originally were more focused on selling products. Product-service systems and circular BMs are a current imperative [135], as an increasing number of customers are environmentally conscious when purchasing consumer goods;
- Spin-offs-based BMs: imply that a company follows open innovation strategies [140], in which a small company with a small overhead starts a new promising but less profitable business [141]; and

- Partners-based BMs: support the creation of new endeavors in its supply-chain or participate as a tier in a larger value chain on I4.0 ecosystems [140]. Partner-based business demands specific mindsets towards horizontal collaboration and new contractual and legal considerations [148]. That involves sharing projects, knowledge, resources, and tools, and is based on willingness and the ability to cooperate [43].

d) Contractual Labor Relations

Regulatory compliance is the "governmental and institutional policies, including procedures, standardization, and security" [61]. It includes labor regulations for I4.0, suitability of technological standards, intellectual property, the I4.0 roadmap implementation, and available resources for realization [64], as well as the environmental context [61].

Internationally, there are many variations in laws and norms for employment. Work-related contracts and standards are emphasized in the I4.0 context [113]. Concurrently, new technologies allow several off-site work environments like a home office, a virtual office, and an AR office [112]. These possibilities are technologically enabled, but a remaining challenge is to align these new work environments with the labor law, which runs on another velocity.

According to Badri et al. [148], in industrialized nations, Occupational Health and Safety (OHS) has been a growing concern in many businesses for at least two decades. Legislation, regulations, and standards have been developed to provide organizations with a framework to practice accident and illness prevention, and to place the worker's well-being at the center of production system design. However, the occurrence of several accidents continues to show that OHS performance evaluation is subject to interpretation. Over the years, many instruments have been developed to assess occupational health and safety in public and private organizations, wherever employees are exposed to the risk of work-related injury or illness. Such tools should also be capable to guide the choice of preventive actions implemented and to measure their effectiveness.

5.5.2.1.2 Human Workforce (or Human Factors - HF)

Human Factors (HF) are probably the major enabler of I4.0 [7], since employees are, directly and indirectly, the driver of the success of the other elements. This includes "people skills: a company's crucial attributes" or "how to hire and fire, motivate, train and educate", going beyond the traditional considerations such as training, salary, performance feedback, and career opportunities [61]. With the I4.0 emergence, employees will need to be empowered across all organizations and along the value chain to be agile and strategic in dealing with new challenges [110] [111].

For Neumann and Dul [149], HF is "the scientific discipline concerned with the understanding of interactions among humans and other elements of a system … to optimize human wellbeing and overall system performance". According to IEA 2000 Council (International Ergonomics Association), this definition of HF spans the physical, cognitive, and psychosocial interface between the operator and the production system. It is operationally defined as synonymous with the term "ergonomics", which is sometimes seen as a narrower issue by those outside the discipline. HF differs from Human Resource Management (HRM) in that HRM focuses more on selecting and developing people to fit into the system. In contrast, HF focuses on adapting the system design to fit people ("HF engineering"). In the CUBE-4.0 Model, HF is treated as a basis for the human workforce sub-dimension and includes "leadership", "internal communication", "training", and an "innovation culture".

a) Leadership

Leadership is defined as a person's process of guiding, orienting, and influencing a group of people to achieve a shared vision [43]. Any company can become smarter and closer to the I4.0 league. However, Organization and Management (OM) are often the obstacles to this development. Several MMs are introduced to assess the company's maturity towards I4.0, and leadership and people are usually treated as organizational aspects [150]. This includes a willingness to lead and manage competencies and methods [64], besides motivating, developing, and directing people as they work (World Economic Forum, [151]).

b) Internal Communication

Communication is the "…effective exchange of ideas and a clear understanding of what it takes to guarantee successful strategies, ensuring the ongoing knowledge sharing across organizations" [61]. Internal communication is a set of principles, actions, and practices designed to foster ownership and cohesion, encourage everyone to communicate better, and promote joint work [43]. Vertical communication occurs between the company's hierarchical levels, while horizontal communication occurs between different sectors at the same level.

Communication is probably the major concern regarding human resources in I4.0 [43]. Communication technologies alone are insufficient if people do not use them properly [108] to gather customer, product, manufacturing, and logistics data [112]. While different enterprise systems - such as Enterprise Resource Planning (ERP), Supply-Chain Management (SCM), Management Information Systems (MIS), and Product Lifecycle Management (PLM) - support their tasks very well, their data are often stored in separate databases and partly stored in different formats. This sub-optimal level of integration must be improved to implement I4.0 business processes, so the information must be accessible and useable at the right time in the right "place" along the entire supply-chain and for all business partners [18].

c) Training

Continuous training enables people to deal with new technologies, interpret data and understand its impact on the whole process [62]. I4.0 increasingly depends on highly skilled people who adapt to new business processes and respond quickly to competitive challenges [112]. Besides, there is a need for new I4.0 platforms for on-the-job training and personnel qualification [93]. Talent management is the set of practices related to the acquisition, development, and promotion of an organization's talents, such as training and development, succession management, career management, and compensation [43].

d) Innovation Culture

Organizational culture is generally defined as a “complex set of values, beliefs, assumptions, and symbols that define how a firm conducts its business” [114]. Regarding I4.0, organizational culture is associated with people's assumptions about the digital transformation shared across all hierarchical environments in the company [6]. It is “a pattern of shared basic assumptions that was learned by a group in solving its problems of external adaptation and internal integration, that worked well enough to be considered valid … to new members as the correct way to perceive, think, and feel about those problems” [61]. In the I4.0, the main characteristics of innovation culture are: “agility” and “willingness to change”:

- “Agility”: agile manufacturing is an organization’s ability to create value and delight its client while promoting and adapting - in time - to changes in its environment. “Agility” refers to more easily meeting customer changes, adapting to different contexts, or to new and disruptive challenges imposed by competitors [43]. According to Sjödin et al. [57], it is important to introduce “agile” processes to leverage rapid technological development, because the traditional Stage-Gate model and similar techniques for developing and implementing process innovations cannot keep pace with technological change. “Agile” implementation processes, incorporated into formal work approaches, provide autonomy and flexibility in smart factory implementation. Sprints, daily stand-ups, short development cycles, and minimum viable solutions create a continuous evaluation cycle that provides opportunities to constantly improve production processes in the face of changing demands.

Thus, process improvements that incorporate "agile" elements provide the flexibility to redirect efforts, as new technologies and new opportunities emerge.

- "Willingness to change": means that new endeavors must be faced by bringing improvement opportunities for people in terms of work enrichment and personnel competencies [23]. If a company fosters a culture of change and establishes processes that value it, DT efforts will be easily implemented.

5.5.2.2 Technological enablers

In the I4.0 context, the technological dimension is at the center of discussion [115]. The following sub-dimensions have been included:

- Production Technology
- Information Technology

5.5.2.2.1 Production Technology

Production technology aims to support humans in their increasingly complex work context and is one of the most prominent research areas in I4.0 [117]. Ergonomic support can be digital or physical [116] and can cover anthropomorphic, cognitive, and managerial skills [118]. A general discussion of employee safety is a background in the ergonomic context of supporting technologies [148]. Moreover, a discussion regarding the reliability of artificial intelligent objects in the production process, mainly for cognitive and managerial support, should envelop this whole discussion. New technologies enable off-site manufacturing [125]. Considering a large amount of existing I4.0 technologies and the speed at which they appear and disappear, CUBE-4.0 does not focus on specific ones. Therefore, the "production technology" can be presented in four areas, generically: "anthropomorphic support systems" – e.g. *Robots*, "cognitive support systems" – e.g. *Artificial Intelligence*, "management support systems" – e.g. *Big Data*, and "driving network production" – e.g. *Additive Manufacturing*.

a) Anthropomorphic Support Systems

A robot is an anthropomorphic support system since it allows to increase the productivity of human labor from the physical point of view. Anthropomorphic support [119] implies a wide utilization of robotics along the value chain: manufacturing processes (as primary use cases for support when anthropomorphic limits exist for humans, such as painting, forging, pressing, or welding), as well as assembly processes. Some logistic processes, such as material handling and collection, are also suitable for technological support [121]. On a CNC machine (Computer Numeric Command), it is possible to change tools automatically and rotate the machining axis of the workpiece without operator interference. These human factors elements belong to the production technology because the operator is part of the productive system [118].

b) Cognitive Support Systems

Cognitive ergonomics deals with mental processes related to interactions between people and other system elements, such as perception, memory, reasoning, and motor response. Relevant topics include mental load, decision-making, human-computer interaction, stress, and training [118]. Therefore, cognitive support systems, such as mobile apps, tablet-based interfaces, industrial panels, or AR/VR devices [122] are also ergonomic solutions applied to I4.0 processes [118]. The company must design the interfaces to help line workers, managers, and other employees. Intensive knowledge-based operations such as technical sales, after-sales services, maintenance, and scheduling are important application areas for cognitive support [120]. Cognitive work analysis is suggested to design well-structured jobs [123].

c) Management Support Systems

Management support systems deal with the management tasks of all organizations [118] [120]. The managerial body needs simpler and highly focused information to permit quick decision-making. Top and middle managers have specific user requirements for their daily activities, weekly appointments, and tracking goals and metrics for decision support system design.

d) Driving Network Production

The last element, “driving network production”, comprises technologies like additive manufacturing, which enable not only the main manufacturer to produce the full product or parts of it, but various actors in the value chain by the concept of shared manufacturing [124], even the final consumer [125].

5.5.2.2.2 Information Technology

Information technology is differentiated into the following elements: “data transparency and interconnectivity”, “information security”, and “decentralized decisions”.

a) Data Transparency and Interconnectivity

Based on Merkus et al. [61] concepts, data management can be broken down into three main elements: (1) data analysis, (2) data transparency (integrity and quality), and (3) data interconnectivity (collection and delivery). All of these processes are operated in a business by acquiring, controlling, protecting, delivering, and improving the quality of the data and information assets [61].

Data analysis defines the transformation process from data into information. The digitalization and production plants’ interdependence degrees are increasing, directly resulting in a cumulative amount of data. The literature describes data analysis in four levels: (1) descriptive analysis defines the evolvement from data to information; (2) cause-effect relationships are revealed by conducting a correlation analysis (diagnostic analysis); (3) the predictive data analysis predicts future events by simulation methods; and (4) prescriptive data analysis provides recommendations for action by optimization and simulation approaches. Within an I4.0 environment, a large and poly-structured amount of data is available and exceeds traditional analytic methods, generating the need for Big Data technology use, for example, to forecast machine failures or optimize the production planning process [152].

About transparency, data quality means that the data provided to employees enables analysis and decision-making based on valid information, while data integrity represents activities that maintain the context, consistency, standardization, and sharing of accurate, up-to-date, and relevant information [43].

Interconnected company data implies "to enable real cross-domain and inter-company collaboration, [to make] context-aware data from production, development, and usage […], available in real-time, at a reasonable tier of granularity, and in a potentially global scale" [126]. When it comes to interconnection, a company should be horizontally and vertically integrated to allow a continuous exchange of data and information [127]. The horizontal integration must go across the entire value chain. Indeed, a company needs an adequate data management system to support integration and allow all users access to the same data set [43]. The information must always be linked to the product, work, process instructions, and customer information [43]. In this context, data collection/delivery means the data design, implementation, deployment, maintenance, and mechanisms for capturing and transferring data in an operating system [61]. Therefore, by collecting data from connected objects and people in real-time, information transparency is achieved. Linking this data to digitalized models makes it possible to create a virtual copy of the physical world, for example. Hence, all objects and people access the same relevant data [116].

b) Information Security

Information security, or "cybersecurity", can affect internal storage, cloud services, and inter and intra-enterprise communications. Cybersecurity includes developing, planning, and implementing security procedures to prevent breaches, information leaks, and piracy [43]. An Information Security Management System (ISMS), according to the ISO/IEC

27001, is a system for "…establish, implement, operate, monitor, review, maintain and improve information security". ISO/IEC 27001 defines the requirements and process for implementing an ISMS. However, implementing this standard without a detailed plan can burden organizations [153]. The increasing integration of information systems, human factors, and other contributors bear the risk of criminal attacks. The degree of integration can cause increases in proportion to the potential damage of these attacks. IT security encompasses different strategies for identifying and implementing security measures. Also, compliance with standards such as IEC-62443 can help contain the risks [152].

c) Decentralized Decisions

Decentralized decisions refer to the possibility of making informed decisions as autonomously as possible by both, systems and humans, since they can access relevant data [128]. Analytics is one of the I4.0 main pillars. Nowadays, it is clear that manufacturing companies have to learn to manage and use a large amount of data, once advanced analytics can transform these data into useful information [15].

5.5.2.3 Process Maturity

A process is "...a set of structured activities and measures aimed at resulting in a product specified for a particular customer or market" [129]. Three types of processes are presented in companies: (1) business processes, (2) organizational processes, and (3) managerial processes. Business processes connect customers to the company value chain, while organizational and managerial processes focus on decisions regarding the company's resources. Organizational and managerial processes are treated in CUBE-4.0 as organizational enablers. To analyze business process maturity, we focused on value under the product lifecycle concept, based on Simetinger and Zhang [24], including product development, process development, procurement, and manufacturing.

In the CUBE-4.0, the views found in Zeller et al. [43], Agca et al. [8], and De Carolis et al. [15] are considered for the process maturity evaluation in the value chain, similar to CMMI. Therefore, it included two main processes:

- Product-service Development
- Order Fulfillment

5.5.2.3.1 Product-service Development

Product-service development addresses the effort to meet customer requirements based on customization, product-service systems, and shared manufacturing [130] [124] [20], and implies simultaneous products and services development [131]. This sub-dimension comprises the following elements: “engineering, research, and development integration with other companies”, “customer-centric new product development (NPD)”, and “supply-chain development”.

a) Engineering, Research, and Development integration with other companies

“Engineering, research, and development integration with other companies” implies a horizontally and vertically integrated innovation process [132], within and outside the company. For example, interdepartmental integration in NPD projects comes from concurrent engineering discussions in the 1990s [133]. Today, a company must be innovation-driven, which means every department must be involved to provide ideas regarding new products or businesses [115].

b) Customer-centric NPD

Customer-centric NPD is a customer-centered approach [134] that puts the client at the center of the NPD effort in digital servitization BMs [135]. In doing so, new products will take the form of a co-created design, partly with physical products but also as value-added services on IT platforms and VR/AR [136]. IT/cloud-based tools result from technological enablers in I4.0, which can directly connect customers to companies [137]. Every company can use these connections to explore new business opportunities, even if they are not directly linked to its core business. Knowledge creation and management are essential issues here [138], as well as the use of Big Data [147] and cloud computing [139]. Customer experience represents the effort to provide more than one product to the customer in terms of design, associated service, and communication throughout the product lifecycle. It includes co-creation and open innovation, which use partners or crowds to develop new products and processes [43].

c) Supply-chain Development

Supply-chain development is centered on optimizing a value chain's efficiency to increase its profitability [142]. Purchases, as well as inventories at the supplier, have to be synchronized. Only then a “one-piece flow” within a manufacturing plant is achievable [144]. According to Barbalho and Rozenfeld [59], the supply-chain design is architected into the NPD process. It includes the manufacturing, assembly, supply, and distribution structures development. So, the production and supply-chain design consist of the activities related to “process engineering”, as well as the manufacturing structure design necessary to introduce the product into the company's production line.

5.5.2.3.2 Order Fulfillment

The order fulfillment sub-dimension integrates the entire manufacturing process, from production to product delivery [143]. Production is the main value-added chain inside a manufacturing company and has been the primary focus of I4.0 MMs [43]. However, in the new technological context, logistics must also be integrated [142]. Business logistics was born with a vision of integration. In this case, it means that there would be greater possibilities for integration without needing so many specialized and technological systems. Furthermore, in an I4.0 approach, an international player must plan long, medium, short, and last-mile terms for product delivery times [120]. This sub-dimension is sub-divided into a "customized/personalized production system", "sales and operations integration", and a "quality management system".

a) Customized/personalized Production System

A customized/personalized production system has been a long-term goal for process improvement activities. Customization means offering the customer an individual approach that meets specific needs [43]. New IT solutions, robotics, IoT, and intelligent cyber-physical system architectures enable customization of production and small batches [144]. Consequently, the whole production planning, resource planning, and the shop floor can be realigned to customized production. The use of data and information technology enables the development of new BMs and creates original value for the customer.

b) Sales and Operations Integration

Sales and operations integration covers the traditional sales and operations planning of the main operations management [143], such as marketing and customer feedback. Still, it can be improved and highlighted by I4.0 technologies [145] [146]. First, the medium-term planning horizons can be shorter to reduce inventory and manufacturing costs. Secondly, new technologies can bring more agility to sales and operations decisions, gathering current data, enabling better communication, and supporting the decision-making processes. As in other integrative demanding areas, people must be aware of the integration's effectiveness [112]. The degree to which the operations network is integrated, in general, can be measured by the number of connections between two companies.

c) Quality Management System

Quality management system considers that increased product quality is achieved through real-time monitoring and continuous optimization (characteristic of the smart factory). Enhanced predictive and detective approaches allow quality defects to be spotted sooner. In addition, the system can facilitate the identification of the root defects' causes, whether human, machine, or environmental. Interviewees cited the benefits of lower scrap rates, and reduction of product defects and recall incidence [57].

5.5.3 CUBE-4.0 Readiness Vector Score Calculation (Final Version)

In the CUBE-4.0 Model (Final Version), the company evaluation still focuses firstly on each element, with a score from 0 to 5, and then on the sub-dimensions and dimensions. But now, with some differences, that were detailed below.

5.5.3.1 Readiness Vector

As detailed on Chapter 4, the vector now is (X, Y, Z), instead of (O, T, M):

$$R^{\rightarrow} = \text{READINESS} = (\boldsymbol{X}, \boldsymbol{Y}, \boldsymbol{Z})$$

X: organizational enabler

Y: technological enabler

Z: process maturity enabler

Where: R, X, Y, Z = [0,5]

5.5.3.2 Calculation Method

During the Model pretests, the "Company A" informed that the low vector "R" results had caused discomfort in the process. Therefore, considering this feedback and the suggestion of the Consulting Firm (see item 4.5.5), ways to solve this problem were studied. As most companies nowadays are still with low readiness values, these low results may not generate relevant and manageable information for the company, in addition to running the risk of discouragement the CUBE-4.0 Model's use and then stopping its DT.

According to Bonnafous-Boucher [154], the primary principle of civil society is similar to that of stakeholder theory in that, in both, individuals exclusively seek their personal well-being by means of satisfying their vital interests. For him, corporations have a permanent objective, namely, to increase their size, and, consequently, negotiate power and economies of scale by boosting production and thereby decreasing marginal costs. So, it is unlikely that stakeholder theory will ever be entirely appropriated by the competitive advantage perspective. To paraphrase this last, we could say that: "making the biggest cake is cooperation, while sharing it, is competition". According to the competition model developed by Bradenburger and Nalebuff [154], competition is compatible with selective cooperative projects, including, in terms of products, substitutes, and complements that are relative values. Thus, according to this theory, when sharing results with the interlocutors, in our case, the clients (companies), it is important to choose the best technique to pass on such information, in order to keep the negotiation advantageous.

So, considering that the Model was already satisfactory, it was realized the need to change only the methodology to present the results to the company. In this regard, it was added another approach for the disclosure process of results to companies.

Therefore, for calculating the final readiness vector "R", there are now two approaches: the Minimum Value of Vector "R" (Approach 1) and the Maximum Value of Vector "R" (Approach 2). Both are based on the same elements' scores, the only difference is the final value of the vector, depending on the approach: $\mathbf{R_{min}}$ or $\mathbf{R_{max}}$.

Below, there were described the two selected and validated approaches.

Approach 1: $\mathbf{R_{min}}$ **= Minimum Value of Vector "R" (Conservative Approach):** in order to verify the elements, sub-dimensions, and dimensions that most need improvement. This first approach is exactly the same calculation methodology pre-defined in Chapter 4 and used during the pretests of the Model. Remaining with the philosophy used on the pre-defined version, each sub-dimension will receive the same score from its respective element that obtained the lowest score, i.e., the scores of all elements from a specific sub-dimension will be compared and the lowest score found will be the sub-dimension score. The same logic will be applied from the sub-dimension to the respective dimension score. Summarizing: for each dimension (X, Y, Z), the evaluation includes its sub-dimensions, while for each sub-dimension (X_1, X_2, Y_1, Y_2, Z_1, Z_2), the evaluation includes its elements (see Table 12):

Table 12 - Vector R_{min} Calculation (Source: Author).

X = the lowest value between (X_1, X_2)	**Y** = the lowest value between (Y_1, Y_2)	**Z** = the lowest value between (Z_1, Z_2)
X_1 = the lowest value between (X_{11}, X_{12}, X_{13}, X_{14})	**Y_1** = the lowest value between (Y_{11}, Y_{12}, Y_{13}, Y_{14})	**Z_1** = the lowest value between (Z_{11}, Z_{12}, Z_{13})
X_2 = the lowest value between (X_{21}, X_{22}, X_{23}, X_{24})	**Y_2** = the lowest value between (Y_{21}, Y_{22}, Y_{23})	**Z_2** = the lowest value between (Z_{21}, Z_{22}, Z_{23})

Where:
X_1, X_2, Y_1, Y_2, Z_1, Z_2, X_{11}, X_{12}, X_{13}, X_{14}, X_{21}, X_{22}, X_{23}, X_{24}, Y_{11}, Y_{12}, Y_{13}, Y_{14}, Y_{21}, Y_{22}, Y_{23}, Z_{11}, Z_{12}, Z_{13}, Z_{21}, Z_{22}, Z_{23} = [0 , 5]

As the CUBE-4.0 has three dimensions, that is, three enablers, the company's final score will be a 3D vector $R_{min}{}^{\rightarrow}$, to define if the company readiness is at level 0, 1, 2, 3, 4, or 5, according to Table 13 below.

Table 13 - Vector R_{min} Matrix (Source: Author).

LEVEL	READINESS VALUES MATRIX: R_{min} = (X, Y, Z)						
0	(0,0,0)	(0,0,1)	(0,1,0)	(1,0,0)	(0,1,1)	(1,1,0)	(1,0,1)
1	(1,1,1)	(1,1,2)	(1,2,1)	(2,1,1)	(1,2,2)	(2,2,1)	(2,1,2)
2	(2,2,2)	(2,2,3)	(2,3,2)	(3,2,2)	(2,3,3)	(3,3,2)	(3,2,3)
3	(3,3,3)	(3,3,4)	(3,4,3)	(4,3,3)	(3,4,4)	(4,4,3)	(4,3,4)
4	(4,4,4)	(4,4,5)	(4,5,4)	(5,4,4)	(4,5,5)	(5,5,4)	(5,4,5)
5	(5,5,5)						

Approach 2: R_{max} = Maximum Value of Vector "R" ("The company reaches" Approach): in order to motivate the company, by analyzing the maximum readiness level that has already been achieved. This is the vector used during the Model's validation process (see Chapter 5), which from now on the CUBE-4.0 Roadmap will focus on. Each sub-dimension will receive the same score from its respective element that has obtained the highest score, i.e., the scores of all elements from a specific sub-dimension will be compared and the highest score found will be the sub-dimension score. The same logic applies from the sub-dimension to the respective dimension score.

Summarizing: for each dimension (X, Y, Z), the evaluation includes its sub-dimensions, while for each sub-dimension (X1, X2, Y1, Y2, Z1, Z2), the evaluation includes its elements (see Table 14):

Table 14 - Vector R_{max} Calculation (Source: Author).

X = the highest value between (X_1, X_2)	**Y** = the highest value between (Y_1, Y_2)	**Z** = the highest value between (Z_1, Z_2)
X_1 = the highest value between (X_{11}, X_{12}, X_{13}, X_{14})	**Y_1** = the highest value between (Y_{11}, Y_{12}, Y_{13}, Y_{14})	**Z_1** = the highest value between (Z_{11}, Z_{12}, Z_{13})
X_2 = the highest value between (X_{21}, X_{22}, X_{23}, X_{24})	**Y_2** = the highest value between (Y_{21}, Y_{22}, Y_{23})	**Z_2** = the highest value between (Z_{21}, Z_{22}, Z_{23})

Where:
X_1, X_2, Y_1, Y_2, Z_1, Z_2, X_{11}, X_{12}, X_{13}, X_{14}, X_{21}, X_{22}, X_{23}, X_{24}, Y_{11}, Y_{12}, Y_{13}, Y_{14}, Y_{21}, Y_{22}, Y_{23}, Z_{11}, Z_{12}, Z_{13}, Z_{21}, Z_{22}, Z_{23} = [0, 5]

As the CUBE-4.0 has three dimensions, that is, three enablers, the company's final score will be a 3D vector $\vec{R_{max}}$, defining if the company readiness is at level 0, 1, 2, 3, 4, or 5, according to Table 15 below.

Table 15 - Vector R_{max} Matrix (Source: Author).

LEVEL	**READINESS VALUES MATRIX: R_{max} = (X,Y,Z)**						
0	(0,0,0)						
1	(1,1,1)	(0,0,1)	(0,1,0)	(1,0,0)	(0,1,1)	(1,1,0)	(1,0,1)
2	(2,2,2)	(1,1,2)	(1,2,1)	(2,1,1)	(1,2,2)	(2,2,1)	(2,1,2)
3	(3,3,3)	(2,2,3)	(2,3,2)	(3,2,2)	(2,3,3)	(3,3,2)	(3,2,3)
4	(4,4,4)	(3,3,4)	(3,4,3)	(4,3,3)	(3,4,4)	(4,4,3)	(4,3,4)
5	(5,5,5)	(4,4,5)	(4,5,4)	(5,4,4)	(4,5,5)	(5,5,4)	(5,4,5)

According to the final vector score $\vec{R_{min}}$ and $\vec{R_{max}}$, it is possible to define, respectively, the lowest and highest company readiness level, for each dimension (sub-dimension and element), in order to improve its processes and management assertively.

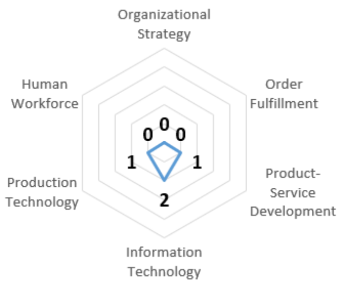
For example, if a company has the 21 elements' scores below, its final readiness vectors $\vec{R_{min}}$ and $\vec{R_{max}}$ could be, respectively: (0,1,0) and (2,3,2), see Figure 39:

Organizational enablers		
Organizational Strategy		
1.	TOP-DOWN SUPPORT and CORPORATE GOVERNANCE	**2**
2.	ORGANIZATIONAL STRUCTURE	**2**
3.	BUSINESS MODEL	**0**
4.	CONTRACTUAL LABOR RELATIONS	**1**
Human Workforce		
5.	LEADERSHIP	**2**
6.	INTERNAL COMMUNICATION	**1**
7.	TRAINING	**0**
8.	INNOVATION CULTURE	**1**

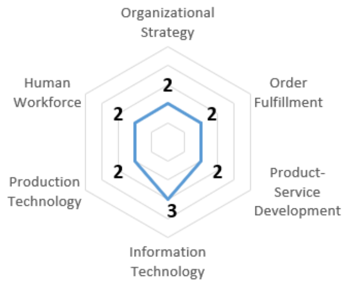
Technological enablers		
Production Technology		
9.	ANTROPOMOPHIC SUPPORT	**1**
10.	COGNITIVE SUPPORT	**1**
11.	MANAGEMENT SUPPORT	**2**
12.	NETWORK PRODUCTION	**1**
Information Technology		
13.	DATA TRANSPARENCY AND INTERCONNECTIVITY	**2**
14.	INFORMATION SECURITY	**3**
15.	DECENTRALIZED DECISIONS	**2**

Process Maturity Enablers		
Product-Service Development		
16.	ENGINEERING, RESEARCH AND DEVELOPMENT	**1**
17.	Customer-centric New Product Development (NPD)	**2**
18.	SUPPLY-CHAIN DEVELOPMENT	**1**
Order Fulfillment		
19.	CUSTOMIZED / PERSONALIZED PRODUCTION	**0**
20.	SALES and OPERATIONS	**1**
21.	QUALITY MANAGEMENT SYSTEM	**2**

Approach 1: Rmin



Approach 2: Rmax



		Sub-dimension min	Sub-dimension max	Dimension min	Dimension max
ORGANIZATIONAL ENABLER	**Organizational Strategy**	0	2	**0**	**2**
	Human Workforce	0	2		
TECHNOLOGICAL ENABLER	**Production Technology**	1	2	**1**	**3**
	Information Technology	2	3		
PROCESS MATURITY	**Product-Service**	1	2	**0**	**2**
	Order Fulfillment	0	2		

Approach 1: READINESS$_{MIN}$ is R$_{min}$ = (0,1,0)
Company is on Level: 0

Approach 2: READINESS$_{MAX}$ is R$_{max}$ = (2,3,2)
Company reaches Level: 3
(only for some elements)

Figure 39: Examples of the readiness vector "R" (Source: Author).

These two approaches could help a company to analyze its "as-it-is" stage with a complete information, besides signaling which elements it needs to focus on to improve its readiness.

5.5.4 CUBE-4.0 Data Collection and Survey (Final Version)

It was used the pre-designed Data Collection methodology (see Chapter 4), but with some changes in each step (see Figure 40). The final version methodology still included five steps, but with an approximately 16 days total duration for execution (almost the half-estimated period in comparison to the pre-designed methodology): Launching – *1 day*, Interview (Introduction and Self-diagnosis) – *1 day*, and Tabulation, Recommendations, Planning, and Presenting the Results (Roadmap) – *14 days*.

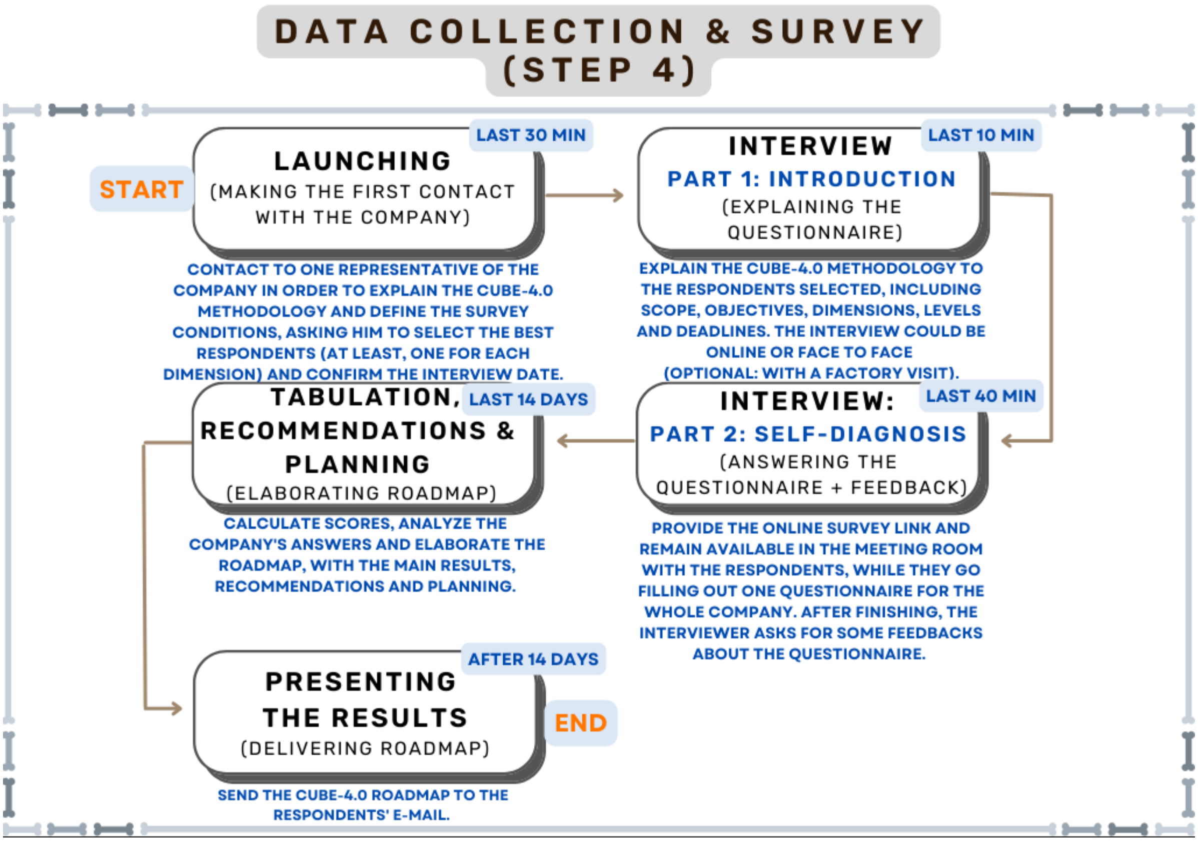


Figure 40: Data collection and Survey continuous application (Source: Author, based on Gamache et al. [50]).

Each step will be described below.

5.5.4.1 Launching

According to Ramos et al. [30], this step is relevant because is the best moment to align the theoretical concepts with those seen by specialists daily. Such a point allows for a better understanding of what is intended to be delivered. This step lasts 30 minutes maximum and includes first contact with a company representative, to explain the CUBE-4.0 methodology and define the survey conditions. This includes the interview's date and requesting the company to indicate the most appropriate respondents to answer the questionnaire, with at least, one respondent of each dimension (primarily manager). According to the University of Warwick (WMG) methodology [155], the questionnaire completion and who will complete it are very important steps in the process of assessing the company's maturity. Thus, as a criterion to select the respondents, for Ifenthaler and Egloffstein [78] is relevant to consider gender, enterprise position, years of experience, and participant’s age. Additionally, for Caiado et al. [22] the research also needs to consider the internal processes knowledge level, the access to external organizations within the supply-chain, and the expertise area in the organization, while for AlBar and Hoque [103] respondents must be asked about their gender, age, marital status, educational qualifications, and IT experience. About the number of respondents in the CUBE-4.0 Model, the ideal would be one respondent representing each sub-dimension (six respondents in total), to cover all the main processes.

Therefore, based on this literature, it is understood that the respondents’ selection is one of the most important parts of this process, since it is the secret of the survey’s success. So, the following methodology was selected: explain how CUBE-4.0 works and ask the company’s own representative to commit to choosing the most appropriate respondents (that is, who knows more about the processes to be evaluated, generally the process leaders/ manager) and to motivate them to participate in the survey. Thus, it is expected to make an interview with the most appropriate people, who in fact can answer the questions assertively and reliably. The objective of this methodology is to have quality in the answers, not quantity.

This step is also significant, since usually, the company representative requests a summary of the questionnaire, to better analyze the context and which respondents will be invited to participate in the survey. Thus, before the interview to fill out the questionnaire, the company has already pre-analyzed the questions, prepared itself to answer them and, most of the time, has already triggered the process leaders to clarify some doubts about their readiness.

Finally, this step is crucial to verify if the company has the necessary requirements to participate in this research (such as: if it is an industry, if it has all processes mapped, if it has I4.0 as a goal, and others).

5.5.4.2 Interview Part 1: Introduction

The interview can be online or face-to-face, depending on where all respondents are physically. In this step, there is a brief CUBE-4.0 methodology explanation to all respondents selected at the same time (no more than 10 minutes), including the scope, objectives, dimensions, levels, and deadlines of the interview. Finally, if it is possible, a factory visit is done to allow the evaluator to better understand the reality of the company's plant.

5.5.4.3 Interview Part 2: Self-diagnosis

This step includes answering the questionnaire. Currently, field research can be performed mainly by two distinct methods:

- the questionnaire can be sent to different business departments just via an Online Survey link [50] [78]. About the deadline for filling up the questionnaire, for Ifenthaler and Egloffstein [78] it must have a maximum of three days for the whole process. It is important to pay attention to only use this method if there is a guarantee that everyone will fill out the questionnaire. This is due to the fact that many cases of non-compulsory questionnaires end up not being filled out, thwarting the workforce goal.
- the questionnaire can be answered question by question during an interview (face-to-face or online), to help to put into context the answers provided [86]. For AlBar and Hoque [103], it is recommended to prioritize, when it is possible, the face-to-face, in-person, one-on-one, and infield (on-site) survey interaction techniques, since they provide maximum response rates compared to telephone, postal mail, and online surveys. As well as they improve accuracy, minimize missing data, and avoid delays. The problem with this method is that it can be very time-consuming and, depending on the respondents and their

schedules, there may not be time to complete the entire project with the desired quality.

In the CUBE-4.0 methodology, there is a mix of the two previous methods, by providing the Online Survey link [86] and remaining available in the meeting room with the respondents (even online), while they fill out together a single questionnaire for the company, whose process lasts on average 40 min. So, for the CUBE-4.0 methodology, it is always important to bring people from different departments together in the same environment (virtual or in-person), at the same time (up to 50 min), in order to complete the questionnaire. Many perceptions can be obtained by non-verbal language, as well as being an excellent opportunity for respondents to share information about I4.0 and ask possible questions, choosing more appropriate answers during the process.

In any case, for Agca et al. [8] it is recommended that the questionnaire be available on a digital platform, so that it can facilitate the process for the respondents and the results tabulation by the interviewer. For instance, the CCMS model [79] is operating as an online survey, whose results and graphs are generated promptly and automatically after completing the process. So, the CUBE-4.0 Questionnaire is available in a Google Forms, besides using Excel and statistics methods for further tabulation.

About the language, the questionnaire must be originally developed in English and then translated into the enterprise-specific language, if it is necessary [103]. So, the CUBE-4.0 Questionnaire is available in two languages: English and Portuguese.

Regarding content, for AlBar and Hoque [103], the research questionnaire must have three parts: Part A - contains relevant information about the organization, Part B - includes the demographic questions, and Part C - comprehends the main questions about the research model. Following this methodology, the CUBE-4.0 Questionnaire has five parts:

- **Part A:** Introduction;

- **Part B:** Respondents' Data (e-mail, full name, cell phone number, age, instruction level, years of experience in the company, and current position in the company);
- **Part C:** Company's Data (company name, company full address, company size, company's economic sector);
- **Part D:** 21 questions, one for each CUBE-4.0 element; and
- **Part E:** Initial Question, Final Question, and Questionnaire Feedback, in order to understand the company's perception about its readiness to DT and about the CUBE-4.0 Questionnaire.

Regarding the score tabulation, the answers are exactly the options of the company's readiness level, which facilitate the questionnaire understanding and optimize its tabulation. Besides, the CUBE-4.0 Questionnaire has a question-and-answer structure with a "pace" that facilitates the respondent to concentrate better and understand the questions without impedance. The survey is structured in such a way that a reliable and accurate assessment of all the attributes related to the CUBE-4.0 Model are achieved, in order to generate a scoring vector for the new readiness model [25].

In relation to the number of questions, it is recommended [16] that the questionnaire has an extremely assertive and effective quantity of items, without being too extensive (to avoid respondent disinterest and contribute to the process's reliability). The CUBE-4.0 Questionnaire has 21 effective questions, which is considered a sufficient quantity.

It is important to note, that as the implementation of technology improves quickly and the experience with its use is gathered, the necessity could arise at any time to formulate new or modify questions to keep the model up to date [79]. The CUBE-4.0 Model is prepared for these changes, so its continuous adaptation to the fast-changing world does not require a massive effort from the developers.

5.5.4.4 Tabulation, Recommendations, and Planning

This step includes calculating, analyzing, and writing up the results, recommendations, and planning, in a presentation report, as is, a CUBE-4.0 Roadmap, based on the "Company reaches" Approach for the final vector score calculation. So, the tabulation is based on the CUBE-4.0 methodology explained in topic 4.2.4. Only for elements that received grades below 3, improvement suggestions are performed in the CUBE-4.0 Roadmap, so the company can move to the next stage of readiness.

Regarding the method of presenting the results, maturity results are usually presented in a radar diagram, with the intervention points connected to each dimension [79], so this is the method selected by the CUBE-4.0 Model.

Therefore, a CUBE-4.0 Roadmap shall be constructed for each enterprise, based on the following methodology: filling in the CUBE-4.0 Questionnaire, analyzing and presenting the questionnaire's results, proposing recommendations for elements with a score < 3, and filling in the CUBE-4.0 Questionnaire again (after six months), periodically repeating this whole process.

The proposed Model will make possible a continuous re-evaluation flow with an improvement process after each result obtained because it is proposed with a cyclic process of improvement validation. So, the model will allow the client to continue with the enhancement and assessment process as many times as necessary until it reaches an acceptable level for the company's readiness.

For this thesis, it was realized that it was not necessary to change the initial CUBE-4.0 Roadmap proposal. However, it is intended to improve this roadmap for future work.

5.5.4.5 Presenting the Results

For Ifenthaler and Egloffstein [78], a period of approximately seven days is required following the interview, to assess the results and detect the strengths and opportunities to improve the company, concluding the roadmap guide strategies. In the CUBE-4.0 methodology, it was stipulated a maximum period of 14 days for the results delivery to the company, only for security - although it is very frequent to deliver them in up to seven days, in practice.

Based on Rafael et al. [86], it is recommendable to arrange a final meeting with the company (online or face-to-face) to provide and explain the main results, evaluate the application of the model, and collect feedback on it, including the model´s scope, purpose, completeness, clarity, and objectivity. For Ifenthaler and Egloffstein [78], upon receiving the results of the self-diagnosis, face-to-face interviews with the various managers of the company should also be conducted. Considering the assertiveness already achieved with the previous steps, the CUBE-4.0 Roadmap will be sent to the respondents’ e-mail. Only in case of need and if the company requests, a final meeting will be held to clarify the results.

Therefore, according to De Bruin and Rosemann [68] and Joblot et al. [72], the CUBE-4.0 Model will have a last step called “Deploy and Maintain”, as is, the improvements identified with the Roadmap will be implemented in the company. Thus, after six months, the CUBE-4.0 Questionnaire will be applied again to analyze the evolution of the company’s readiness. This step will be developed in future research.

5.5.5 CUBE-4.0 Questionnaire (Final Version)

The CUBE-4.0 Questionnaire can be seen in Appendix C and has 21 questions, one for each CUBE-4.0 element.

5.5.6 CUBE-4.0 Roadmap (Final Version)

The CUBE-4.0 Roadmap can be seen in Appendix D. Examples of the CUBE-4.0 Roadmap (final version) could be seen on topics 5.1, 5.2, and 5.3.

6. Results and Discussion Analysis

According to topic 1.1 of this thesis, the CUBE-4.0 Model was able to solve all the problems found in the 63 existing models, as summarized below (see Table 16):

Table 16 - CUBE-4.0 addressing the main problems of the 63 existing models (Source: Author).

MAIN PROBLEMS OF THE 63 EXISTING MODELS	SOLVED WITH CUBE-4.0?	HOW?
Problems / lacks already detected by previous literature review, from other authors (before CUBE-4.0) – see item 1.1		
a. Are preliminary works	Yes	CUBE-4.0 Model is complete and has its Framework (dimensions, sub-dimensions, elements, levels, graphic type, calculation, and data collection method), Questionnaire, and Roadmap well described and validated.
b. Have only a theoretical development	Yes	CUBE-4.0 Model has an extensive empirical development, as well as it was tested, applied, and validated.
c. Focus only on technology	Yes	CUBE-4.0 Model focuses on technological, organizational, and operation process maturity enablers.
d. High implementation costs	Yes	CUBE-4.0 Model has practically zero implementation cost, considering its easy application by anyone.
Problems / lacks analyzed with the CUBE-4.0 method (during the systematic bibliographic review for this thesis) - see item 2.3.3		
e. Have poor bibliograph review	Yes	CUBE-4.0 Model has a more complete and detailed systematic bibliograph review.
f. Just repeat the same concepts of existing models	Yes	CUBE-4.0 Model is a disruptive and innovative Model.
g. Fails to consider some key technologies	Yes	CUBE-4.0 Model considers the main types of technology.
h. Have limitations during the validation process	Yes	CUBE-4.0 Model was well validated by deduction from prior literature, expert consultation (judgment and opinion), and case study.
i. Have limitations for application in the companies	Yes, but can be improved	CUBE-4.0 Model can be applied to all kinds and sizes of engineering companies, and considers the respondents (managers) of various departments, but in future work, it will be studied its application in other types of companies (not only industries).
j. Have only general diagnostics and recommendations	Yes, but can be improved	CUBE-4.0 Model has a Roadmap with general recommendations. But for future work, it will be studied specific plannings with development steps.
k. Do not have monitoring indicators	Not applied	As established in the last step “Deploy and Maintain” of the CUBE-4.0 Model, only in this stage our model will have indicators (future work).

So, according to Table 16 and comparing CUBE-4.0 to others, our Model could address all the main limitations found:

a) Are preliminary work

According to Chapter 2, many models are preliminary works, as is the case, lack scientific documentation (in the framework concepts, calculation and application methodology, questionnaire, or roadmap) and/or present difficulty in distinguishing concepts (established x "in development" processes, uni x multi-dimensional framework, maturity x readiness). On the other hand, CUBE-4.0 Model has all its Framework (dimensions, sub-dimensions, elements, levels, graphic type, calculation, and data collection method), Questionnaire, and Roadmap, well described, besides using concepts related with "in development processes" (more suitable for maturity), multi-dimensional framework (as a more complete and assertive model) and better distinguishing important concepts like "maturity" and "readiness".

Traditional models, such as CMM and its variations, were built only for well-established processes. Thus, solving this problem and considering that the outcomes of the new industrial revolution are still uncertain, CUBE-4.0 brought a new maturity concept as an input, i.e., to know the readiness level of my company is also necessary to assess how mature its main operation processes are, because processes are extremely dynamic and with maturity also evolving.

For example, unlike the models Unny and Lal [74], Gaur and Ramakrishnan [76], Nick et al. [79], Azevedo and Santiago [80], Basl [48], and Amaral and Peças [19], CUBE-4.0 details all its elements and output levels. Similarly, while some models, such as Rojas et al. [28], have no input dimensions, CUBE-4.0 has its input dimensions intensively detailed.

Moreover, unlike models, such as Ganzarain and Errasti [42] and Weber et al. [92], which do not have a questionnaire to implement their evaluation, the CUBE-4.0 Questionnaire is easy to fill out, short, efficient, and presents a practical and objective calculation method. The CUBE-4.0 Model was applied to three different sizes of engineering companies, and was tested and validated in practice, fully evaluating its usefulness as a benchmarking tool.

While models, like Schuh et al. [7], lack technological aspects and make it difficult to understand the differences between "maturity analysis for I4.0" and a "generic improvement analysis to increase anything in the company's performance", the CUBE-4.0 Model has a technological dimension with seven elements just to analyze this in detail.

Therefore, unlike models such as Schumacher et al. [6], Trotta and Garengo [73], Nick et al. [79], Azevedo and Santiago [80], Rojas et al. [28], Basl [48], Ifenthaler and Egloffstein [78], Osorio-Sanabria et al. [81], Merkus et al. [61], Amaral and Peças [19], Ramos et al. [30], and Zoubek and Simon [27], which do not present essential information about their models, CUBE-4.0 Model has all its structure, dimensions, sub-dimensions, elements, stages, layers, evaluating levels, tools, questionnaire, roadmap, and data collection and calculation's method, extensively described and detailed with well-defined and transparent concepts, making it easier and avoiding subjectivity for practical application.

b) Have only a theoretical development

Some models, like Leyh et al. [18] (see Chapter 2), have only a theoretical development (based on Literature Review), not validated in the real-life application; while CUBE-4.0 Model has an extensive empirical development, as well as tested, applied, and validated in engineering companies.

c) Focus only on technology

Some models like Rockwell [84] and Schuh et al. [7] focus only on the technological facets, inadequately addressing the organizational and operational-related dimensions (including the whole supply-chain integration). However, CUBE-4.0 Model, beyond the technological aspect (IT and Production Technology), includes organizational (Organizational Strategy and Human Workforce) and operation process maturity (Product-service Development and Order Fulfillment) enablers. Thus, all company factors could be evaluated with this Model, avoiding a technologically heavy approach to process improvement.

Besides, CUBE-4.0 analyzes the entire supply-chain integration in the enterprise, while many models do not deal with a process view connecting this value chain.

d) High implementation costs

While Felch and Asdecker [29] identify MMs with high implementation costs, CUBE-4.0 has practically zero implementation costs for the company. For example, there is a low cost involved during the step "Data Collection and Survey", precisely because it involves few respondents and little time in this process. However, for the future CUBE-4.0 step "Deploy and Maintain", the costs of implementing improvements will depend on the level of readiness and commitment of each company.

e) Have poor bibliograph review

As well as some existing models, such as Zoubek and Simon [27], Silva et al. [65], Basl [48], Pirola et al. [14], and Caiado et al. [22], the CUBE-4.0 Model also provides a systematic review of the literature, but with a more complete and detailed approach (it has the largest number of models analyzed: 63 models).

f) Just repeat the same concepts of existing models

Although some models just repeat or extend the same concepts of existing ones, CUBE-4.0 Model is a disruptive and innovative Model, with unprecedented characteristics and advantages, as described before.

g) Fails to consider some key technologies

Even for models that focus only on technology, some of them (like IMPULS, [26]) do not consider some key technologies and how they impact enterprise performance, such as AI (Artificial Intelligence). Besides, they have a vague description of how technologies can be used for company integration, compared to the CUBE-4.0 Model. In many cases, digital skills and technologies outside of IT are not discussed, while the CUBE-4.0 Model considers the major types of technology, broadly classified between anthropomorphic, cognitive, managerial, network production, and IT systems.

h) Have limitations during the validation process

Many models have limitations during the validation process: (1) apply only in a few enterprises, (2) in a specific country (regional bias), (3) within a specific industry, (4) with a small number of respondents, and/or (5) do not consider people from different departments to fill out the questionnaire.

About the target audience, CUBE-4.0 Model was applied in three enterprises in Brazil (three different and important types: steel, electric and electronic enterprises), with an average of three respondents per survey, such as Felch and Asdecker [29] and Santos and Martinho [66]. This is part of a recognized and efficient scientific methodology (explained previously). Besides, models like Singapore [87] do not consider people from different departments to fill out the questionnaire, while CUBE-4.0 Model considers managers from various departments, corresponding to the main processes analyzed. So, for CUBE-4.0 the most important is the origin, quality, and reliability of the answers, not the number of them.

Finally, although the CUBE-4.0 Model has few falsifiability tests and is strongly based on deductive thinking, it has been well-validated by subject matter experts in scientific, academic, and business contexts.

i) Have limitations for application in the companies

Some models have application limitations: (1) cannot be applied to every type of company, size, and economic sector, (2) limit the target audience of respondents, (3) use delayed data from companies, so the survey is always no longer up-to-date, (4) have difficulty applying the validated questionnaire (because it has no web application, many types of output levels, difficulties for score calculation, and/or needs professional judgment to interpret the results).

In this context, while some models, such as Rojas et al. [28], Pacchini et al. [46], and Zoubek and Simon [27], are only applicable to a specific industry, the CUBE-4.0 Model can be applied to every type of industry, size, and economic sector, and considers respondents (managers) from various departments. Besides, in future work, its application in other types of companies (not only industries) will be studied. Moreover, considering the CUBE-4.0 methodology of survey application, the information obtained with the CUBE-4.0 Questionnaire is always up-to-date and can be used reliably.

Different from models, such as Lichtblau et al. [26], Rockwell [84], De Carolis et al. [15], Akdil et al. [64], and Canetta et al. [10], filling out the CUBE-4.0 Questionnaire is easy and efficient, which emphasizes the process view with tracking common company functions (such as IT and Production Technologies, Management and Human Factors, Engineering, R&D, Supply-chain, Production, and Sales), making easier to identify the right person in a company to answer the queries.

CUBE-4.0 is already available on internet-based, although there are already studies to improve the platform, also contributing to better results.

While models such as CMMI present two types of output levels ("continuous representation" and "staged representation"), making it difficult to use in the enterprise, in the CUBE-4.0 Model there is only one scale for readiness levels, facilitating its application.

Finally, CUBE-4.0 is so easy to apply that anyone in the company can employ it with the desired routine, reducing process costs and its dependence on external technology, including not requiring professional judgment to interpret the results.

Additionally, CUBE-4.0 created a methodology for presenting the results in a specific Roadmap (based on the "Company reaches" Approach), which was able to prevent companies with low readiness vector scores, from feeling embarrassed or unmotivated (see item 5.5.3.2).

j) Have only general diagnostics and recommendations

Considering the final results report, many models do not have recommendations and some models, like Schumacher et al. [6], Leyh et al. [18], Schuh et al. [7], Gökalp et al. [41], De Carolis et al. [15], Agca et al. [8], Pessl et al. [62], and Gajsek et al. [60], have only general diagnostics and recommendations. CUBE-4.0 Model also has a Roadmap with general recommendations to drive the transition from the current readiness level to the desired one. But for future work, specific recommendations with detailed planning and development steps will be studied, with a clear definition of the action plan to instrument the I4.0 improvements. In addition, as Chonsawat and Sopadang [90] and Caiado et al. [22], CUBE-4.0 future research will develop decision-making in selecting the priority of improvement deployment and will evaluate readiness at different times, by applying a roadmap with periodic goals.

k) Do not have monitoring indicators

Many models, such as Chonsawat and Sopadang [90], do not have monitoring indicators and will develop them, like CUBE-4.0, in future work. As established in the CUBE-4.0 step - "Deploy and Maintain", only in this stage our model will have indicators to manage the CUBE-4.0 Model performance and the continuous improvements implemented in the company.

Therefore, based on the 63 models presented, the relevance of the CUBE-4.0 Model is verified as an essential contribution to this research stream, which addresses the limitations encountered, specially to provide a practical and easy-to-apply methodology with unprecedentedly defined and structured framework aimed at a company's readiness in the DT context.

7. Conclusion and Future Work

The CUBE-4.0 Model was structured in an unprecedented way and was approved after application and validation steps. Thus, the model demonstrated to be a potential tool for managing companies' readiness through the DT context, as it is easily applicable, complete, innovative, practical, and inexpensive. Only after practical application, in several engineering companies, of the Model's stage – "Deploy and Maintain", it will be possible to analyze if the Model helps a company to improve its readiness in this context.

The systematic literature review for the **OB.1** was performed with a specific 8-Steps Search Flow, whereby was possible to select relevant information from 486 studies out of ten databases, considering all the scientific literature on this subject worldwide. Sixty-three maturity and readiness existing models were analyzed and compared to identify the current problems and limitations in traditional approaches.

Then, to attend **OB.2**, the CUBE-4.0 Model was developed based on this previous information, and overcame the existing models' flaws, which contributes to this research stream. So, as an unprecedented contribution to the scientific literature related to this theme, through this new Model was possible to address these limitations by means of detailed features - including its **Framework** (dimensions, sub-dimensions, elements, levels, graphic type, calculation, and data collection method), **Questionnaire** and **Roadmap** - which provides: more benefits, best results, and easier practical forms of application in engineering enterprises.

Therefore, this thesis proposes the CUBE-4.0, as a Readiness Model for DT in any type, size, and readiness level of an engineering company, together with its Framework, Questionnaire, and Roadmap.

As a theoretical contribution, the CUBE-4.0 framework was elaborated, with 3 dimensions (X = Organizational Enabler, Y = Technological Enabler, and Z = Process

Maturity Enabler), 6 sub-dimensions, and 21 elements, along with a 0 to 5 scale to assess the company readiness level.

The CUBE-4.0 Model had six satisfactory steps for development. An industry experts focus group evaluated and validated the CUBE-4.0 Model's Framework, Questionnaire, and Roadmap granularity appropriateness. The CUBE-4.0 was also validated and praised with the application in three renowned engineering companies.

As expected, after testing the investigated phenomena (regarding the empirical validation of the deductive hypotheses), were found more situations in which the technological dimension of the Model was dominant. It will probably be the case for most Brazilian companies, which need to build the appropriate organizational enablers in an economic crisis and find that technological enablers are paths to reduce labor hours. As found in the case studies, more evolved companies might have a stronger balance among technological and organizational enablers. A strict focus on operation process maturity would probably be the least common profile. An interview-based protocol stressed this issue when this Model has been longitudinally applied in some companies to test its application as an improvement tool.

As a practical contribution, it presents an easy-to-apply form and provides a modern, innovative, and complete methodology for data collection (survey) and for a three-dimensional readiness vector R= (X,Y,Z) calculation. Additionally, CUBE-4.0 Model created a methodology for presenting the results, which was able to prevent companies with low readiness vector scores, from feeling embarrassed or unmotivated. All these implements result in a value for future comparison and allow to analyze the companies’ readiness level by showing a radar chart for easy understanding of their improvement profiles.

Therefore, the CUBE-4.0 Questionnaire provides an easy way to identify actions that can increase companies' readiness for DT. In addition, CUBE-4.0 Roadmap guides general strategies and important insights, based on the CUBE-4.0 Questionnaire results, to improve their readiness through the DT context.

Thus, about **OB.3**, based on these CUBE-4.0 concepts, it was possible to propose and validate a “CUBE-4.0 Questionnaire” for data collection and survey on readiness for DT in engineering companies.

Besides, relating to **OB.4**, it was proposed and validated a generical “CUBE-4.0 Roadmap”, based on the CUBE-4.0 Questionnaire results, to help corporate boards to guide strategies and plan improvements in their companies in this I4.0 Age.

After the bibliographic review and the CUBE-4.0 validation steps, this study also demonstrates findings about the previous propositions **PROP1** and **PROP2**.

About **PROP1**, it was concluded by theoretical analysis, that “maturity” is truly different from “readiness” when analyzing whether a company is prepared to implement DT. This difference could be better explained by Figure 41:

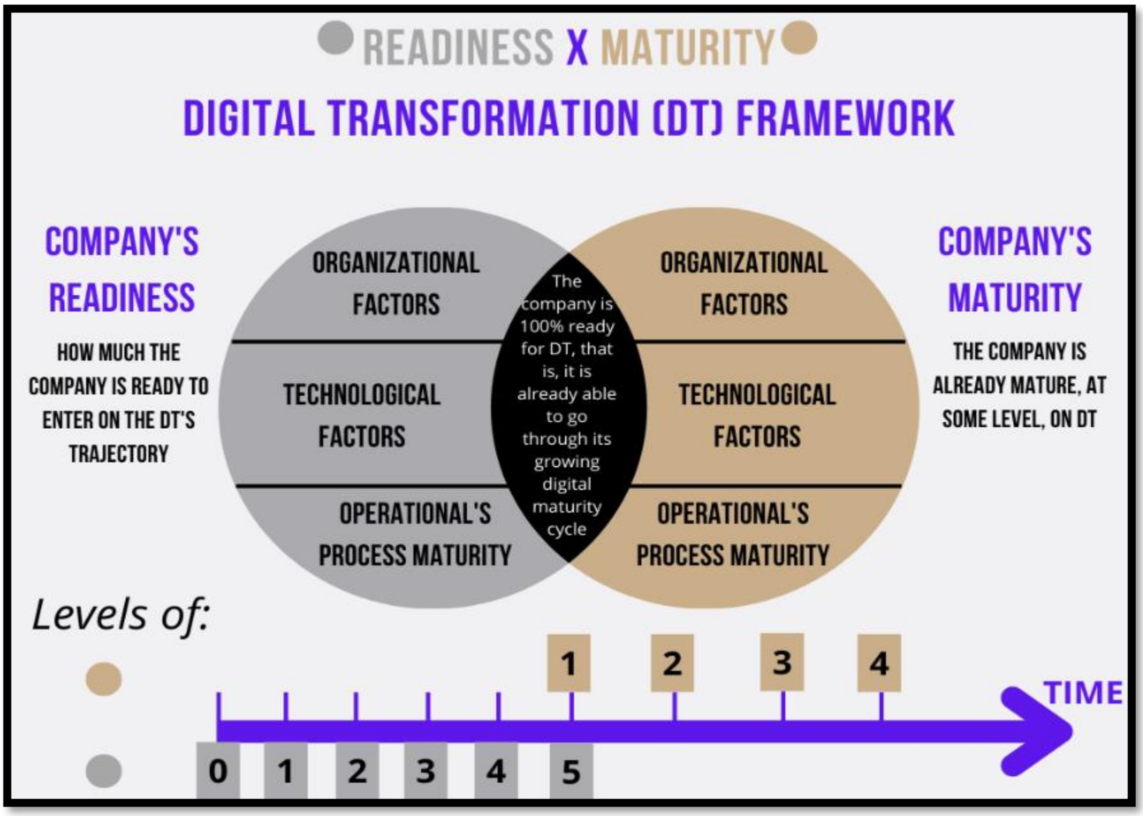


Figure 41: Digital Transformation Framework (Source: Author).

Accordingly, based on these concepts about "readiness" and "maturity" and, considering that DT is a new stretch, without a solid and consolidated maturity pattern, this thesis states that: "readiness" is related to how prepared the company is to enter the DT trajectory, while "maturity" is an idea that the company is already mature, at some level, in the DT context. We noted that no company has nowadays a mature process for I4.0 and DT. Consequently, our model is named as a Readiness Model, not a maturity model.

For future work, only after practical application, in several engineering companies, of the CUBE-4.0 Model's stage – "Deploy and Maintain", it will be possible to analyze the veracity of the four maturity levels proposed in Figure 41.

Regarding **PROP2**, one can conclude, also from the theoretical analysis, that process maturity can be an "input" (not "output" like in all other models), when analyzing whether a company is ready to implement I4.0 technologies in its operations, as it is, in the Product-Service Development and Order Fulfillment processes.

More so, according to the framework proposed in this thesis (see Figure 42), in future work it can be studied a new **PROP 3**: "the development of Digital Data is directly proportional to the company's level of digital maturity". In Figure 42, it is noted that the digitalization status represents the intersection between the 3rd and 4th industrial revolutions, which is being consolidated along processes 01 to 04. So, depending on its level of digital data integration, the company's processes can be evaluated from a maturity point of view. Future work could validate more deeply this new proposition.

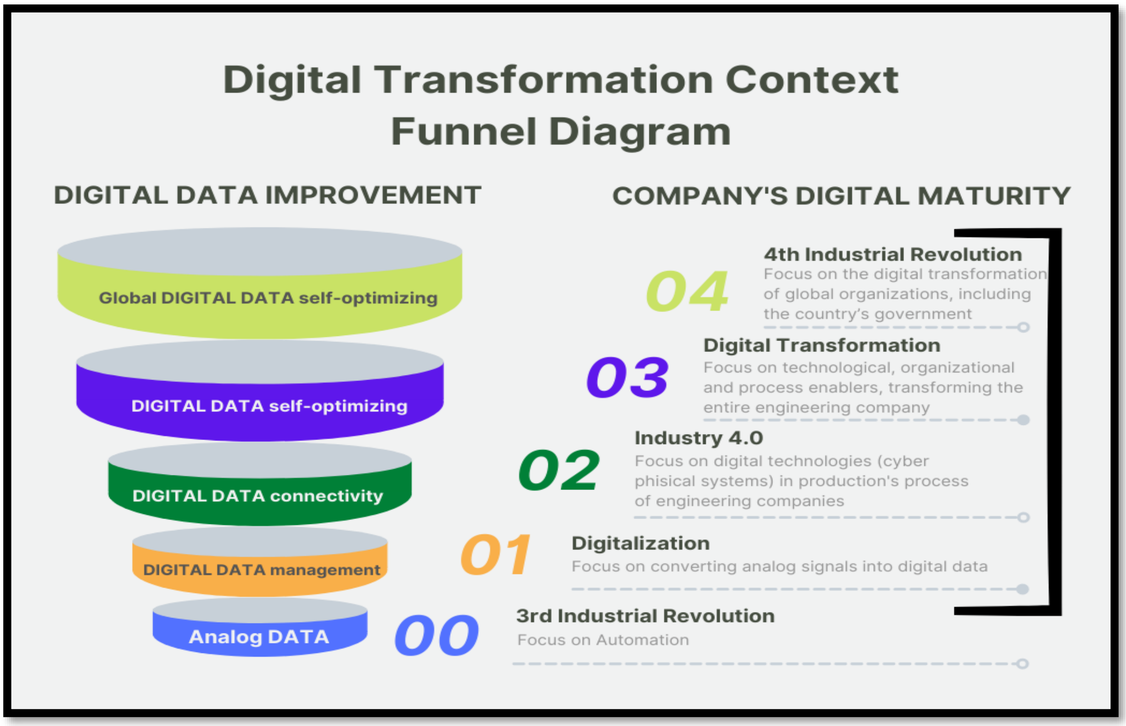


Figure 42: Framework about Digital Data and Digital Maturity (Source: Author, based on the Company Consultancy – see Chapter 4).

However, CUBE-4.0 has some limitations. The Model was built primarily by deduction from a literature review and observation of the current business environment. Although it has been tried out on a company and subjected to expert feedback, it has little falsifiability testing and is heavily based on deductive thinking. Consequently, like many current models for I4.0, most of its dimensions, sub-dimensions, and elements can be viewed as a hypothesis. In another hand, unlike many other models that tested their methodologies only in one company (as described in Appendix B), the CUBE-4.0 Model was validated in 3 different sizes and types of companies, generating satisfactory results. However, specific investigation protocols can be constructed to emphasize the Model in real-world based situations to test specific concepts. For example, a research protocol might explore the relationships between product-service development and order fulfillment for a specific company. Building a model as CUBE-4.0 at such an inopportune historical moment brought the research team many questions. Only specific protocols can help to clarify all the elements mixed up in the Model.

The Model has another limit, focusing on manufacturing companies. Therefore, its applicability is limited to this kind of company, and the transferability to other types is not yet addressed. Since I4.0 is outside the boundaries of the manufacturing industry (such as logistics, banking, agriculture, or trading companies), precise analysis and adaptation should be done before trying to implement CUBE-4.0 in these companies. This is a question to be addressed in forthcoming research. Furthermore, in the future, it may be applied to engineering companies outside Brazil, which has not yet occurred only due to the difficulties of the COVID-19 protocols.

In addition, the questionnaire will be published on a specific web-based platform to ensure confidentiality and obtain anonymous feedback since it is designed to allow self-assessment. Future research can evaluate the applicability of CUBE-4.0 in this access' format.

Possibilities of cross-checking between an Internet-based filling, and a face-to-face-based application, may be interesting to understand possible differences in the Model dimensions, sub-dimensions, and elements. In addition, the Model was constructed with our best knowledge of technology trends in mind. Future research could question these expectations, and CUBE-4.0 is a solid framework for exploring them.

For future work, the roadmap's specific recommendations will be studied further, with detailed planning, practical development steps, and a clear definition of the final action plan implementation. These improvements could be combined with the organization's Business Intelligence (BI), displaying the results in a dashboard for real-time management.

Besides, it will be studied, for the future step "Deploy and Maintain", an improvement implementation in monitoring during the next six months after the CUBE-4.0 Questionnaire first application, such as some indicators, using the proposed CUBE-4.0 Roadmap to achieve the DT Readiness.

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9. APPENDIX

APPENDIX A: STEPS OF THE BIBLIOGRAPHIC METHODOLOGY

In Table A.1, it will be detailed the steps of the Bibliographic Synonyms Test (BST):

Table A.1 - Bibliographic Synonyms Test steps (Source: Author).

STAGES OF THE BIBLIOGRAPHIC SYNONYMS TEST	
START: WHEN IT IS NOT POSSIBLE TO SEARCH WITH ALL STRINGS FOUND (ACCORDING TO THE EQUATION BELOW) OR WHEN THE RESULT OF THIS SEARCH HAS BEEN NULL. **Initial Equation:** **(ALL STRINGS FOUND IN THE PICOS DIAGRAM)** ***Note:*** *use AND between different keyword strings and OR between strings referring to the same keyword.*	
1.	Search in the PICOS diagram, third column "Keyword origin", the keyword for "$O_{OUTCOME}$" **– THAT WILL BE THE MAIN KEYWORD 1** ***Note:*** *Whenever possible, you should choose only one keyword as OUTCOME. However, in case of impossibility, put all OUTCOME keywords as MAIN KEYWORD 1.*
2.	Search in the PICOS diagram, third column "Keyword origin", the keyword for the "$S_{STUDYDESIGN}$" **– THAT WILL BE THE MAIN KEYWORD 2** ***Note:*** *Whenever possible, you should choose only one keyword as STUDY DESIGN. However, in case of impossibility, put all STUDY DESIGN keywords as MAIN KEYWORD 2.*
3.	Search the PICOS diagram, third column "Keyword origin", all other keywords found.
	3.1 If the total number of selected keywords (including the main keywords 1 and 2) is > 8, it is suggested to redo the PICOS diagram, in order to find a maximum of 8 keywords. For a total number greater than 8, a scientific search may lose focus and be impaired.
	3.2 If the total number of keywords selected is ≤ 8, you can go to step (4).
4.	Elaborate a table "$STRING_{(ROW)}$ x $DATABASE_{(COLUMN)}$" with all selected keywords and their respective strings, which are in the last column "Keyword Strings" of the PICOS Diagram
5.	In each database, perform the search for each string, separately, and include in the table its respective total number of studies found (S)
6.	For each database, within each keyword, the string with the highest number of studies should be selected ($S_{\text{MÁX}}$)
	5.1 If the total number of keywords selected is = 8, you can go directly to step (8).
	5.2 If the total number of keywords selected is < 8, you can go to step (7).
7.	To select the other strings, for each keyword, the following steps should be followed:
	7.1 Select those strings whose number of studies found (S) is up to 20% lower than the number of studies of the string that has the highest number of studies ($S_{\text{MÁX}}$), that is, select all synonyms whose number of studies (S) is in the interval between: ($S_{\text{MÁX}}$) and ($S_{\text{MÁX}}$ - 20% $S_{\text{MÁX}}$). The objective is to verify if there is any other string with a number of studies (S) justifiable to be selected, along with the string chosen in item (6).
	7.2 If, in this step (7.1), one or more strings satisfy this requirement, follow directly to step (8).
	7.3 However, if the result of this analysis (7.1) is zero, the second step would be, for each keyword and in each database, to calculate the average of the total number of studies of all respective synonyms ($S_{AVERAGE}$), selecting those synonyms whose $S > S_{AVERAGE}$.
	7.4 If, in this step (7.3), one or more strings satisfy this requirement, follow directly to step (8).
	7.5 However, if this stage (7.3) presents zero result, the synonym selected in item (6), that is, having the largest number of studies ($S_{\text{MÁX}}$), will be, in fact, the only one selected.
	7.6 If the total number of strings selected after (7.5) is = 8, go to step (8).
	7.7 If the total number of strings selected after (7.5) is < 8:

	- include strings, perhaps not yet considered, referring to keywords 1 and 2, in descending order of the number of studies to complete the 8 strings - later, if the 8 strings are not yet obtained, those with a greater number of studies should be selected, comparing them among all the keywords considered, until the 8 strings are completed - if it still doesn't reach 8 strings, you must go to step (8)
	7.8 If the total number of strings selected after (7.5) is > 8, only 8 strings should be selected as follows: - note the need for at least 1 string for each PICOS keyword - keep only strings referring to keywords 1 and 2 in descending order of number of studies - later, if there are still more than 8 strings, those in increasing order of number of studies should be excluded until the 8 strings are completed - go to step (8)
8.	Elaborate two Boolean equations and perform the search, for each database, with the 8 strings selected, as follows: **1st Equation: ("MAIN STRING 1" AND "MAIN STRING 2") AND ("STRING 3" AND/OR "STRING 4" AND/OR "STRING 5" AND/OR "STRING 6" AND/OR "STRING 7" AND/OR "STRING 8")** **2nd Equation: ("MAIN STRING 1" AND "MAIN STRING 2") AND ("STRING 3" OR "STRING 4" OR "STRING 5" OR "STRING 6" OR "STRING 7" OR "STRING 8")** Where: - MAIN STRING 1 = is the main keyword string 1 selected. If there is more than one string and/or more than one main keyword 1, all its selected strings should be placed in step (7) within these quotes **"MAIN STRING 1"**, separated by OR from each other - MAIN STRING 2 = is the main keyword string 2 selected. If there is more than one string and/or more than one main keyword 2, all its selected strings should be placed in step (7) within these quotes **"MAIN STRING 2"**, separated by OR from each other - **AND/OR** (from 1st Equation) = means that AND will be used between different keyword strings and OR between strings referring to the same keyword In cases of specific strings, unpublished and/or with few studies, it is also recommended to perform the search with this 3rd Equation, for each database, to obtain a general idea of the theme in the scientific environment: **3rd Equation: (("STRINGS OF THE MAIN KEYWORD 1") AND ("STRINGS OF THE MAIN KEYWORD 2"))** Where: - for the 3rd Equation, these are the strings selected in step (7) for the main keywords 1 and 2 - AND will be used between different keyword strings and OR between strings referring to the same keyword - if they exceed 8 strings, go to step (4) Only in exceptional cases where it is impossible to use Equations IE, (1), (2), and (3), it is recommended to use Equation (4) below: **4th Equation: (("STRINGS OF THE MAIN KEYWORD 1") AND ("STRINGS OF THE MAIN KEYWORD 2"))** Where: - for the 4th Equation, these are all strings found in the column of the PICOS Diagram: Keyword Strings, for the main keywords 1 and 2 - AND will be used between different keyword strings and OR between strings referring to the same keyword - if they exceed 8 strings, go to step (4)
9.	To choose the number of studies to be considered, for each database, among the 4 options generated by the 4 equations, we must follow the steps below in this order:
	9.1 where possible, prioritize the results generated by the IE
	9.2 if the results of 9.1 are null, ≤10, or ≥ 200, the results of Equation 2 shall be used

	9.3 if the results of 9.2 are null, ≤10, or ≥ 200, the results of Equation 3 shall be used
	9.4 if the results of 9.3 are null, ≤10, or ≥ 200, the results of Equation 4 shall be used
	9.5. if the results of 9.4 are null or ≤ 10: 9.5.1: use the result of the equation with the largest number of studies 9.5.2: if the highest result is repeated for two or more equations, the equation should be chosen in this order of priority: (EI), (1), (2), (3), or (4) 9.5.3: if the result has been null for all equations, the database should be discarded
	9.6 if the results of all equations are ≥ 200, use the result of the equation which has obtained the least number of studies.
THE END: FINALIZE THE SYNONYMS TEST.	

NOTE: it is important to note that the restriction of the sampling space of the search is in descending order from equation (1) to (4), therefore the number of studies tends to increase from (1) to (4). thus, whenever possible use the IE – Initial Equation (it is the equation that best transcribes the subject under study, more assertively and completely), then a (1), (2), (3), and (4) successively.

Therefore, in Table A.2, it can be seen the BST results: for each keyword, it is possible to verify, for each of the 10 databases, the number of studies found for each researched synonym (for example: for the keyword "model", different amounts of studies were found for the three correlated synonyms: “capability model”, “maturity model” and “readiness model”). Besides, for each keyword, in the line “20%”, there is the result, for each database, of 20% of the highest number of studies (considering all synonyms), while in the line “average” it can be seen the average of the numbers of studies for all correlated synonyms. Finally, in the line “approved string”, there are the final results synonyms for each keyword.

Table A.2 - Bibliographic Synonyms Test results (Source: Author).

SYNONYMS		SCOPUS	WoS	SCIENCE DIRECT	SPRINGER	WILEY	EBSCO	AAAS	ACM	RG*	ERIC
MODEL	CABABILITY MODEL (CM)	713	0	825	1.568	437	219	6	201	100	54
	MATURITY MODEL (MM)	4.650	2.453	3.393	6.231	2.544	1.105	1	1.124	100	62
	READINESS MODEL (RM)	304	207	200	314	151	294	0	23	100	69
	20%	3.720	1.962	2.714	4.985	2.035	884	5	899	*	55
	AVERAGE	1.889	887	1.473	2.704	1.044	539	2	449	*	
	APPROVED STRING	MM	MM	MM	MM	MM	MM	CM	MM	*	MM RM
4.0	INDUSTRY 4.0 (I 4.0)	14.666	8.234	8.440	9.664	1.337	2.125	5	794	100	60
	DIGITAL TRANSFORMATION (DT)	6.026	3.183	3.163	8.724	1.509	2.666	8	686	100	66
	20%	11.733	6.587	6.752	7.731	1.207	2.133	6	635	*	53
	AVERAGE	10.346	5.709	5.802			2.396	7		*	
	APPROVED STRING	I 4.0	I 4.0	I 4.0	I 4.0 DT	I 4.0 DT	I 4.0	I 4.0	I 4.0 DT	*	I 4.0 DT
ROADMAP**		26.535	16.634	42.218	50.120	20.521	31.814	753	6.217	100	753
SKILL	SKILL	578.458	99.960	796.808	867.303	272.999	397.019	6.415	25.322	100	286.249
	SKILL 4.0	7	0	27	18	6	4	0	38	4	6
	20%	462.766	79.968	637.446	693.842	218.399	317.615	5.132	20.258	80	228.999
	AVERAGE	289.233	49.980	398.418	433.661	136.503	198.512	3.208	12.680	52	143.128
	APPROVED STRING	skill	skill	skill	skill	skill	skill	skill	skill	skill	skill
COMPANY	BUSINESS	1.096.517	359.065	860.070	3.165.197	838.265	2.098.962	24.974	93.325	100	68.429
	CORPORATE	162.086	124.163	263.395	351.920	297.173	539.223	3.785	21.110	100	8.816
	COMPANY	905.236	180.421	1.854.822	1.404.458	828.884	1.786.845	39.539	62.942	100	13.783
	ENTERPRISE	322.643	103.810	290.651	509.325	186.299	375.481	7.467	43.277	100	10.432
	20%	877.214	287.252	1.483.858	2.532.158	670.612	1.679.170	31.631	74.660	*	54.743
	AVERAGE		191.865	817.235	1.357.725			18.941	55.164	*	25.365
	APPROVED STRING	business company	business	business company	business company	business company	business company	business company	business company	*	business
EDUCATION	TRAINING	1.208.786	791.240	1.362.734	1.754.591	934.172	1.495.207	29.696	130.897	100	201.960
	EDUCATION	2.140.624	1.058.147	1.688.010	1.889.544	1.629.727	2.601.268	42.503	104.363	100	1.273.797
	LEARNING	1.747.902	1.119.868	1.132.584	1.945.839	763.948	1.347.569	20.216	198.752	100	503.288
	EDUCATION 4.0	201	97	103	314	55	48	0	14	100	27
	DIGITAL EDUCATION	765	591	322	4.907	240	17.903	1	186	100	521
	20%	1.712.499	895.894	1.350.408	1.556.671	1.303.782	2.081.014	34.002	159.002	*	1.019.038
	AVERAGE					665.628	1.092.399	18.483	86.842	*	395.919
	APPROVED STRING	education learning	education learning	education training	education learning training	education learning training	education learning training	education learning training	education learning training	*	education learning

Notes:
* For the Research Gate database, the largest number of studies per survey is 100 studies. Therefore, this database was not considered for the BST. So, by limiting the Research Gate software, it is not possible to select strings for the equations (1), (2), and (3).
** This term has no synonyms.
- Strings must be in the English language for their search in the databases.
- A keyword may have one or more strings (descriptors, synonyms).
- Based on the Authors' experience and the bibliographic references studied, the main strings were selected for each keyword contained in the previous table.
- To find more results and not to limit the search in the database about the chosen context (Brazil), we chose to consider these more generic strings.
- "O" and "S" shall be the essential search requirements in the databases, that is to say, they have the main keywords 1 and 2 respectively, in Bibliographic Synonyms Test - BST.
- The search fields for the database search were limited to abstract, title, and keywords. The search terms themselves resulted from a short preliminary search according to [155] and were afterward discussed with researchers at the respective university institutes.

Finally, in Table A.3, there are the final Boolean Equations for each database:

Table A.3 - Results of the Boolean Equations after the BST (Source: Author).

DATABASES	BOOLEAN EQUATIONS WITH SELECTED STRINGS
BEFORE BST:	
FOR ALL	**INITIAL EQUATION (IE):** (((“CAPABILITY MODEL” OR “MATURITY MODEL” OR “READINESS MODEL”) AND (“INDUSTRY 4.0” OR “DIGITAL TRANSFORMATION”)) AND ((SKILL OR “SKILL 4.0”) AND (BUSINESS OR CORPORATE OR COMPANY OR ENTERPRISE) AND (TRAINING OR EDUCATION OR LEARNING OR “EDUCATION 4.0” OR “DIGITAL EDUCATION”)))
AFTER BST:	
SCOPUS	**1st:** (“MATURITY MODEL” AND “INDUSTRY 4.0”) AND ((ROADMAP) AND (SKILL) AND (BUSINESS OR COMPANY) AND (EDUCATION OR LEARNING)) **2nd:** (“MATURITY MODEL” AND “INDUSTRY 4.0”) AND ((ROADMAP) OR (SKILL) OR (BUSINESS OR COMPANY) OR (EDUCATION OR LEARNING)) **3rd:** (“MATURITY MODEL” AND “INDUSTRY 4.0”)
WoS	**1st:** (“MATURITY MODEL” AND “INDUSTRY 4.0”) AND ((ROADMAP) AND (SKILL) AND (BUSINESS) AND (EDUCATION OR LEARNING)) **2nd:** (“MATURITY MODEL” AND “INDUSTRY 4.0”) AND ((ROADMAP) OR (SKILL) OR (BUSINESS) OR (EDUCATION OR LEARNING)) **3rd:** (“MATURITY MODEL” AND “INDUSTRY 4.0”)
SCIENCE DIRECT	**1st:** (“MATURITY MODEL” AND “INDUSTRY 4.0”) AND ((ROADMAP) AND (SKILL) AND (BUSINESS OR COMPANY) AND (EDUCATION OR TRAINING)) **2nd:** (“MATURITY MODEL” AND “INDUSTRY 4.0”) AND ((ROADMAP) OR (SKILL) OR (BUSINESS OR COMPANY) OR (EDUCATION OR TRAINING)) **3rd:** (“MATURITY MODEL” AND “INDUSTRY 4.0”)
SPRINGER	**1st:** (“MATURITY MODEL” AND (“INDUSTRY 4.0” OR “DIGITAL TRANSFORMATION”)) AND ((ROADMAP) AND (SKILL) AND (BUSINESS) AND (EDUCATION OR LEARNING OR TRAINING)) **2nd:** (“MATURITY MODEL” AND (“INDUSTRY 4.0” OR “DIGITAL TRANSFORMATION”)) AND ((ROADMAP) OR (SKILL) OR (BUSINESS) OR (EDUCATION OR LEARNING OR TRAINING)) **3rd:** (“MATURITY MODEL” AND (“INDUSTRY 4.0” OR “DIGITAL TRANSFORMATION”))
WILEY	**1st:** (“MATURITY MODEL” AND (“INDUSTRY 4.0” OR “DIGITAL TRANSFORMATION”)) AND ((ROADMAP) AND (SKILL) AND (BUSINESS OR COMPANY) AND (EDUCATION OR TRAINING))

	2nd: ("MATURITY MODEL" AND ("INDUSTRY 4.0" OR "DIGITAL TRANSFORMATION")) AND ((ROADMAP) OR (SKILL) OR (BUSINESS OR COMPANY) OR (EDUCATION OR TRAINING)) **3rd:** ("MATURITY MODEL" AND ("INDUSTRY 4.0" OR "DIGITAL TRANSFORMATION"))
EBSCO	**1st:** ("MATURITY MODEL" AND "INDUSTRY 4.0") AND ((ROADMAP) AND (SKILL) AND (BUSINESS OR COMPANY) AND (EDUCATION OR LEARNING OR TRAINING)) **2nd:** ("MATURITY MODEL" AND "INDUSTRY 4.0") AND ((ROADMAP) OR (SKILL) OR (BUSINESS OR COMPANY) OR (EDUCATION OR LEARNING OR TRAINING)) **3rd:** ("MATURITY MODEL" AND "INDUSTRY 4.0")
AAAS	**1st:** ("CAPABILITY MODEL" AND "INDUSTRY 4.0") AND ((ROADMAP) AND (SKILL) AND (BUSINESS OR COMPANY) AND (EDUCATION OR LEARNING OR TRAINING)) **2nd:** ("CAPABILITY MODEL" AND "INDUSTRY 4.0") AND ((ROADMAP) OR (SKILL) OR (BUSINESS OR COMPANY) OR (EDUCATION OR LEARNING OR TRAINING)) **3rd:** ("CAPABILITY MODEL" AND "INDUSTRY 4.0")
ACM	**1st:** ("MATURITY MODEL" AND "INDUSTRY 4.0") AND ((ROADMAP) AND (SKILL) AND (BUSINESS OR COMPANY) AND (EDUCATION OR LEARNING OR TRAINING)) **2nd:** ("MATURITY MODEL" AND "INDUSTRY 4.0") AND ((ROADMAP) OR (SKILL) OR (BUSINESS OR COMPANY) OR (EDUCATION OR LEARNING OR TRAINING)) **3rd:** ("MATURITY MODEL" AND "INDUSTRY 4.0")
RG	*
ERIC	**1st:** (("MATURITY MODEL" OR "READINESS MODEL") AND ("INDUSTRY 4.0" OR "DIGITAL TRANSFORMATION")) AND ((ROADMAP) AND (SKILL) AND (BUSINESS) AND (EDUCATION OR LEARNING)) **2nd:** (("MATURITY MODEL" OR "READINESS MODEL") AND ("INDUSTRY 4.0" OR "DIGITAL TRANSFORMATION")) AND ((ROADMAP) OR (SKILL) OR (BUSINESS) OR (EDUCATION OR LEARNING)) **3rd:** (("MATURITY MODEL" OR "READINESS MODEL") AND ("INDUSTRY 4.0" OR "DIGITAL TRANSFORMATION"))
IN THIS STUDY, THE 4th EQUATION BELOW WILL BE USED ONLY IF THE PREVIOUS ONES ARE NOT SATISFACTORY:	
FOR ALL	**4th:** (("MATURITY MODEL" OR "READINESS MODEL" OR "CAPABILITY MODEL") AND ("INDUSTRY 4.0" OR "DIGITAL TRANSFORMATION"))

Therefore, after testing the synonyms, these were the final keywords selected for this doctoral thesis: *READINESS, MATURITY MODEL, ENGINEERING COMPANY, INDUSTRY 4.0, DIGITAL TRANSFORMATION.*

APPENDIX B: Analysis of 63 models (Source: Author).

N	Author	Country	Year	Enterprise Type	Model Name	Model Type	Input Dimensions	Output Levels	Main Output	Tested?	Critical Analysis
1	R. L. Nolan	EUA	1973	General Enterprises	Computer Resource MM	Computer Resource	(1) Priority setting (2) Budget (3) Computer operations (4) Programming control (5) Project management (6) Mgt. reporting system (7) Data base policies (8) Chg. out/non-chg. out systems (9) Audits (10) Quality control (11) Manual systems and procedures	1: Initiation 2: Contagion 3: Control 4: Integration	Maturity	Yes	Topic not applicable nowadays. This model was important for later models but had old templates and no web application. Similarly, some models use delayed data of the enterprises, so they are no longer up-to-date.
2	K. Lichtblau et al.	Germany	2015	Large and SME Enterprises (Mechanical, Plant Engineering, and Manufacturing industries)	IMPULS	Smart Manufacturing	(1) Strategy & organization (2) Smart factory (3) Smart operations (4) Smart products (5) Data-driven services (6) Employees	0: Outsider 1: Beginner 2: Intermediate 3: Experienced 4: Expert 5: Top performer	Readiness	Yes	Lichtblau et al. (2015) state some questions of the online IMPULS form that do not follow a profile of the six levels as the maturity model proposes. It brings a question of why they appear in the form. Moreover, a juxtaposition of dimensions, for example, among smart factories and smart operations, could generate doubts for respondents regarding the clarity of each dimension and their questions to answer. It emphasizes the process view without tracking the common company functions such as engineering, marketing, manufacturing, and finance; however, most companies are structured in these functional units. Therefore, it can be difficult to identify the right person in a company who is familiar with the model's queried information. The model is only empirically grounded. It uses a questionnaire, but it is not transparent and not validated, and it has just an online self-assessment based on a questionnaire. It doesn't describe an assessment method; it is for readiness only and doesn't consider all organizational aspects. The model is only empirically grounded. The model does not consider a few key technologies such as AI, AR, VR, smart glasses, and Blockchain Technology. The weights of each dimension are decided but not for the items, and they are decided only with the help of a survey conducted in the firms.
3	M. C. Paulk, B. Curtis, M. B.	EUA	1993	General Enterprises	CMM (Capability Maturity Model)	General	(1) Commitment to perform (2) Ability to perform	1: Initial 2: Repeatable	Capability	Yes	Traditional models, like CMM and its variations, were built only for well-established processes, such as software or product development. However, the outcomes of the

	Chrissis, C. V. Weber						(3) Activities performed (4) Measurement and analysis (5) Verifying implementation	3: Defined 4: Managed 5: Optimizing			new industrial revolution are still uncertain, especially when the processes involved are not known. So, the CMM is not a silver bullet and does not address all the important issues for successful projects in Industry 4.0. For example, it does not currently address expertise in particular application domains, advocate specific software technologies, or suggest how to select, hire, motivate, and retain competent people. However, these issues are crucial to a project's success.
4	A. Schumacher et al.	Austria	2016	General Manufacturing Enterprises (not SME)	I 4.0 Schumacher MM	Smart Manufacturing	(1) Strategy (2) Leadership (3) Customers (4) Products (5) Operations (6) Culture (7) People (8) Governance (9) Technology	1: Complete lack of attributes 2: (no info) 3: (no info) 4: (no info) 5: State-of-the-art	Maturity	Yes	Schumacher et al. (2016) lack a process view connecting the whole supply-chain. The model didn't address the lean aspects or identify improvement opportunities or a roadmap for further developments. Furthermore, an SME perspective is also missing from the model. It uses a validated questionnaire, but it is not a transparent methodology. It doesn't have a maturity definition or just general recommendations. The model extends existing maturity models and focuses on discrete manufacturing firms. It lacks details regarding maturity items and inadequate information regarding maturity levels.
5	M. B. Chrissis et al.	EUA	2003	General Enterprises	CMMI (Capability Maturity Model Integration)	General	(1) Systems Engineering (2) Software Engineering	0: Incomplete - Doesn´t have any process 1: Performed - No support infrastructure 2: Managed - Not performed across the organization 3: Defined - Doesn't have a way to measure and improve 4: Quantitatively Managed - Can quantitatively maximize business 5: Optimized - Has all of these characteristics	Capability	Yes	Chrissis et al. (2003) state some clauses that are difficult to map. It is difficult to use and needs professional judgment to interpret the results, and input dimensions are difficult to understand. Output levels differ from Continuous and Staged representation capability levels. Not feasible for a web-based application.
6	De Bruin et al.	Australia	2005	General Enterprises	BPM - MM (Business Process Management Maturity Model)	General	(1) Factor (2) Maturity Stage (3) Scope Organizational Entity (4) Scope Time (5) Coverage (6) Proficiency	1: Initial State 2: Defined 3: Repeated 4: Managed 5: Optimized	Maturity	Yes	This model is incomplete at this stage and the impact of their findings and success in overcoming/minimizing inherent criticism is unknown. At this stage, there is no empirical evidence for the correlation between the factors of the BPMM model and BPM success. Further testing of the relationship between independent and dependent variables will be the core of future work.

7	C. Leyh et al.	Germany	2016	SME	SIMMI 4.0 (System Integration Maturity Model Industry 4.0)	IT and Software (digital integration technologies)	(1) Vertical integration (2) Horizontal Integration (3) Digital product development (4) Intersection of technologies (cross-sectional technology criteria)	1: Basic Digitalization 2: Crossed 3: Horizontal 4: Vertical 5: Total	Maturity	No	Leyh et al. (2016) are rather vague when describing how technology can be used for integration. Organizational enablers are treated as elements of maturity levels. Digital competencies and technologies outside the field of IT are not discussed. The model is simple to understand with a focus on the IT landscape in SMEs, but it doesn't have a questionnaire, assessment method described, or continuous assessment. It just has general recommendations. The scientific documentation of model development is missing, and it is not empirically developed, validated, and tested. The details about the maturity assessment and readiness level are missing. Derivated from RAMI 4.0 (The Reference Architectural Model Industry 4.0), the model is missing in crucial dimensions, like organizational awareness and cybersecurity.
8	M. Kerrigan	Ireland	2013	General Enterprises	DI-CMM (Digital Investigations Capability MM)	Digital investigations	(1) Processes (2) People (3) Technology	1: Ad-hoc 2: Performed 3: Defined 4: Managed 5: Optimized	Capability	Yes	Kerrigan (2013) proposes the DI-CMM Model. It needs to be tested against more organizations to assess its usefulness fully as a benchmarking tool. While the DI-CMM has been developed with the needs of regulatory bodies and criminal investigations in mind, further refinement could make it applicable to various other sectors; for example, large corporations that maintain internal digital investigations capabilities.
9	R. Geissbauer et al.	USA	2016	Companies with more than 500 employees, interaction company-customer	PwC SA (PriceWaterhouseCoopers)	SCM scope	(1) Processes & Infrastructure (2) Vision, Strategy & Business Model (3) Customer Engagement (4) People, Culture, Governance & Organization (5) Product and service portfolio (6) Market and customer access (7) Value chain (8) IT architecture (9) Compliance, risk, security, tax	1: Beginner 2: Vertical Integrator 3: Horizontal Collaboration 4: Digital Specialist	Readiness	Yes	Geissbauer et al. (2016) is a consulting-based model, not an applied scientific effort. The maturity dimensions are not elaborated on in detail. Considering it was proposed in 2016 when the effort to propose maturity models was starting, some maturity levels and dimensions lack synergy. It doesn't use a traditional questionnaire and a transparent methodology. It has just an online self-assessment. The scientific documentation of the model is missing.
10	Rockwell Automation Inc	USA	2014	General Enterprises	ROCKWELL	Smart Manufacturing	(1) Customer-focused innovation (2) Process improvements (3) Supply-chain management & collaboration (4) Human-resource management (5) Sustainability (6) Global Engagement	1: Assessment 2: Secure & upgraded network and controls 3: Defined & organized working data capital 4: Analytics 5: Collaboration	Readiness	Yes	It uses a validated questionnaire but is not a transparent methodology with no explicit assessment approach. The model focuses only on the facets of the existing IT/OT network and inadequately addresses the organizational and operations-related dimensions. The model has insufficient details about its structure and maturity items and notably lacks scientific documentation.

11	J. Ganzarain, N. Errasti	Spain	2016	SME	3SMM (3 Stage MM)	Smart Manufacturing	(1) envision (2) enable (3) enact	1: Initial 2: Managed 3: Defined 4: Transformation 5: Detailed Business Model	Maturity	No	Doesn't have a questionnaire.
12	B. Gajsek et al.	Slovenia	2019	General Enterprises	FDMM4.0 (Forrester Digital Maturity Model 4.0)	General I4.0	(1) Culture (2) Organization (3) Technology (4) Insights	1: Skeptics 2: Adopters 3: Collaborators 4: Differentiators	Capability	Yes	Gajsek (2019) presents a digital maturity model that is useful for general diagnostics but insufficient for more detailed improvement planning.
13	G. Schuh et al.	Germany	2016	General Enterprises	ACATECH Industrie 4.0 Maturity Index	General	(1) Resources (2) Information Systems (3) Corporate Culture (4) Organizational Structure	1: Informatization / Computerization 2: Connectivity 3: Visibility 4: Transparency 5: Predictive Capacity 6: Adaptability	Maturity	No	Despite its well-integrated concepts, it lacks clarity in its evaluation, with few and incomplete examples provided. Moreover, the suggested improvements are area-specific. Consequently, the model only suggests capability improvements, not maturity improvements, which can strengthen differences in silo-areas. A lack of technology consideration for the proposed process analysis makes it difficult to comprehend the differences between the maturity analysis for Industry 4.0 and a generic improvement analysis for increasing something in the company´s performance. Even though the study is designed specifically for manufacturing companies, a section dedicated to Lean Production Systems (LPS) or existing production systems is missing. The model is also missing the perspectives concerning SMEs. It has a proposal of generic archetypes related to the different digital maturity stages but no explicit indications of activities for enabling maturity stage transition. It has just general recommendations and doesn't have a continuous assessment. Detailed information regarding the structure of the model is given, but the quantitative assessment process is missing.
14	E. Gökalp et al.	Turkey	2017	General Enterprises	SPICE MM	Smart Manufacturing	(1) Asset Management (2) Data Governance (3) Application Management (4) Process Transformation (5) Organizational Alignment	0: Incomplete 1: Performed 2: Managed 3: Established 4: Predictable 5: Optimizing / Innovating	Maturity	No	Gökalp et al. (2017) don't have a questionnaire and assessment method described. It is not a transparent methodology, and it has just general recommendations. The readiness evaluation process is not explained in detail, and the model lacks an account of scientific and empirical-based development. There is no testing and validation of the model in real-life applications.
15	A. De Carolis et al.	Italy	2017	General Enterprises	DREAMY (Digital REadiness Assessment MaturitY)	Smart Manufacturing	(1) Processes (2) Control (3) Monitoring (4) Organization (5) Technology	1: Initial 2: Managed 3: Defined 4: Integrated & Interoperated 5: Digitally Oriented	Maturity	Yes	De Carolis et al. (2017) did not explore the technological enablers of its interconnectivity dimension. It has a validated questionnaire, but it is not a transparent methodology. There are no explicit indications for maturity improvement. It doesn't have an assessment method described and presents just general recommendations.

16	C. Weber et al.	Germany	2017	General Enterprises	M2DDM (Maturity Model for Data-Driven Manufacturing)	Smart Manufacturing, IT architecture, IoT	(1) Data storage and compute (2) Service-oriented architecture (3) Information integration (4) Digital twins (5) Advanced Analytics (6) Real-time capabilities	0: Nonexistent IT integration 1: Data and system integration 2: Integration of Cross-lifecycle data 3: Service orientation 4: Digital twins 5: Self-optimizing factory	Capability	No	Doesn't have a questionnaire.
17	O. Agca et al.	United Kingdom	2017	General Enterprises	WMG (The University of Warwick)	General	(1) Strategy & Organization (2) Products & Services (3) Manufacturing & Operations (4) Supply-chain (5) Business Model (6) Legal Considerations	1: Beginner 2: Intermediate 3: Experienced 4: Expert	Maturity	Yes	Agca et al. (2017) present a model that lacks an alignment among maturity levels and technology applications. It doesn't have an assessment method described and has just general recommendations. The model structure is elaborated along with details about sub-dimensions. However, it has fewer details regarding maturity assessment and identification of maturity level. The model is not scientifically developed, and no empirical validation in a real-life environment is done.
18	E. Pessl et al.	Austria	2017	General Enterprises	Capability Human Roadmap 4.0 MM	Human	(1) Acceptance & Application of new Technologies and Media (2) Professional Competence (3) Learning Competence (4) Corporate Strategy (5) Human Resources Development Strategy (6) Organization & Democratization (7) Flexible Working Models (8) Health & Safety (9) Information & Communication (10) Employer Branding (11) Change Management (12) Process Orientation (13) Knowledge Management	1: I 4.0 is not considered 2: Company has begun to deal with I 4.0 3: Measures are implemented in some areas. 4: Measures are implemented by a majority 5: Measures are consistently implemented and evaluated	Maturity	Yes	Pessl et al. (2017) present a well-described but complex model where people from different divisions should ideally be included in the maturity assessment process. Moreover, the definition of the target requirements and the implementation of the final action plan become especially challenging if industry 4.0 has not yet been an embedded part of the overall strategy. It has a questionnaire not validated and is not a transparent methodology. It doesn't have an assessment method or continuous assessment and incorporates just general recommendations.
19	SINGAPORE Economic Development Board (EDB)	Singapore	2017	General Enterprises	SINGAPORE READINESS INDEX	Manufacturing Enterprises	(1) Vertical Integration (2) Horizontal Integration (3) Leadership Competency (4) Strategy & Governance	0: Undefined 1: Defined 2: Digital 3: Integrated	Readiness	Yes (tested by T. Lin, K. J.	It is well-done research intended to analyze only manufacturing sites. However, first: the questionnaires were only distributed to Taiwanese enterprises within a specific industry, thus limiting the validity of the findings. Second, the subjects of this study

							(5) Inter- Intra Company Collaboration (6) Integrated Product Lifecycle (7) Workforce Learning & Development	4: Automated 5: Intelligent		Wang, M. L. Sheng)	are only manufacturers. Third, this study examines only manufacturing sites (not including executives and senior managers).
20	K. Y. Akdil et al.	Turkey	2018	General Enterprises (Retail Sector)	Akdil MM	SCM scope	(1) Smart products & services (2) Smart business processes (3) Strategy & Organization	0: Absence 1: Existence 2: Survival 3: Maturity	Maturity and Readiness	Yes	The diagnostic maturity form is unclear regarding the four levels for each question. It doesn't have a traditional questionnaire, just some complex architecture with an index to translate answers to a specific maturity level. The model fails to provide empirical validation of maturity items, and important levels of items and dimensions are not considered.
21	S. Mittal et al.	USA	2018	SME	SM3E (Smart Manufacturing Maturity Model for SMEs)	General	(1) Finance (2) People (3) Strategy (4) Process (5) Product	1: Novice 2: Beginner 3: Learner 4: Intermediate 5: Expert	Maturity	No	Mittal et al. (2018) present only one (digital) capability: "data-driven decision-making".
22	L. Canetta et al.	Switzerland	2018	General Enterprises	Digitalization Canetta MM	Smart Manufacturing	(1) Strategy (2) Processes (3) Products & Services (4) Human Resources (5) Technologies	1: Absence 2: Beginner 3: Intermediate 4: Experienced	Maturity	No	In Canetta et al. (2018), some steps were not available yet for analysis. It has a questionnaire, but it is not a transparent methodology.
23	S. Rübel et al.	Germany	2018	General Enterprises	Business Model Management MM	Business Model and SCM scope	(1) costumer segment (2) value proposition (3) channels (4) customer relationship (5) source of income (6) key resources (7) key activities (8) key partners (9) cost structure	1: Implicit 2: Defined 3: Validated / Standardized 4: Analyzed 5: Optimized	Maturity	No	Rübel et al. (2018) don't have a questionnaire. Further development levels need to be reached to achieve satisfactory results.
24	D. R. Sjödin et al.	Sweden	2018	General Enterprises	Sjödin MM	General	(1) Processes (2) People (3) Technologies	1: Connected Technologies 2: Structured Data Collection & Sharing 3: Real-time Process Analysis & Optimization	Maturity	Yes	Sjödin et al. (2018) did not present the details of its dimensions, and the reported results suggest only a general analysis without the necessary granularity level to define process improvements.

							4: Intelligent & Predictive Manufacturing			
25	F. Facchini et al.	Italy	2018	General Enterprises	Logistics 4.0 Facchini MM	Logistics / SCM scope	(1) management (2) flow of material (3) flow of information	1: Ignoring 2: Defining 3: Adopting 4: Managing 5: Integrated	Maturity	Yes	It is a preliminary model. Just for logistics.
26	B. Asdecker, V. Felch, E. Sucky	Germany	2018	General Enterprises	DPMM 4.0 (Delivery Process MM)	Deliver Processes in Supply-chain (SCM)	(1) Plan (2) Source (3) Make (4) Deliver (5) Return (6) Enable	1: Basic digitization 2: Cross-department digitization 3: Horizontal & vertical digitization 4: Full digitization 5: Optimized full digitization	Maturity	Yes	Asdecker et al. (2018) presented a MM validated through expert opinions and judgments. The model doesn't have a validated questionnaire, just a verified architecture. Moreover, the population and evaluation process were mostly based on experts from German industrial companies. Therefore, further research should consider a more international perspective.
27	J. Puchan et al.	Germany	2018	General Enterprises	I4-MMM / MUAS MM (Munich University of Applied Sciences)	General	(1) Key Factors (2) Employees (3) Organization (4) Product (5) Production	0: Basic Level 1: Novice Level 2: Advanced Level 3: Expert Level 4: Pioneer Level	Maturity	No	It is a preliminary model.
28	J. Tavčar et al.	Slovenia	2018	Automotive supply-chain enterprises	Engineering Change Management MM	Lean criteria	(1) ECM process flow (2) Set-based CE (3) Chief engineer - technical leadership (4) Customer-defined value (5) Knowledge management (6) Continuous improvement culture	0: The criterion is not implemented at all. 1: There is a modest 2: The criteria are specified in written procedures, but are not practiced strictly in everyday work. 3: The criterion is practiced, but over 40% of employees do not recognize it as very helpful. 4: The criteria are defined and practiced at a good level, and are well accepted by 80% of employees. 5: The implementation of the criterion is at the top level, and	Maturity	Yes	In Tavčar et al. (2018), the ECM (Engineering Change Management) maturity assessment tool was tested and validated at eight automotive suppliers of different sizes, presenting state-of-the-art on this specific topic. So, there is a strong emphasis only on a reliable supply of automotive enterprises.

								can be used as a reference for others.			
29	Y. Jin et al.	China	2018	SME	EMMMs (Energy Management Maturity Models)	Energy	(1) Energy Management System (2) Leadership (3) Planning (4) Support and Operation (5) Performance evaluation (6) Improvement	1: Initial 2: Managed 3: Systematic 4: Improved 5: Optimized	Maturity	Yes	In Jin et al. (2018), the main limitation of their model is that it presents difficulty to apply the SMEs in China, whose EM (Energy Management) practices were seldom summarized or even raised. Another limitation is that there are no standardized EM tools, although the first-stage standardization is moving forward. And this lack increases the difficulty of applying the maturity model.
30	M. Colli et al.	Denmark	2018	General Enterprises (not SME)	360 Digital MM (based on PBL - Problem-Based Learning)	Smart Manufacturing	(1) Governance (2) Technology (3) Connectivity (4) Value creation (5) Competence	1: None 2: Basic 3: Transparent 4: Aware 5: Autonomous 6: Integrated	Maturity	Yes	Colli et al. (2018) present no development of toolboxes to operationally address the improvement of each defined digital dimension and quantify the related potential. It has been tested only in large companies, not in SMEs. Further work has to be directed towards an efficiency improvement of the proposed assessment approach.
31	A. P. T. Pacchini et al.	Brazil	2019	General Industry Enterprises	SAE RM	General	(1) Cloud Computing (2) Cyber-Physical System (3) Co-bots (4) Additive Manufacturing (5) Augmented Reality (6) Artificial Intelligence (7) IoT (8) Big Data	1: Embryonic 2: Initial 3: Primary 4: Intermediate 5: Advanced 6: Ready	Readiness	Yes	Pacchini et al. (2019) rely on only eight enabling technologies and a few prerequisites for each technology. The enabling technologies cannot have the same impact as far as I 4.0 implementation is concerned. In addition, the inter-relations among enabling technologies possibly affect the degree of readiness. The model is tested and validated only in a Brazilian auto-parts manufacturing organization.
32	L. Gaur et al.	India	2019	General Enterprises	IoT MM	IoT	(1) Strategy (2) IT (3) Data (4) Process (5) People (6) Assets (7) Products (8) Technology (9) Financial	0: No Adoption 1: Work in Progress 2: Successful implementation & results	Maturity	No	It is a preliminary model.
33	F. Pirola et al.	Italy	2019	SME	Pirola RM	Digital	(1) Strategy (2) People (3) Processes	1: $(1< I \leqslant 1.8)$ not involved in I 4.0 2: $(1.8 < I \leqslant 2.6)$ intermediate 3: $(2.6 < I \leqslant 3.4)$ I 4.0	Readiness	Yes	Pirola et al. (2019) do not extend capabilities assessments by defining specific roadmaps and action steps to drive the transition from the current maturity level to the desired one while considering SMEs' often limited resources.

							(4) Technology (5) Integration	strategy & investing 4: $(3.4 < I \leqslant 4.2)$ already implementing 5: $(4.2 < I \leqslant 5)$ already implemented			
34	J. Vrchota et al.	Czech Republic	2019	General Enterprises	Human Vrchota RM	Human Resources / Skills	(1) Technical (2) Personal	0: None 1: Low 2: Medium 3: High	Readiness	No	Vrchota et al. (2019) analyze the employee competencies in Industry 4.0. However, national data of individual countries are always delayed by approximately 2 years, so it is always an analysis of data that is no longer up-to-date. Research does not include the economic situation of individual countries and market developments.
35	D. Trotta et al.	Italy	2019	SME	I 4.0 Trotta MM	General	(1) Strategy (2) Technology (3) Production (4) Products (5) People	1: not implemented/not present 2: (no info) 3: (no info) 4: (no info) 5: completely implemented/ present	Maturity	No	Trotta et al. (2019) present a preliminary model. Further research could improve the goodness of the proposed model, expanding the list of items emerging from the on-site feedback collection.
36	A. Tobołа et al.	Poland	2019	General Enterprises	AI MM	Artificial Intelligence	(1) Management (2) Flow of material (3) Flow of information	1: AI Novice 2: AI Ready 3: AI Proficient 4: AI Advanced	Maturity	No	It is a preliminary model.
37	F. Odważny et al.	Poland	2019	General Enterprises	ISO 9004:2000 MM	General	(1) Work environment (2) People (3) Communication (4) Mission, vision, values, culture (5) Natural resources (6) Infrastructure (7) Technology (8) Resource management (9) Organizational knowledge (10) Performance analysis (11) Self-assessment	1: Ignoring 2: Defining 3: Adapting 4: Managing 5: Integrating	Maturity	No	Odważny et al. (2019) propose a preliminary model with many lacks, such as a clear definition and specific value for each maturity level. This model will be ready for validation across companies with all values identified.
38	R. C. Santos et al.	Portugal	2020	General Enterprises (automotive industries)	I 4.0 Santos MM	General	(1) Organizational strategy, structure & culture (2) Workforce (3) Smart factories	0: low or no degree of implementation 1: pilot actions 2: actions initiated, with some	Maturity	Yes	Santos et al. (2020) developed a maturity model for Industry 4.0 to collaborate with companies to implement main related concepts and technologies and academics to understand the phenomenon better. The proposed model was adapted from three existing maturity models (Schuh et al, 2016), (Lichtblau, et al., 2015) and

							(4) Smart processes (5) Smart products & services	benefits 3: partial implementation 4: advanced implementation 5: reference in applying Industry 4.0			(Schumacher, et al., 2016), and a pilot test was performed on two Brazilian companies, both from the automotive industry. The main limitation of this research is the small number of professionals in the industry that participated in the validation phase of the model.
39	O. K. K. Bandara et al.	Sri Lanka	2019	General Enterprises	Banking MM	Bank processes	(1) Products & services (2) Technology & Resources (3) Strategy & organization (4) Operations (5) Customers (6) Governance (7) Employees	1: Initial 2: Managed 3: Defined 4: Established 5: Digital Oriented	Maturity	Yes	The model of Bandara et al. (2019) can be further optimized by studying the importance of each dimension separately when calculating the overall maturity from a future research perspective.
40	G. Nick et al.	Hungary	2020	SME	CCMS (Company CoMpaSs)	Manufacturing	(1) Strategy & organization (2) Smart factory (3) Intelligent processes (4) Smart products (5) Services (6) Employees	Not considered	Readiness	No	It does not have information about output levels and hasn't been tested.
41	A. Azevedo et al.	Brazil	2019	General Enterprises	PIM 4.0 MM (Industrial Pole of Manaus)	Manufacturing	(1) Products and Services (2) Manufacturing (3) Business Model (4) Strategy (5) Supply-chain (6) Interoperability	Not considered	Maturity	Yes	Tested just in a pilot company. Doesn't have output levels.
42	R. Rojas et al.	Peru	2019	Security of Web Enterprises	Security of Web Attac MM	Security of web attacks	Doesn't have, only has tests matrix	1: Incipient 2: Basic 3: Intermediate 4: Strategic 5: Optimized	Maturity	Yes	Just applicable for the security of the web. Doesn't have input dimensions.
43	J. Basl	Czech Republic	2018	General Enterprises	Metamodel Basl	General	(1) ERP applications (2) Production planning (3) Workplace ergonomics (4) Security (5) Maintenance	Not considered	Readiness	No	Doesn't have output levels.

						(6) Connectivity (7) Data & processes				
44	D. Li et al.	Sweden	2019	SME	Li CM	General I4.0	(1) Resources (2) Information systems (3) Organizational structure (4) Culture	1: "World of Mouth" 2: "Pen and Paper" 3: Computerization 4: Connectivity 5: Visibility 6: Transparency 7: Predictability 8: Adaptability	Capability	Yes	Li et al. (2019) have qualitatively assessed the Industry 4.0 capabilities of two case companies based on their employees' understanding of their working conditions. While previous research requires company managers to possess a certain amount of knowledge about Industry 4.0, this paper exhibits the possibility of exploring the subject based on individuals' situational awareness.
45	L. Joblot et al.	France	2019	General Enterprises	BIM2FR (Building Information Modeling Maturity Model For Renovation)	Renovation work	(1) Strategy (2) Foundations (3) Collaboration (4) Process (5) People (6) Technology (7) Standards (8) Enabling Tools (9) Resources	1: Pre-BIM 2: Modelling 3: Collaboration 4: Integration 5: Post-BIM	Maturity	Yes	Joblot et al. (2019) is just a preliminary model. In agreement with the work presented by De Bruin (2005), this BiM2FR will next be tested at a larger scale as a way to adjust the first version.
46	S. Elnagar et al.	USA	2019	General Enterprises	ARE-MMI4.0 (Agile Requirement Engineering Maturity Model for Industry 4.0)	Agile	(1) Technology (2) Governance (3) Products (4) Customers (5) Operations (6) Leadership (7) Strategy (8) Culture (9) People	1: Basic 2: Cross-departmental 3: Horizontal and vertical 4: Full digitization 5: Optimized	Maturity	No	Elnagar et al. (2019) presented the first version of ARE-MMI4.0, which is currently still at phase three, "populate", according to the general model (De Bruin, 2005). So, the next phases are the "evaluation" in developing the framework and the "action and observation" in integrating the maturity models, and the model still needs to be evaluated for user perception and technical excellence.
47	D. Ifenthaler et al.	Germany	2020	General Enterprises	EOMM (Educational Organizations MM)	Educational Organizations	(1) Equipment and technology (2) Strategy and leadership (3) Organization (4) Employees (5) Culture (6) Digital learning and teaching	Not considered	Maturity	Yes	Ifenthaler et al. (2020) present practical concerns about organizational culture. Its model doesn't have output levels. An executive survey could provide valuable information on organizational conditions and cultural factors - 'digital leadership' (i.e., leadership that is in line with the affordances of digital transformation) is likely to play a crucial role. Doesn't have output levels.

48	R. G. G. Caiado et al.	Brazil	2020	General Enterprises	3M4.0 (Maturity Model for Manufacturing 4.0)	General	(1) Supply-chain Management (2) Technology (3) Sales & Operations Management (4) Knowledge, Skills & Attitude	1: Conceptual 2: Managed 3: Advanced 4: Self-optimized	Maturity	No	Caiado et al. (2020), through a systematic literature review, could demonstrate that no maturity model currently exists that meets the needs of manufacturing 4.0 in terms of socio-technical skills, production operations management, and supply-chain, considering the context of an emergent country. Therefore, as in (Leyh, et al., 2016), 3M4.0 development is not yet complete.
49	A. A. Wagire et al.	India	2020	General Enterprises	Digital Novice MM	Manufacturing	(1) People and culture (0.12) (2) Industry 4.0 awareness (0.06) (3) Organizational strategy (0.18) (4) Value chain and processes (0.17) (5) Smart manufacturing technology (0.13) (6) Product and service-oriented technology (0.15) (7) Industry 4.0 base technology (0.18)	$1.00 \leq Mo < 2.00$ Level 1: Outsider $2.00 \leq Mo < 3.00$ Level 2: Digital Novice $3.00 \leq Mo < 4.00$ Level 3: Experienced $4.00 \leq Mo \leq 5.00$ Level 4: Expert	Maturity	Yes	The maturity model of Wagire et al. (2020) is supported by prior literature, expert consultation and case study, and experts' judgment and opinions. Further efforts may be directed to measure the degree of readiness of the organization for Industry 4.0 as suggested by Pacchini et al. (2019), which is based on the assessment of prerequisites adopted by an organization for each maturity item mentioned in this study. Next, the important weight identification of each maturity item is based on opinions from a comparatively limited number of experts. Additionally, the existing model could introduce more maturity items related to legal and regulatory issues.
50	V. Margariti et al.	Greece	2020	Public Sevice	Organizational Interoperability MM	Organizational interoperability maturity	(A1) Procurement criteria (A2) Specification Process (A3) Design methodology (A4) Collaboration (B1) Compatibility (intergovernmental legislation) (B2) Certification (B3) Business Process Modelling (C1) Compatibility with EIF (C2) Compatibility with GDPR (D1) Procedural transparency (D2) User Feedback (D3) Service Level Agreements (E1) Service Consumption (F1) Reuse and sharing (G1) Once-Only Principle (G2) Cross-border service delivery	1: Ad hoc 2: Opportunistic 3: Essential 4: Sustainable 5: Seamless	Maturity	No	The model of Harokopio et al. (2020) must be applied to test it and turn it into a standard for the objective sector.

							(H1) Staff restructuring (H2) Training				
51	M. A. O. Sanabria et al.	Colombia	2020	Public institutions	Open Government Data RM	Open government data	(1) Normativity (2) Organizational (3) Technology (4) Strategies	Not considered	Readiness	No	In Sanabria et al. (2020), the model must be applied to test it and turn it into a standard for the sector. It doesn't have output levels.
52	J. Merkus et al.	Netherlands	2020	General Enterprises	GCR MM (Generic Capabilities Reference)	Organizational interoperability maturity	(1) Strategy (2) Governance & Control (3) Organization & Processes (4) Information Technology (5) Human Resources (6) Leadership (7) Communication (8) Culture (9) Value chain (10) Legislation (11) Environment	Not considered	Maturity	No	The model of Merkus et al. (2020) is limited to the selection made in its Literature Research (LR). Further research is necessary to validate the outcomes of this research, and the model doesn't have output levels.
53	L. D. Rafael et al.	Spain	2020	General Enterprises	Machine Tool MM	Machine Tool	(1) Strategy & organization (2) Smart factory (3) Smart operations (4) Smart products (5) Data-driven services	0: Outsider 1: Beginner 2: Intermediate 3: Experienced 4: Expert 5: Top performers	Maturity	No	Rafael et al. (2020) present a model that must be applied to test it and turn it into a standard for the sector. A future improvement for the model could lie around using a more scientific and rigorous method for weighing the dimensions.
54	S. Gamache et al.	Canada	2020	Quebec Manufacturing SMEs	Gamache MM	General	(1) Leadership; (2) Culture and organization; (3) Technology management; (4) Data management; (5) Measurement system (decision-making process); (6) Customer experience.	0: Non-existent: absence of the business practice. 1: Handwork: a worker works for this activity in a traditional way. 2: Disciplined: the use of several non-integrated tools 3: Integrated: the use of an integrated, but not automated, management software package 4: Predictable: is the maximum achievable and means that a	Maturity	Yes	Gamache et al. (2020) present a sound study, but it needs a more comprehensive assessment of the SMEs' tools to target those that offer the most benefits. A longitudinal study with the sample would also be interesting to validate the impact of the approach, the number of projects and the progress of the projects that have been put in place, and the gains made by the digital tools implemented.

							respondent functions for the activity in an integrated, connected, and real-time manner, and uses up-to-date and real-time data to make effective decisions.			
55	N. Chonsawat et al.	Thailand	2020	SME	SMEs Readiness Indicators	General	(1) Organizational Resilience (2) Infrastructure System (3) Manufacturing System (4) Data Transformation (5) Digital Technology	1: Not Achieved 2: Partially Achieved 3: Achieved 4: Fully Achieved	Readiness	Yes	Chonsawat et al. (2020) have a limitation: this research has tested only a simple example. Future research will develop decision-making in selecting the priority of improvement implementation. Then, the researcher will develop indicators to cover more SME cases.
56	H. T. Maier et al.	Austria	2020	General Enterprises	LSM MM (Lean Smart Maintenance Maturity Model)	General	(1) Philosophy & Target System (2) Corporate Culture (3) Business Model & Service Strategy (4) Asset Strategy (5) Controlling & Budget (6) Organizational Structure (7) Process Organization (8) Knowledge Management (9) Data & Technology	0: Incomplete 1: Initial 2: Managed 3: Defined 4: Quantitatively Managed 5: Optimizing	Maturity	Yes	In Maier et al. (2020), a more intensive investigation of the category 'Business & Service Strategy' is needed. Besides, only the data from Austrian companies were analyzed.
57	M. I. Sanchez-Segura et al.	Spain	2020	SME	ALTUS MM	Software engineers and IT professionals	(1) Configuration (2) Training (3) Operational (4) Proactive (5) Transactive memory (6) SP3 valuation (7) Social	1: covers the capabilities that allow company employees to improve their knowledge individually 2: covers the capabilities that allow company employees to generate and improve collective knowledge 3: covers the capabilities that allow the company knowledge to be sustainable 4: covers the capabilities that allow the company knowledge to evolve	Maturity	Yes	Sanchez-Segura et al. (2020) discuss the tools that support the ALTUS model (excel sheet and interview templates). They will improve the tool to be used as a web application and to be applied in different sizes of companies to see the results.

58	R. B. Unny et al.	India	2020	General Enterprises	Blockchain in Supply-chain Management	Blockchain Technology	(1) Network (2) Information Systems (3) Computing Methodologies (4) Security and Privacy (5) Skills	1: Initial 2: Repeatable 3: Defined 4: Managed 5: Optimizing	Maturity	No	It is a preliminary model.
59	P. J. Hsieh et al.	Taiwan	2020	General Enterprises	KNM 2.0 (Knowledge Navigator Model)	General	(1) Strategy (2) KM Promotion (3) Knowledge Sharing (4) Data and Knowledge Acquire (5) Knowledge Store (6) Knowledge and Intelligent Application (7) Knowledge Creation and Innovation (8) Knowledge Protection (9) Knowledge Learning	1: Knowledge Chaotic Stage 2: Knowledge Conscientious Stage 3: Knowledge Management Stage 4: KM Advanced Stage 5: KM Integration Stage	Maturity	Yes	In Hsieh et al. (2020), further research may focus on analyzing data collected from their model to reveal the difference in maturity status across the production/service industry and large/small-medium companies. In addition, the relationship among KM (Knowledge Management) culture, process, technology, and KM performance is worthy of being observed, as also the interplay between knowledge and intelligent application.
60	R. G. G. Caiado et al.	Brazil	2021	General Enterprises	OSCM4.0 (Smart Operations and Supply-chain Management)	Operations and Supply-chain	(1) Customer (2) Logistics (3) Supplier (4) Integration (5) Planning & control of production (6) Quality (7) Maintenance	0: Non-existent 1: Conceptual 2: Managed 3: Advanced 4: Self-optimized	Maturity	Yes	Caiado et al. (2021) have a well-done and complete model with a fuzzy rule-based industry 4.0 maturity model. However, it focuses only on operations and supply-chain management. For future works, this research suggests is to conduct a longitudinal survey and evaluating maturity at different times by applying a roadmap with periodic goals.
61	A. Amaral, P. Peças	Portugal	2021	SME	Framework SME 4.0	General	(1) People (2) Production Processes (3) Technology (4) Smart Products (5) Organization (6) Changes	0: Depends on the dimension (not informed) 1: Depends on the dimension (not informed) 2: Depends on the dimension (not informed) 3: Depends on the dimension (not informed) 4: Depends on the dimension (not informed)	Maturity	No	Outputs are not transparent.

								5: Depends on the dimension (not informed)			
62	L. F. P. Ramos et al.	Brazil	2021	General Enterprises	I 4.0 Ramos RM	General	(1) Innovation (2) Culture (3) Strategy and Leadership (4) Smart Factory (5) Agile and Modular Management (6) Governance and processes (7) Digital Infrastructure (8) Smart Logistics (9) Smart Product and Services	Not considered	Readiness	Yes	In Ramos et al. (2021), the main contribution of this research is the need to align the theoretical concepts with those seen by specialists daily. Such a point allows a better understanding of what is intended to be delivered. All professionals stressed that the evaluation models aimed at I4.0 are essential to avoid too many trials and errors. Nonetheless, there is still a gap between a theoretical conception and a realistic view. Doesn't have output levels.
63	M. Zoubek, M. Simon	Czech Republic	2021	General Enterprises	Logistics 4.0 Zoubek MM	Logistics Internal Processes	(1) Manipulation (2) Storage (3) Supply (4) Packaging (5) Material identification.	Level 0: Processes are not explicitly defined. Information systems and simple software are not used. Level 1: Certified process management takes place here, which is controlled by the human factor. It uses simple software and basic information systems. Level 2: The use of automated elements in standardized processes is beginning. Data collection is partially digitized and data are processed by information systems only within the company. Level 3: Most processes are automated with partial human cooperation. Digitized technologies and information systems are used for data collection, which are also connected to external sources.	Readiness	No	Specific just for logistics processes.

								Level 4: Processes are digitized and automated, with limited human intervention. It uses smart information systems that connect all areas, including external sources. Level 5: Processes are fully automated and human-controlled. The control of all systems is autonomous. Online communication thanks to sophisticated information systems that connect all company areas, including external sources.			

APPENDIX C: CUBE-4.0 Questionnaire

Through an innovative methodology sponsored by the Brasília (**UnB**[1]) and Germany (**Aachen**[2]) Universities, you can identify, by answering only 21 questions, how prepared your company is (that is, what is the readiness level of the main processes - from 0 to 5), related to the new digital transformation context, including the Industry 4.0 (I4.0).

To improve the answers quality, it is recommended that this questionnaire be answered by at least 1 leader/manager from each CUBE-4.0 macroprocess: **Organizational** [Management / Human Resources], **Technological** [**IT**[3] / Production Technologies], and **Operational** (maturity) [Engineering / R&D / Supply-chain / Production / Sales].

Please enter an e-mail address at which you would like to receive this survey results.
E-mail:____

I4.0 is more than automation: it is an environment with high interconnectivity in the physical world (between products, systems, processes, machines, people, materials, information, and communication) and digitalization or virtualization (that is, there is a physical world virtual copy, with interdependent sensors between both), where all data exchange uses 4.0 technologies to share unified and real-time information throughout the company's value chain, moving toward a smart world.

RESPONDENTS' DATA

Respondent's Information
This questionnaire allows up to three respondents' participation (Respondents 1, 2 & 3).

Respondent 1 - E-mail: _______________________________________
Respondent 2 [if exists] - E-mail: _______________________________________
Respondent 3 [if exists] - E-mail: _______________________________________

Respondent 1 - Full Name: _______________________________________
Respondent 2 [if exists] - Full Name: _______________________________________
Respondent 3 [if exists] - Full Name: _______________________________________

Respondent 1 - Cell Phone (+ [DDI] [DDD]): ___________________________
Respondent 2 [if exists] - Cell Phone (+ [DDI] [DDD]): ___________________________
Respondent 3 [if exists] - Cell Phone (+ [DDI] [DDD]): ___________________________

Respondent 1 - Age: _______________________________________
Respondent 2 [if exists] - Age: _______________________________________
Respondent 3 [if exists] - Age: _______________________________________

Instruction Level (Respondent 1):

( ) Elementary School
( ) High School
( ) Higher Education
( ) Master's Degree
( ) Doctorate
( ) Post-Doctorate

Instruction Level (Respondent 2, if exists):

( ) Elementary School
( ) High School
( ) Higher Education
( ) Master's Degree
( ) Doctorate
( ) Post-Doctorate

Instruction Level (Respondent 3, if exists):

( ) Elementary School
( ) High School
( ) Higher Education
( ) Master's Degree
( ) Doctorate
( ) Post-Doctorate

Respondent 1 - years of experience in the Company: ________________________________
Respondent 2 [if exists] - years of experience in the Company: ________________________________
Respondent 3 [if exists] - years of experience in the Company: ________________________________

Which one of the options below best characterizes your current position in the Company (Respondent 1)?

( ) Technical level - equipment and/ or production lines
( ) Technical level - administrative sector
( ) Analyst - higher level occupation
( ) Manager, Sector Chief or Department Chief
( ) Director or President

Which one of the options below best characterizes your current position in the Company (Respondent 2, if exists)?

( ) Technical level - equipment and/ or production lines
( ) Technical level - administrative sector
( ) Analyst - higher level occupation
( ) Manager, Sector Chief or Department Chief
( ) Director or President

Which one of the options below best characterizes your current position in the Company (Respondent 3, if exists)?

( ) Technical level - equipment and/ or production lines
( ) Technical level - administrative sector
( ) Analyst - higher level occupation
( ) Manager, Sector Chief or Department Chief
( ) Director or President

YOUR COMPANY DATA

If you work for a several companies group (such as a multinational), here you must fill in only for the one unit that intends to implement I4.0. If the goal is to implement I4.0 in all the group companies, you must select the one in the most incipient stage or make an average among the readiness of all units.

Company Name: ____

Company Full Address: ____

Company Size:

( ) 1 to 5 employees
( ) From 6 to 19 employees
( ) From 20 to 99 employees
( ) From 100 to 499 employees
( ) More than 500 employees

Company's economic sector:

( ) Mineral Industry
( ) Ceramic Industry
( ) Chemical Industry
( ) Composites Industry
( ) Electrical and/or Electronic Industry
( ) Food and/or Beverage Industry
( ) Leather Industry
( ) Paper Industry
( ) Pharmaceutical Industry
( ) Polymer Industry
( ) Steel Industry and/or Other Metals
( ) Textile Industry
( ) Tobacco Industry
( ) Wood Industry
( ) Smart Materials Industry
( ) Petroleum Industry
( ) Automobile Industry
( ) Other

INITIAL QUESTION

<u>About your company's readiness for digital transformation perception.</u>

How would you describe the I4.0 implementation status in your company?

0. NOT STARTED: My company values I4.0 but doesn't know how to implement it.
1. EXPERIMENTED: My company ends up taking random and incipient initiatives.
2. PLANNED: My company establishes planning to implement it, with support from tools/software, and starts implementation, but still with individual/modular solutions for some of the company's processes.

3. MANAGED: My company completes the implementation in the whole company and starts monitoring I4.0 (with goals, methods, and performance indicators), providing forecasts and possible causes.
4. OPTIMIZED: My company has a data-driven (with I4.0 technologies) and regularly executes the I4.0 optimization process with prior approval.
5. SELF-OPTIMIZED: My company has autonomous systems (like exception messages in MRP II[4] systems, where the machine identifies data patterns and suggests adaptation strategies) to self-adapt to market contextual changes, including those promoted by I4.0, without prior approval (self-optimization).

Justification (optional): ____

Organizational Strategy and Human Factors

In this topic, the Corporate Governance, Organizational Structure, Business Model, Contractual Labor Relations, Leadership, Internal Communication, Training, and Innovation Culture in the company will be analyzed.

1. How are TOP-DOWN SUPPORT and CORPORATE GOVERNANCE, regarding the I4.0 implementation?

0. Top management wants to but doesn't know how to implement I4.0.
1. Top management takes random and incipient initiatives.
2. Top management establishes planning and starts applying individual/ modular solutions for some processes.
3. Implementation is completed company-wide and I4.0 starts to be monitored.
4. Regular I4.0 optimization takes place, with I4.0 technologies and prior approval.
5. There is I4.0 self-optimization (without prior approval).

Justification (optional): ____

2. How is the ORGANIZATIONAL STRUCTURE adaptation process to I4.0?

[that is, whether the way employees are organized hierarchically (whether by department, function, or position), is flexible, agile, and adaptable to changing requirements, with digital transparency]

0. My company doesn't know how to adapt the organizational structure to I4.0.
1. Takes random and incipient initiatives.
2. Establishes planning and starts to implement individual solutions for just a few processes.
3. Completes the deployment in a unified, company-wide manner and monitors it.
4. Regularly optimizes the new organizational structure (with prior approval).
5. Self-optimizes the new organizational structure (without prior approval).

Justification (optional): ____

3. How is the BUSINESS MODEL conforming to I4.0?

[i.e., how is the strategy defined for your company to create value, deliver to the customer, and capture revenue, which can be based on: "Cloud Computing" (with IT enablers such as Internet of Things - IoT, Big Data, Analytics, Augmented/Virtual Reality and Artificial Intelligence), "Services", "Spin-Offs" (models derived from others already developed previously) and/or "Partnerships"].

0. My company doesn't know how to adapt the business model to I4.0.
1. Takes random and incipient initiatives.

2. Establishes planning and starts deploying individual solutions for just a few processes.
3. Completes the deployment in a unified manner across the entire company and monitors it.
4. Regularly optimizes the new business model (with prior approval).
5. Self-optimizes the new business model (without prior approval).

Justification (optional): ____

4. How are CONTRACTUAL LABOR RELATIONS (with the workforce), in relation to I4.0?
[e.g., new teleworking rules].

0. My company does not know how to adapt labor contractual relations to I4.0.
1. Takes random and incipient initiatives.
2. Establishes planning and begins to implement individual solutions for just a few processes.
3. Completes deployment in a unified manner across the enterprise and monitors.
4. Regularly optimizes new labor contractual relationships (with prior approval).
5. Self-optimizes new contractual labor relations (without prior approval).

Justification (optional): ____

5. How is your company's LEADERSHIP preparation for I4.0?
[for process leaders, at all hierarchical levels, to know how to practice service orientation, that is, to encourage teamwork with empathy, cooperation, creativity, agility, and willingness to change].

0. My company is not yet preparing its leaders for I4.0.
1. Takes random and incipient initiatives.
2. Establishes planning and starts preparing the leadership for just a few processes.
3. Completes leadership preparation in a unified, company-wide manner and monitors.
4. Regularly optimizes leadership development (with prior approval).
5. Self-optimizes leadership development (without prior approval).

Justification (optional): ____

6. How is INTERNAL COMMUNICATION in your company?
[i.e., is the communication reliable (e.g., has a certified digital signature), and is there horizontal (same hierarchical level) and vertical (between different hierarchical levels and/or between machines, products, and smart production resources) integration].

0. My company doesn't know how to adapt internal communication to I4.0.
1. Takes random and incipient initiatives.
2. Establishes planning and starts to implement individual solutions for just a few processes.
3. Completes the deployment in a unified manner across the entire company and monitors it.
4. Regularly optimizes new internal communication (with prior approval).
5. Self-optimizes the new internal communication (without prior approval).

Justification (optional): ____

7. How is the team's TRAINING "on I4.0" *[i.e., is it already tracked with a qualification matrix]* **and "the I4.0 technologies use in its realization"?**

0. My company does not yet offer training on I4.0, nor does it use I4.0 technologies in its realization.

1. Takes random and incipient initiatives.
2. Establishes planning and starts offering this training to only a few teams.
3. Completes team training in a unified, enterprise-wide manner and monitors it.
4. Regularly optimizes these trainings (with prior approval).
5. Self-optimizes these trainings (without prior approval).

Justification (optional): ____

8. How is the INNOVATION CULTURE being managed?
[i.e., the work environment where process leaders support and encourage disruptive and creative thoughts, habits, and solutions, in general, and people have the will and courage to change].

0. My company does not yet have an organizational culture focused on innovation.
1. Takes random and incipient initiatives
2. It establishes planning and starts to implement individual solutions for only a few processes.
3. Completes the implementation in a unified manner throughout the company and monitors it.
4. Regularly optimizes innovation culture (with prior approval).
5. Self-optimizes innovation culture (without prior approval).

Justification (optional): ____

Production and Information Technology

In this topic, the Anthropomorphic, Cognitive and Managerial Supports, Networked Production, Data Management, Information Security, and Mechanisms for Decentralized Decisions will be analyzed.

9. How are the ANTROPOMOPHIC SUPPORT systems in your company?
[e.g., *Robots*].

0. My company doesn't have them yet.
1. Takes random and incipient initiatives.
2. Establishes planning and starts to implement them.
3. Completes the implementation and monitors it.
4. Regularly optimizes these systems (with prior approval).
5. Self-optimizes these systems (without prior approval).

Justification (optional): ____

10. How are the COGNITIVE SUPPORT systems in your company?
[e.g., *Artificial Intelligence*]

0. My company doesn't have them yet.
1. Takes random and incipient initiatives.
2. Establishes planning and starts to implement them.
3. Completes the implementation and monitors it.
4. Regularly optimizes these systems (with prior approval).
5. Self-optimizes these systems (without prior approval).

Justification (optional): ____

11. How are the MANAGEMENT SUPPORT systems doing in providing information for effective decision-making by process leaders?
[e.g., BIG DATA – an advanced analytical technique applied to very large and diverse data sets].

0. My company doesn't have them yet.
1. Takes random and incipient initiatives.
2. Establishes planning and starts to implement them.
3. Completes the implementation and monitors it.
4. Regularly optimizes these systems (with prior approval).
5. Self-optimizes these systems (without prior approval).

Justification (optional): ____

12. How is NETWORK PRODUCTION in your company?
[i.e., *Additive Manufacturing*].

0. My company does not yet have a networked production.
1. Has I4.0 technologies and takes random initiatives, but partners don't yet.
2. Establishes planning and starts deploying individual solutions for only a few processes.
3. Completes deployment in a unified manner across the company and partners, and monitors.
4. Regularly optimizes networked production (with prior approval).
5. Self-optimizes network production (without prior approval).

Justification (optional): ____

13. How is the DATA TRANSPARENCY AND INTERCONNECTIVITY, in real-time (automatically by sensors), with security and guarantee that it has a single source?
[it is about the interconnectivity between products, systems, processes, machines, people, and materials, that is, whether there is a connection that allows the order information to always be linked to the product, the production line, work instructions, and customer information].

0. Data is not yet collected and/ or analyzed.
1. Data is collected and analyzed (manually or automatically), but without interconnectivity and transparency.
2. Data is interconnected without transparency, only within each department.
3. Data is interconnected with transparency and using I4.0 technologies, unified across the enterprise.
4. There is regular data management optimization, with I4.0 technologies and prior approval.
5. There is data management self-optimization (without prior approval).

Justification (optional): ____

14. How is INFORMATION SECURITY in your company?
[including all data generated, received, analyzed, processed, transmitted, and stored].

0. My company doesn't have any system for information security yet.
1. My company has a network that is more than 80% vulnerable to known cyber-attacks.
2. My company already has some controls and validations in place, regarding network components.
3. My company requires controls and validations on all network components; however, they are partial or ineffective.

4. My company can manage the cyber risks involving the company's strategic processes.
5. My company can manage the cyber risks that involve all the company's processes.

Justification (optional): ____

15. How are the systems for DECENTRALIZED DECISIONS in your company?
[i.e., the ability of cyber-physical systems to make decisions on their own, data-driven and with high flexibility].

0. My company does not yet use systems for decentralized decisions.
1. Takes random and incipient initiatives.
2. Establishes plans and begins to implement them for only a few processes.
3. Completes the implementation in a unified manner throughout the company and monitors it.
4. Regularly optimizes these systems (with prior approval).
5. Self-optimizes these systems (without prior approval).

Justification (optional): ____

<u>Product Development (Goods or Services) and Customer Supply/Service</u>

In this topic, the Integration of Engineering, Research, and Development with other companies, New Product Development, Supply-chain, Production, Sales and other Customer Operations, and Quality Management System will be analyzed.

16. How is the ENGINEERING, RESEARCH AND DEVELOPMENT integration with other companies?
[i.e., whether the company is using collaborative tools (such as Big Data and Analytics) daily to track project progress, enable rapid decision-making, and ensure that the entire NPD (New Product Development) process is performed on a multi-departmental basis and with integrated PLM (Product Lifecycle Management) solutions].

0. My company does not yet integrate engineering, research, and development with other companies.
1. Takes random and incipient initiatives.
2. Establishes planning and starts to implement this integration, centrally in the engineering department.
3. Completes this integration, with multi-departmental teams, and monitors.
4. Regularly optimizes this integration (with prior approval).
5. Self-optimizes this integration (without prior approval).

Justification (optional): ____

17. How is the customer-centric New Product Development (NPD) in your company?
[i.e., whether throughout the product lifecycle, there is a procedure for collecting data, in mobile systems, on customer needs (requirements) and experiences, that is integrated and validated with collaborative tools (such as Internet of Things sensors), and that identifies non-traditional requirements using 4.0 tools such as Big Data and Analytics].

0. My company does not yet develop new products based on the customer.
1. Takes random and incipient initiatives.

2. Establishes planning and starts to deploy customer-centric NPD centrally in the marketing and sales department.
3. Completes customer-centric NPD, with multi-departmental teams, and monitors.
4. Regularly optimizes customer-centric NPD (with prior approval).
5. Self-optimizes customer-centric NPD (without prior approval).

Justification (optional): ____

18. How is the SUPPLY-CHAIN development (physical and digital)?
[i.e., the activities set that involve raw material purchasing, production, storage/warehousing, and products transportation (goods or services) to the final customer].

0. My company doesn't know how to integrate the supply-chain.
1. Takes random and incipient initiatives. Logistics is partially integrated, and a large inventory is kept ensuring flexibility.
2. Only some sectors of the supply-chain can supply on demand.
3. On-demand supply and digitalization are applied throughout the supply-chain, but without optimization in terms of flow and inventory.
4. Regularly supply-chain optimization (including flow and inventory), with I4.0 technologies and pre-approval.
5. There is an entire supply-chain self-optimization (without prior approval).

Justification (optional): ____

19. How is the CUSTOMIZED / PERSONALIZED PRODUCTION system in your company?
[i.e., manufacturing in a "single lot" on customer's request].

0. My company does not have customized production yet.
1. Takes random and incipient initiatives.
2. Only some parts of the production system are suitable for custom production, but with extensive setup time and transition efforts.
3. The entire production system (such as machining, assembly, warehousing, picking, and/or transportation) is set up for a "single lot" but without data-driven optimization.
4. Customized production optimization regularly takes place, with I4.0 technologies and prior approval.
5. Customized production is self-optimized (without prior approval).

Justification (optional): ____

20. How is the integration between SALES and OPERATIONS?
[i.e., integration (physical and digital) between company sales and the other operations processes].

0. My company does not yet have integration between sales and operations.
1. Takes random and incipient initiatives.
2. Establishes planning and starts to implement this integration for only a few operations.
3. Completes the deployment in a unified way for all operations and monitors it.
4. Regularly optimizes this integration (with prior approval).
5. Self-optimizes this integration (without prior approval).

Justification (optional): ____

21. How is the QUALITY MANAGEMENT SYSTEM application, with multiple customer integration channels (using I4.0 tools such as social networks and artificial intelligence) to after-sales services?
[After-sales services examples: satisfaction survey, customer feedback management, warranty, and technical assistance].

0. My company doesn't have a quality management system for after-sales yet.
1. Takes random and incipient initiatives.
2. Establishes planning and starts to implement this system for only a few after-sales services.
3. Completes implementation in a unified manner for all after-sales services, and monitors.
4. Regularly optimizes this system (with prior approval).
5. Self-optimizes this system (without prior approval).

Justification (optional): ____

FINAL QUESTION
<u>About your new perception, after the CUBE-4.0 Questionnaire, regarding your company's readiness for digital transformation.</u>

0. NOT STARTED: My company values I4.0 but doesn't know how to implement it.
1. EXPERIMENTED: My company ends up taking random and incipient initiatives.
2. PLANNED: My company establishes planning to implement it, with support from tools/software, and starts implementation, but still with individual/modular solutions for some of the company's processes.
3. MANAGED: My company completes the implementation in the whole company and starts monitoring I4.0 (with goals, methods, and performance indicators), providing forecasts and possible causes.
4. OPTIMIZED: My company has a data-driven (with I4.0 technologies) and regularly executes I4.0 optimization process with prior approval.
5. SELF-OPTIMIZED: My company has autonomous systems (like exception messages in MRP II[4] systems, where the machine identifies data patterns and suggests adaptation strategies) to self-adapt to market contextual changes, including those promoted by I4.0, without prior approval (self-optimization).

Justification (optional): ____

How would you rate this questionnaire?

( ) Difficult to fill out and not effective
( ) Difficult to fill out, but effective
( ) Easy to fill out, but not effective
( ) Easy to fill out and effective

What can your company do to accelerate the processes, tools, skills, and attitudes development needed for I4.0? ____
Other Comments: ____

<u>FOOTNOTES:</u>
1. **UnB**: University of Brasilia.
2. **Aachen**: *Rheinisch-Westfälische Technische Hochschule Aachen* or RWTH Aachen University.
3. **IT**: informational technology.
4. **MRP**: Manufacturing Resource Planning.

Appendix D: CUBE-4.0 Roadmap

CUBE-4.0 General Roadmap proposed (Source: Author).

Appendix E: Título e Resumo estendido em português

PROPOSTA DO "MODELO DE PRONTIDÃO CUBE-4.0" PARA EMPRESAS DE ENGENHARIA NO CONTEXTO DE TRANSFORMAÇÃO DIGITAL

Esta tese propõe um novo Modelo de Prontidão, chamado CUBE-4.0, para avaliar o estado de prontidão e orientar estratégias de melhoria, de forma inovadora, em empresas de engenharia (indústrias) de qualquer tamanho, tipo e nível de prontidão, no contexto da transformação digital.

Foi realizada uma revisão sistemática da literatura e da teoria existente para selecionar, com um "Teste Bibliográfico de Sinônimos (TBS)" e um "Fluxo de Busca com 8 Passos" (ambos criados pelo Autor), informações relevantes dos 486 estudos encontrados em 10 renomadas bases de dados, considerando 63 modelos de maturidade e de prontidão existentes em toda a literatura científica sobre este assunto.

Com base nas deficiências dos modelos de maturidade e de prontidão detectadas e, após a realização do pré-projeto e sistematização, o Modelo de Prontidão CUBE-4.0 foi desenvolvido como uma contribuição essencial para essa linha de pesquisa, incluindo sua estrutura (dimensões, sub-dimensões, elementos, níveis de prontidão, gráfico de radar, cálculo de pontuação e metodologia de coleta de dados), questionário e *roadmap* (roteiro).

Este Modelo fornece uma metodologia prática e de fácil aplicação, com 3 dimensões (X = Facilitador Organizacional, Y = Facilitador Tecnológico e Z = Facilitador da Maturidade do Processo), 6 sub-dimensões e 21 elementos. Além disso, possui uma escala de 0 a 5 para avaliar o nível de prontidão da empresa, definido e estruturado de forma inédita, além de considerar, pela primeira vez, a maturidade como um *input* (entrada) para a avaliação da prontidão da empresa, e não como um *output* (saída), diferenciando-se de todos os outros modelos existentes. O "Questionário CUBE-4.0" foi desenvolvido, com base nesses conceitos, para coletar dados de empresas de engenharia sobre sua prontidão à transformação digital.

Finalmente, com o "*Roadmap* CUBE-4.0", baseado nos resultados do Questionário CUBE-4.0, esse Modelo também pode ajudar à Alta Direção a orientar estratégias e planejar melhorias em suas empresas, nesta era da Indústria 4.0 (I4.0).

Após a apresentação de algumas hipóteses dedutivas, um pré-teste com o Questionário CUBE-4.0 e com o *Roadmap* CUBE-4.0 foi aplicado em seis etapas, cujos resultados satisfatórios serão apresentados nesta tese. Em seguida, o Modelo CUBE-4.0 foi revisado e aplicado em três renomadas empresas de engenharia, possibilitando sua completa validação, mediante métodos teóricos e práticos.

Por último, esta tese apresentará uma discussão sobre os resultados e as principais conclusões, ratificando que o Modelo CUBE-4.0 é completo, útil, barato e eficiente, e poderia ajudar as empresas de engenharia a melhorarem sua prontidão no contexto de transformação digital.

Palavras-chave: PRONTIDÃO, MODELO DE MATURIDADE, EMPRESA DE ENGENHARIA, INDÚSTRIA 4.0, TRANSFORMAÇÃO DIGITAL