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UM MÉTODO DE AVALIAÇÃO DA MATURIDADE BASEADO NO MODELO DE REFERÊNCIA DE ARQUITETURA PARA INDÚSTRIA 4.0 - RAMI 4.0

DISSERTATION

PONTA GROSSA
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READINESS ASSESSMENT METHOD BASED ON THE REFERENCE ARCHITECTURE MODEL FOR INDUSTRY 4.0 - RAMI 4.0

Dissertation presented to the Graduate Program in Computer Science of the Department of Informatics of the Universidade Tecnológica Federal do Paraná – Campus Ponta Grossa as a partial requirement to obtain the title of Master in Computer Science
.
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Trabalho de pesquisa de mestrado apresentado como requisito para obtenção do título de Mestre Em Ciência Da Computação da Universidade Tecnológica Federal do Paraná (UTFPR). Área de concentração: Sistemas E Métodos De Computação.

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ABSTRACT

The Industry 4.0 concept inception definitively provided a disruptive glimpse in terms of possibilities in a multidisciplinary spectrum. The convergence and synergy from technologies generated quite high expectations. In terms of advancements, the efficiency increase is one of the key factors. Smart factories must be capable of producing more and in an ecologically cleaner manner, by benefiting from less environmentally impacting energy sources. The present moment is for digital transformation in the diverse enabling transverse areas. For that to be feasible, the next steps are towards standardization, which brings viability to expand and integrate the assorted devices and processes, bringing intelligence closer to all the involved equipment by capitalization. The gap that this research aims to explore is in the assessment of the ongoing industries, focusing on the current status of the operational plants technologically. In other words, by mapping the present, as-is, situation, the stakeholders obtain a valuable guidance resource to go through the journey upon permeating the Industry 4.0 status, the greater objective. Undoubtedly, a path of considerable length, but with well-proportioned outcomes. The solution's ambition is to rate, grade, and calculate the readiness levels of the institution accordingly to that scope. To achieve that, methods will be developed and applied to gather information and subsequently treat it. Finally, the results will be presented according to the fourth industrial revolution preconized capabilities, as defined by the Rami 4.0 Reference Architecture Model. Having presented the information, there is a possibility to establish a road-map to achieve the desired level.

Keywords: Industry 4.0. RAMI 4.0. Maturity Evaluation Method. Industrial Cyber-Physical Systems. Readiness Level Assessment.

RESUMO

O surgimento do conceito de indústria 4.0 definitivamente teve um vislumbre disruptivo no sentido de possibilidades em um âmbito multidisciplinar. A convergência e sinergia das tecnologias gerou grandes expectativas. Em termos de avanços, o aumento da eficiência é um dos fatores chave. Fábricas inteligentes devem ser capazes de produzir mais de forma limpa ecologicamente, beneficiando-se de fontes de energia menos impactantes ao ambiente. O momento presente é de transformação digital nas diversas áreas transversais que são chaves para possibilitar a mudança. Para que isso seja tangível, os próximos passos são em busca de padronização, o que traz viabilidade para expandir e integrar os mais diversos dispositivos e processos, trazendo a inteligência para mais perto dos equipamentos envolvidos através da capilarização. A oportunidade que esta pesquisa pretende explorar é na avaliação das indústrias em operação, focando no status atual das plantas em termos tecnológicos estão as fábricas atualmente. Em outras palavras, através do mapeamento da situação presente, do ‘como está’, os envolvidos obtêm um recurso de referência de alto valor para atravessar a jornada rumo a entrada no status de indústria 4.0, o grande objetivo. Sem dúvidas um caminho longo, mas com resultados igualmente proporcionais. A solução almejada é avaliar, categorizar e calcular o nível de maturidade e prontidão da instituição de acordo com o escopo. Para atingir isto, métodos serão desenvolvidos e aplicados para levantar informações e em sequência, tratá-las. Finalmente, os resultados serão confrontados com as capacidades preconizadas para indústria 4.0, conforme definição do modelo de referência de arquitetura do RAMI 4.0. Tendo estas informações apresentadas, há a possibilidade de estabelecer uma programação ou projeto para atingir o nível desejado.

Palavras-chave: Indústria 4.0. RAMI 4.0. Método Avaliativo de Maturidade. Sistemas Cyber-Físicos Industriais. Avaliação de nível de prontidão.

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LIST OF ABBREVIATIONS ANS ACRONYMS

AP	Access Point
ADO	ActiveX Data Object
ARM	Advanced RISC Machine
AHP	Analytic Hierarchy Process
XaaS	Anything as a Service
API	Application Programing Interface
AI	Artificial Intelligence
AAS	Asset Administration Shell
ACM	Association for Computing Machinery
AR	Augmented Reality
AGV	Autonomous Guided Vehicle
BS	Base Station
BaaS	Blockchain as a Service
BIM	Building Information Model
BM	Business Model
CCTV	Closed-Circuit Television
CC	Cloud Computing
CoT	Cloud of Things
CSV	Comma Sepparated Value
CDD	Common Data Dictionary
CNC	Computer Numerical Control
COAP	Constrained Application
CPE	Customer Premises Equipment
CPS	Cyber-Physical System
DAQ	Data Acquisition
D2D	Device to Device
DL	Digital Library
EC	Edge Computing
EDDL	Electronic Device Description Language
ERP	Enterprise Resource Planning
FDT	Field Device Tool
FCEM	Fuzzy Comprehensive Evaluation Method
GPIO	General Purpose Input/Output
GPS	Global Positioning System
HANA	High Performance Analytic Appliance
HMI	Human Machine Interface
HR	Human Resources
HTML	Hypertext Markup Language
HTTP	Hypertext Transfer Protocol
IACS	Industrial Automation and Control System
iCyPhy	Industrial Cyber-Physical
ICPS	Industrial Cyber-Physical System
IIoT	Industrial Internet of Things
I4.0	Industry 4.0
IFC	Industry Foundation Classes
Info	Information
ICT	Information and Communication Technoloy
IT	Information Technology
ICN	Information-Centric Networks

SUMMARY

1 INTRODUCTION

Since XVIII century when the mechanization by steam and water power provided a major leap on the manufacturing techniques, followed by the mass production advancement arranged by the assembly line processes in the XIX century. Finally the automation spread based on electronics and computers in the XX century. All considered, there has been three industrial revolutions, which have all contributed to make possible great progress on complimentary information technology. At the third decade of the XXI century, has become evident that there is currently the fourth one ongoing, named also as the Industry 4.0.

This new stage has its core mainly related to cyber-physical systems, where a contextualization of intelligent manufacturing(RAUT et al., 2020) through several technologies such as artificial intelligence, machine learning, cloud computing, fog computing, industrial internet of things, web of things, big data, collaborative robots, autonomous robots, and block chain technology. Such phenomenon can be effortlessly distinguished from the past ones in a sense that the present disruption is not related to equipment resources or any physical aspect, but to the technology and information flow themselves and the potential result gathered from it. More specifically on the soaring importance that data has gained.

With all the simultaneous technological events, it is enlightened the necessity to evaluate the present institution’s situation with accuracy. Acting on it is a very time sensitive matter, that ought to be taken with celerity. The reason being, it might just mean the necessary competitive advantage to be ahead of the rivals.

There is a paradigm transition between online to real time data acquisition and access, therefore disjointing challenges in several fields. In the matter of infrastructure, such transition leads to unprecedented demand for storage and processing capacity. In the telecom area, a wide variety of devices need to communicate between themselves regardless of different media or vendor. Decision and simulation are needed in real time pace with assisting technologies to keep everything safe and cost effective. As far as market competitiveness, the globalization created a quite fierce environment while the customer requirement level keeps growing. All together results in an outcome of a dynamic and not only reactive but predictive ecosystem where ability to adapt quickly is essential.

1.1 JUSTIFICATION

Since the emergence of the Industry 4.0 terminology in 2011(OZTEMEL; GURSEV, 2020) several standards have been established. Along with the conventions come the necessity to appraise and assess the current status, observing that it being a progression from the third industrial revolution, makes elemental that migrating from the predecessor specifications is the most natural course. Despite the fact that a substantial amount of the repertoire of the capabilities and technology references are yet to be defined. In addition, taken into consideration the I4.0 status quo can be classified as fluid and with a long way to be solidified, the demand for readiness analysis is nothing but organic. That is the reason why reference architecture models for industry 4.0 - specially the pioneer - RAMI 4.0, gain such an importance in this scenario. Moreover, the transitioning process planning and road-mapping accessory tools, such as a readiness assessment model may be of great hand, exactly what this research aims to cover. The study of (NAKAGAWA et al., 2021) outlines the several distinctions between the main Industry 4.0 reference models. Given the model worldwide adherence and extensive international cooperation (INTERNATIONAL. . . , 2021), its maturity state and alignment with both the study scope and the suitability to the involved plant's strategic goals, the RAMI 4.0 was elected to be the guideline as a far as reference architectural model.

1.1.1 Objectives

The main objective of this work is to bring a practical and effective industry 4.0 readiness assessment, evaluating the current status regarding the assessed institution against the Industry 4.0 prerequisites, taking the RAMI 4.0 as a guideline. The consolidated technologies and practices compliance will be appointed with their respective considerations and metrics, through definition of referential parameters, defined by a questionnaire, and with the results contrasted to the optimal situation (completely ready).

1.1.1.1 General Objectives

This work's broad objective is to develop an assessment method related to the Industry 4.0 readiness level by the application of an analytic evaluation technique that is effective and cost-effective, having its technical endorsement backed by the Reference Architecture Model for Industry 4.0. The readiness level shall be given segmented with the respective reference model axis performance and the assessed segment as well. The assessment must cover the axis oriented accordingly to the RAMI 4.0 definitions.

1.1.1.2 Specific Objectives

The specific objectives of the proposed research are to gather the response to the research questions in the Frame 1.

Frame 1 – Research questions

Research Question	Description
RQ1	Which are the industry 4.0 key enabling technologies?
RQ2	Which are the industry 4.0 readiness indicator elements?
RQ3	How to contextualize the RAMI 4.0 axes into the smart manufacturing processes and its e technologies?
RQ4	How to implement the readiness assessment level into the industry 4.0?

Source: Self authorship (2021).

The acquiring process will facilitate and aggregate to the development and delivery of the evaluation method.

1.2 THESIS STRUCTURE

This dissertation is presented in the following structure: Chapter 2 consists in a Systematic Literature mapping around the Industry 4.0 in order to gather more preliminary information and clarify the current state of the art, along with the related works, aiming to clarify the overall scientific research status in addition to the intended purpose of this work. Chapter 3 addresses the background studies related to the most relevant themes, by segmenting sections regarding close topics. It presents the background information supported by a theoretical reference. This session encompasses the technologies, methodologies and paradigms related to the core theme with contextualization purposes.

Chapter 4 will cover the proposition of an experiment related to the proposed research and a more detailed displacement of the methodology is also characterized. Four questions orientate the work objective, which by this point shall be answered. There is a fifth section for results presentation followed by the last one with the final discussion and considerations.

2 SYSTEMATIC LITERATURE MAPPING

Systematic Literature Mapping, or SLMs, are researches that have the proposition to put in evidence the current progress, advancements and tendencies concerning the object of study's scrutiny(KITCHENHAM; PEARL BRERETON, et al., 2009). It is widely applied on science and technology related fields, especially on subjects that tend to evolve on a substantially dynamic pace. With the broad outlook provided by the Industry 4.0 constant transition, the execution of a SLM shall be of grand benefit. The orientation provided by its verified information will be used as a guide to narrow this study scope.

Comparative segment The comparative segment will be given by the elaboration of a comparative work from the gathered studies on the systematic literature mapping regarding readiness assessment methods on the industry 4.0, and as such, supporting the differences and particular characteristics motivating its development.

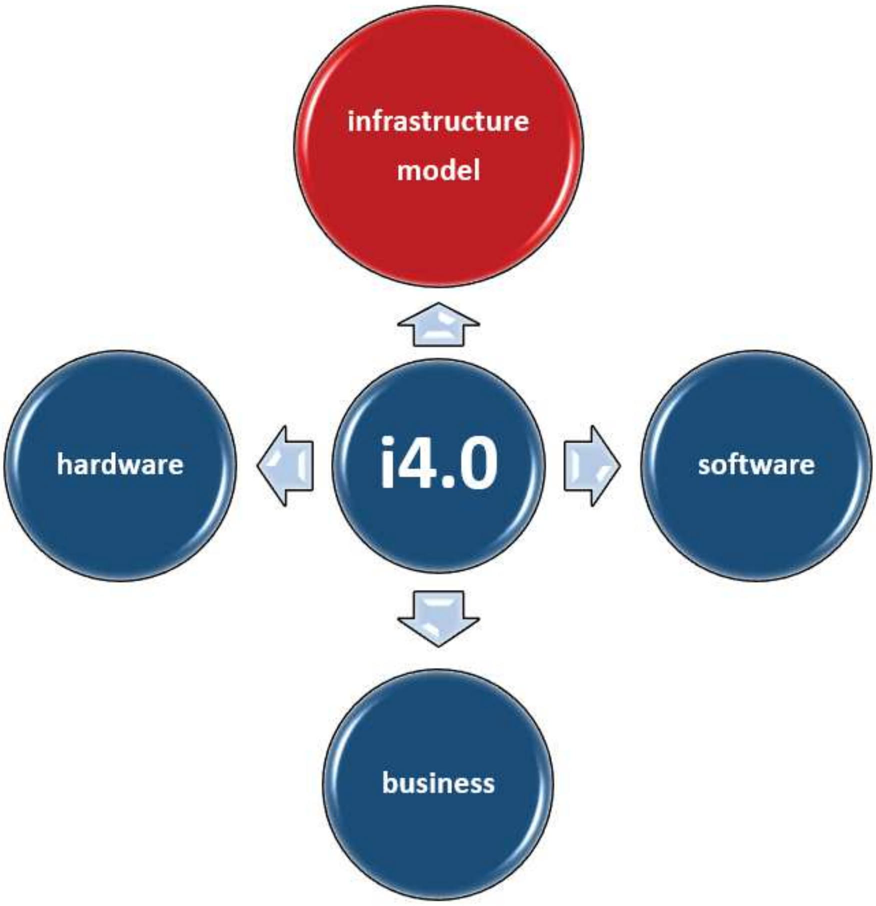
2.1 RELATED SYSTEMATIC MAPPING STUDIES

Having considered the broadness of the industry 4.0 related SLMs, such studies were analyzed, what made possible to note that several distinct points of view have been taken, such as MBSE based modeling(WORTMANN; COMBEMALE; BARAIS, 2017), the impact that SMEs will receive from entrepreneurial standpoint(CORALLO; LAZOI; LEZZI, 2020), how do startups develop IoT systems(DUC et al., 2019), environmental Big Data(CASTELLUCCIA; CALDAROLA; BOFFOLI, 2017), the facilitation of development through application of MDE in CPSs(MOHAMED; CHALLENGER; KARDAS, 2020), solutions related to the link from ICN and IoT(DJAMA; DJAMAA; SENOUCI, 2020). Still in the IoT field and specifically its challenges(LEPEKHIN et al., 2019), the synergy between Internet of Things and cloud computing(DIAS et al., 2020), deployment and orchestration for IoT(NGUYEN, P. H. et al., 2019), and also the study of industrial smart energy grids(BREM et al., 2020) (regardless of its environmental adequacy manufacturing guidance) as well as on industrial WSN(QUEIROZ et al., 2017). Notwithstanding their high-grade and depth content, the vast majority, however, diverge from this work's proposed research questions and objectives.

Despite the variety broadness of exploration, by the time the search was executed on the selected digital academical libraries (ACM, IEEExplore, Science Direct (Elsevier) and Springer Link), only a quite very limited count of studies can be considered analogous or close to the spectrum which this study aims, being them related to architecture, technologies and challenges for cyber-physical systems in industry 4.0(HOFER, 2018), interoperability in IoT(MUNIZ et al., 2019) and (CASTRO DE SOUZA; GONÇALVES PEREIRA FILHO, 2019), the mapping on modelling languages(WORTMANN; BARAIS, et al., 2020), and in a sense of the infrastructure technologies, the survey in an analytical approach(SIOW; TIROPANIS; HALL, 2018) and the analysis framework by Boyes et Al(BOYES et al., 2018).

That observed, those studies also fall into 4 broad classes. Two classes focus directly on software and hardware relation to the industry 4.0. One class focus specifically on the business side, such as processes and strategy. The fourth class, from which this study intend to explore with more depth is the reference and infrastructure models, what includes a more holistic point of view. Taking the gathered info in consideration regarding the specially increasing pace in the past 5 years, an opportunity raises to explore. Those classes are represented in Fig. 1.

Figure 1 – i4.0 SLMs points of view variation



Source: Self authorship (2021).

2.1.1 Mapping Method

This mapping will be conducted considering as a north a combination of the research method conducted by (KITCHENHAM; AL-KHILIDAR, et al., 2006), given its completeness and (WORTMANN; COMBEMALE; BARAIS, 2017) due to the similarities to the topics explored. The process will consist on four stages where first the research questions will be established. Then the search itself will be executed and screened according to the points of reference. In the next steps the researches will be rated and subsequently investigated in the last part.

2.1.2 Mapping Questions

As proposed by Kitchenham, the research questions were defined in order to guide the expected outcome from the mapping. From the three proposed questions, two are from quantitative nature and one from qualitative nature, as they are represented:

1. What are the most frequent keywords associated to industry 4.0 assessment?
2. What countries are leading the scientific content production around the Industry 4.0 maturity assessment?
3. What are the Industry 4.0 evaluation methods?

The first one is intended to bring knowledge regarding the related technologies and applications through the keywords declared joined to the publication. In addition, the answer will the subsidize the steering towards the most demanded topics among the scientific community. The second question will demonstrate the regional tendency. The third question seeks to ascertain the development of evaluation methods regarding the Industry 4.0. The goal of answering such SLR questions is to guide the research into further answering the research questions proposed in Section 1.1.1.2.

2.1.3 Digital Libraries And String Search Plan

Scientific digital libraries were elected based on empiric searching related key words and also taken in consideration the search bases from resembling mapping works gathered on the related papers stage(MEIDAN et al., 2018) and (WORTMANN; COMBEMALE; BARAIS, 2017), shown on the Table 1.

Table 1 – Digital Libraries Publications

Library	Website	Number
ACM	https://dl.acm.org/journals	155
IEEEXplore	https://ieeexplore.ieee.org/Xplore/	644
Science Direct	https://www.sciencedirect.com/search	305
Springer Link	https://link.springer.com/	564
Total		1668

Source: Self authorship (2021).

The exploration was conducted through a search string by the use of a combination of Boolean operators and the execution precedence defined by parenthesis. On the capable DLs, wildcards were used. Despite the fact the different digital libraries particularities demanded adaptations which should not represent any detriment to the results. In the Frame 2 the string versions are shown.

Frame 2 – Search Strings

String	Complete String
R-STR1	("fourth industrial" OR ïndustry 4.0") AND (ässess*" OR ëvaluat*" OR "measur*" OR "matur*") AND (äpproach*" OR "method*" OR "model*")
R-STR2	("fourth industrial" OR ïndustry 4.0") AND (ässessment" OR ëvaluation" OR "measurement" OR "maturity") AND (äpproach" OR "method" OR "model")
R-STR3	("fourth industrial" OR ïndustry 4.0") AND (ässess* approach" OR ässess* method" OR ässess* model" OR ëvaluat* approach" OR ëvaluat* method" OR ëvaluat* model" OR "measur* approach" OR "measur* method" OR "measur* model" OR "matur* approach" OR "matur* method" OR "matur* model")

Source: Self authorship (2021).

The R-STR1 was used as the reference for the R-STR2 and R-STR3. It makes use of ‘*’ as a wildcard, enabling the use of morphemes followed by the wildcard, eliminating the need for multiple searches for derived words. In addition, the Boolean distributive properties are also taken advantage from, which makes the string search shorter, optimizing the use of limited character search engines. The base was adjusted accordingly to the digital library search engines limitations, culminating in two additional variants, being R-STR2 with no wildcards and R-STR3 with no distributive properties. And then compensating it by stating the combinations one by one, making usage of the “OR” logical connector to achieve the same request.

2.1.4 Screening Stage

In order to better adequate the results into the scope of this research, the primary screening will consist in both excluding and including rules. The Frame 3 specifies the rules.

Frame 3 – Exclusion / Inclusion Rules

Rule Type	Conditions
Exclusion	Research not available for access online through CAPES or UTFPR proxy; Research not yet approved for publication; Scope unrelated to this work proposal; Publication date priory to 2016;
Inclusion	Approach on industry 4.0 infrastructure related technologies; Approved and reviewed in journal or conference;

Source: Self authorship (2021).

The screening was executed in 5 steps, consisting in the initial search based on the search string, followed by a 3 phase screening and a final removal step, where the studies that are related but not accessible. The first one eliminated 50 studies that had a publication date done before 2016. The next run removed more 165 works, being them mixed between not available for online access, or short publications - as newsletters and mini reviews. The steps are detailed in the Frame 4:

Frame 4 – Detailed Screening Steps

Step	Description
First	Initial search result based on the search string
Second	Screening Phase 1: Removal of studies out of the publication date range
Third	Screening Phase 2: Removal of newsletters, mini reviews and publications that did not endorse online access
Fourth	Screening Phase 3: In depth analysis of scope relation
Fifth	Removal of inaccessible papers according to the defined access methodology

Source: Self authorship (2021).

The third phase of the screening was done in a qualitative manner, which will be explored with more depth in the next subsection.

2.1.5 Screening Stage Result Analysis

Based on the studies that remained as result of the screening, was possible to notice at least 3 distinct categories that will be explored in the following paragraphs.

2.1.5.1 Modeling Related Studies

Aiming to represent the physical infrastructure according to the chosen model, such as (HORSTKEMPER; STAHMANN; HELLINGRATH, 2019) and (NIE et al., 2017). Hence they remain out of the objective of this study, those works were excluded from the selection.

2.1.5.2 Execution Of Assessment Studies

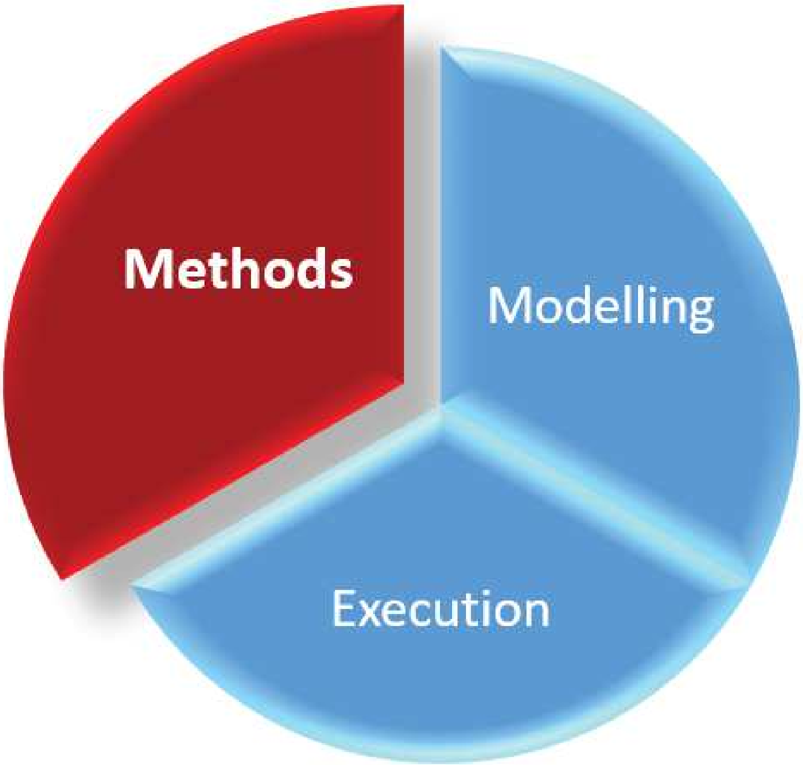
The second type of studies identified are related to the process of application a maturity assessment itself in a determined demographic, being (SHEEN; YANG, 2018) and (NICK et al., 2019) examples of this nature. Despite their detailed and illustrated execution, the studies from that category were also left out of the whole mapping screening process, as represented by Fig. 2.

2.1.5.3 Method Proposition Studies

The category of study representing assessment, maturity and readiness levels, was related to the study scope, and will be explored with more depth.

The three classes are illustrated in the Fig. 2, with the red representing the selected ones.

Figure 2 – Types of studies found during the screening



Source: Self authorship (2021).

After the screening, it was possible to notice that a portion of the studies were theme aligned, however 13 of them could not be accessed through the UTFPR proxy access agreement, as stated in Frame 3, and as such they were also excluded.

Having the process completed, the result was composed by (COLLI et al., 2019); (ESSAKLY; WICHMANN; SPENGLER, 2019); (JENDERNY et al., 2018); (LEYH et al., 2016); (LIN et al., 2019); (LUCATO et al., 2019); (PACCHINI et al., 2019); (PISCHING et al., 2018); (PUCHAN; ZEIFANG; LEU, 2018); (RAFAEL et al., 2020); (RAJ et al., 2020); (SCHUMACHER; EROL; SIHN, 2016); (SCHUMACHER; NEMETH; SIHN, 2019); (SHARPE et al., 2019); (UNTERHOFER et al., 2018); (WEKING et al., 2020); (XIA et al., 2019). Those studies were selected to a more in depth analysis and comparison.

2.1.6 Screening quantification

The evolution of studies quantity through all of the screening stages is now represented in the Table 2:

Table 2 – Screening Phases Result

Digital Library	Screening Phase				
	1	2	3	4	5
ACM	155	150	146	24	1
IEEEExplore	644	631	630	14	4
ScienceDirect	305	299	284	20	12
SpringerLink	564	538	393	13	0
Total	1668	1618	1453	71	17

Source: Self authorship (2021).

2.1.7 Perceptions

By the aforementioned research analysis, the current advancement on Industry 4.0 maturity assessment becomes tangible, as well as the tendencies of research for present time being and the paths to follow. The respective research question quantification will be represented by 2 charts and a description in the following paragraphs:

2.1.7.1 Question 1: What Are The Most Frequent Keywords Associated To Industry 4.0 Assessment?

The Fig. 3 represent the keywords that were used more than once in the selected studies. The font size is proportional to the frequency they were used.

Figure 3 – Keyword word-cloud

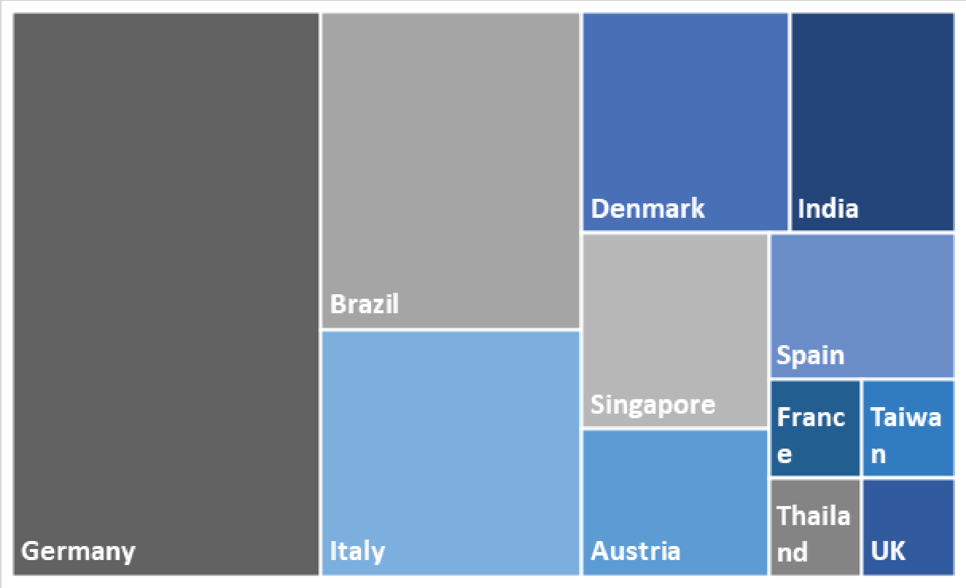
Source: Self authorship (2021).

With that it becomes clear that the fourth industrial revolution is treated as a transverse theme, bringing together subjects that commonly tented to be far apart.

2.1.7.2 Question 2: What Countries Are Leading The Scientific Content Production Around The Industry 4. 0 Maturity Assessment?

The Fig. 4 represent countries with the highest academic production rates on the study field. The area dimension is proportional to the country production.

Figure 4 – Production per country



Source: Self authorship (2021).

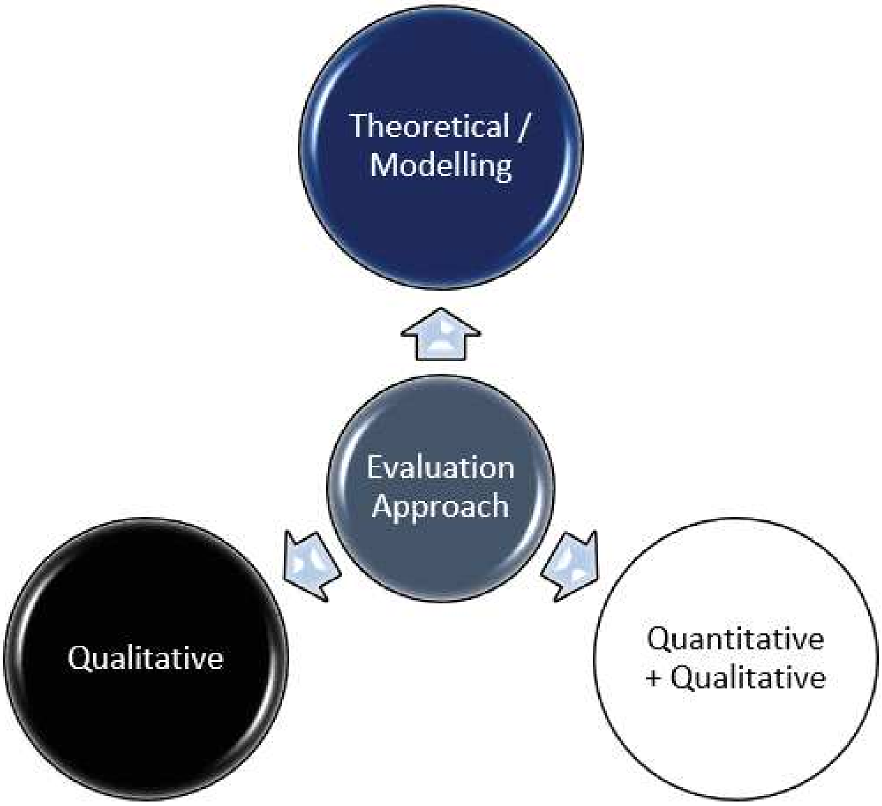
2.1.7.3 Question 3: What Are The Industry 4.0 Evaluation Methods?

As a general outcome, the ultimate goal of the industry 4.0 models is to improve the performance through the optimization of four areas: Process (operations,) automation, connection, and business intelligence. They can be approached from several methodologies, from classical engineering to fuzzy techniques.

With the recent participation of Tüv Süd(INDUSTRY. . . , 2021) on the I4.0 initiative, there is already a standard under development and perfectly aligned with the Industrie 4.0 Platform Working Groups'(THE. . . , 2021) premises. That itself is a great step forward. The partnership began with the Singapore government along with TuV(LIN et al., 2019) and is now on replication by several industries around the world, and more than ever is clear that convergence between OT and IT through CPSs will be a key factor.

The question 3 explorations also led to the classification of the screened results. Seeking for patterns among them brought into surface three distinct approaches when it comes to evaluation techniques. Taken as object of study, the method proposition works analyzed on the Section 2.1.5, it became clear that part of the studies took as north for assessing the readiness, qualitative characteristics of the organization. Mostly process oriented, and not part of a model itself. A second class of approach additionally explored quantitative characteristics, categorizing among levels of readiness for each measured field, yet not related to a architecture or model. A third type of approach explored how procedures were adherent to established architectural models. The evaluation criteria are represented by Fig. 5. The classification will be explored in the following items.

Figure 5 – Identified industry 4.0 evaluation approaches



Source: Self authorship (2021).

2.1.7.3.1 Qualitative Evaluation Approaches

The studies that take in consideration primarily qualitative specifications and characteristics to make the assessment are shown in the Table 3, as comparative table exploring the nuances among them.

Table 3 – Assessments oriented primarily on qualitative data

Title	Authors	Date	Focus	Differential	Misc.
Leveraging industry 4.0 – A business model pattern framework	J. Weking, M. Stöcker, M. Kowalkiewicz, M. Böhm, and H. Krcmar	Jul. 2020	Business model oriented	Enterprises Cases study initiatives	Sort by BM
Application of SIRI for Industry 4.0 Maturity Assessment and Analysis	W. D. Lin, M. Y. H. Low, Y. T. Chong, and C. L. Teo	Dec. 2019	Guidance from RAMI through SIRI	Use of SIRI	Closer to RAMI practical guide
A reference framework for the holistic evaluation of Industry 4.0 solutions for small-and medium-sized enterprises	A. Essakly, M. Wichmann, and T. S. Spengler	Jan. 2019	SMEs assessment	Oriented specifically to its scope	Practical approach
A maturity assessment approach for conceiving context -specific roadmaps in the Industry 4.0 era	M. Colli, U. Berger, M. Bockholt, O. Madsen, C. Møller, and B. V. Wæhrens	Jan. 2019	Design oriented research	Systematic Assessment approach review	Competence study
Investigation of Assessment and Maturity Stage Models for Assessing the Implementation of Industry 4.0	M. Unterhofer, E. Rauch, D. T. Matt, and S. Santiteerakul	Dec. 2018	Maturity Model itselft	Consolidation of different model	Based on a a systematic mapping

Industry 4.0 in Practice- Identification of Industry 4.0 Success Patterns	Jörg. Puchan , A. Zeifang, and J.-D. Leu	Dec. 2018	Identifying the key elements related to business success	Determines fields of actions and action elements	Consider IEEM topics oriented
Development of an instrument for the assessment of scenarios of work 4.0 based on socio-technical criteria	S. Jenderny *et al*	Jun. 2018	Assessment based on the alignment from business, technology and human	Socio-technical approach	Large exploration of human dimension on the context
SIMMI 4.0 - a maturity model for classifying the enterprise-wide IT and software landscape focusing on Industry 4.0	C. Leyh, K. Bley, T. Schäffer, and S. Forstenhäusler	Sep. 2016	Software and IT	The integration as a primary goal	Model from an IT standpoint

Source: Self authorship (2021).

2.1.7.3.2 Qualitative and Quantitative Evaluation Approaches

The studies that take in consideration both qualitative and quantitative characteristics to make the assessment are compared in the Table 4.

Table 4 – Assessments oriented both on qualitative and quantitative data

Title	Authors	Date	Focus	Differential	Misc.
An Industry 4.0 maturity model for machine tool companies	L. D. Rafael, G. E. Jaione, L. Cristina, and S. L. Ibon	Oct. 2020	Maturity model assessment	Includes HR as a dimension	Dimensions and sub dimensions structure
Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: An inter-country comparative perspective	A. Raj, G. Dwivedi, A. Sharma, A. B. Lopes de Sousa Jabbour, and S. Rajak	Jun. 2020	Challenges and critical points of difficulty	Approach from a difficulty standpoint	Context and equation calculation
The degree of readiness for the implementation of Industry 4.0	A. P. T. Pacchini, W. C. Lucato, F. Facchini, and G. Mummolo	Dec. 2019	Readiness from a infrastructure standpoint	Enabling technologies review	Definition of readiness degrees
A Method Towards Smart Manufacturing Capabilities and Performance Measurement	Q. Xia *et al*	Jan. 2019	Elements and capabilities	Mix between FCEM and AHP evaluation	Takes in consideration multiple techniques
Roadmapping towards industrial digitalization based on an Industry 4.0 maturity model for manufacturing enterprises	A. Schumacher, T. Nemeth, and W. Sihn	Jan. 2019	Improve the authors' previous method	Specifies and contextualizes the abstract on the assessment	Tested in Austria, China and India industries
Model to evaluate the Industry 4.0 readiness degree in Industrial Companies	W. C. Lucato, A. P. T. Pacchini, F. Facchini, and G. Mummolo	Jan. 2019	Mensurate the readiness level of the enabling technology	Uses the SAE standards as reference	Grounded by equations

A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises	A. Schumacher, S. Erol, and W. Sihn	Jan. 2016	Assets and strategy	3 step and 9 dimensions	Most cited and pioneer work

Source: Self authorship (2021).

2.1.7.3.3 Theoretical and Modelling Evaluation Approaches

The studies that take in consideration theoretical and modelling characteristics to make the assessment are compared in the Frame 5.

Frame 5 – Assessments oriented on theoretical and/or modelling data

Title	Authors	Date	Focus	Differential	Misc.
An industrial evaluation of an Industry 4.0 reference architecture demonstrating the need for the inclusion of security and human components	R. Sharpe, K. van Lopik, A. Neal, P. Goodall, P. P. Conway, and A. A. West	Jun. 2019	Improving RAMI usability	Proposes the addition of layers to RAMI	Security and HR focused
An architecture based on RAMI 4.0 to discover equipment to process operations required by products	M. A. Pisching, M. A. O. Pessoa, F. Junqueira, D. J. dos Santos Filho, and P. E. Miyagi	Nov. 2018	Identifying the procedure based on product	Completely based on RAMI 4.0	Can be considered a modelling study as well

Source: Self authorship (2021).

3 THEORETICAL REFERENCE

Taken the obtained information from the executed Systematic Literature Mapping as a north, in this chapter, the addressed technologies, protocols, terminologies and characteristics will be put into context and explained. The agenda will strictly cover attributes related to this study's scope. Deepening and advanced detailing of each topic shall not be done, once it is not part of its goals. The individual descriptive about the following items comprehend their concept, comparison to its predecessor and role contextualization into the fourth industrial revolution.

The fourth revolution phenomena can be briefly translated into the application of CPS and all of its dependent technologies(OZTEMEL; GURSEV, 2020) integrated to achieve the status of smart manufacturing, real time data gathering, autonomous decision making and predictive maintenance. By the arrangement of diverse technologies, paradigms and protocols, becomes possible a new horizon of solutions. This theoretical reference approach is regarding the technologies that are base, or infrastructure related to the I4.0, or putting in other words, that compose this horizon of solutions.

The focus is on changing the manufacturing structure form as pointed by the Frame 6

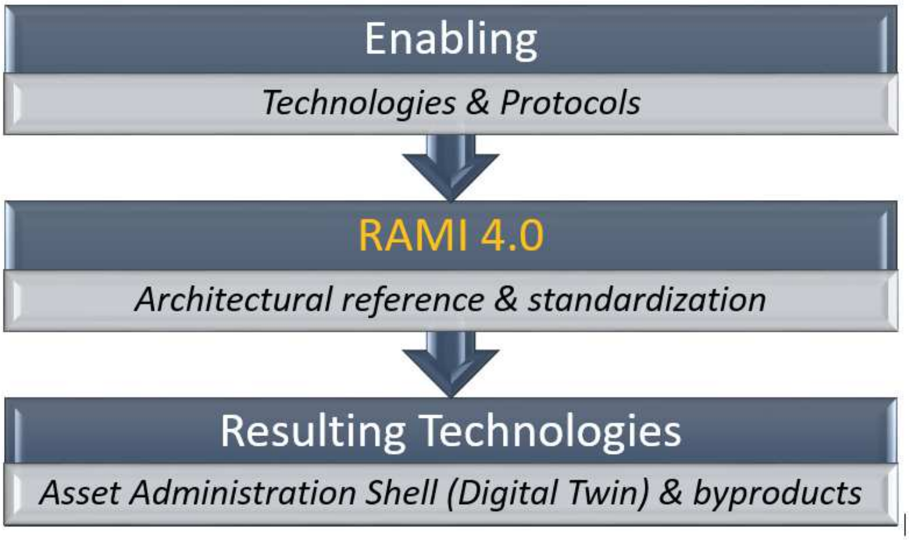
Frame 6 – Industry 3.0 vs Industry 4.0

Industry 3.0	Industry 4.0
Hardware-based structure	Flexible systems and machines
Functions bound to hardware	Functions distributed throughout the network
Hierarchy-based communication	Participants interact across hierarchy levels
Isolated product	Communication among all participants
	Product is part of the network in the Rami 4.0 structure

Source: (INDUSTRY. . ., **2021).**

The Fig. 6 illustrates RAMI into the industry 4.0 context, as well as the flow and relation among the enabling technologies and protocols and the outcome with the resulting technologies.

Figure 6 – Flowchart around the enabling, RAMI and resulting segments



Source: Self authorship (2021).

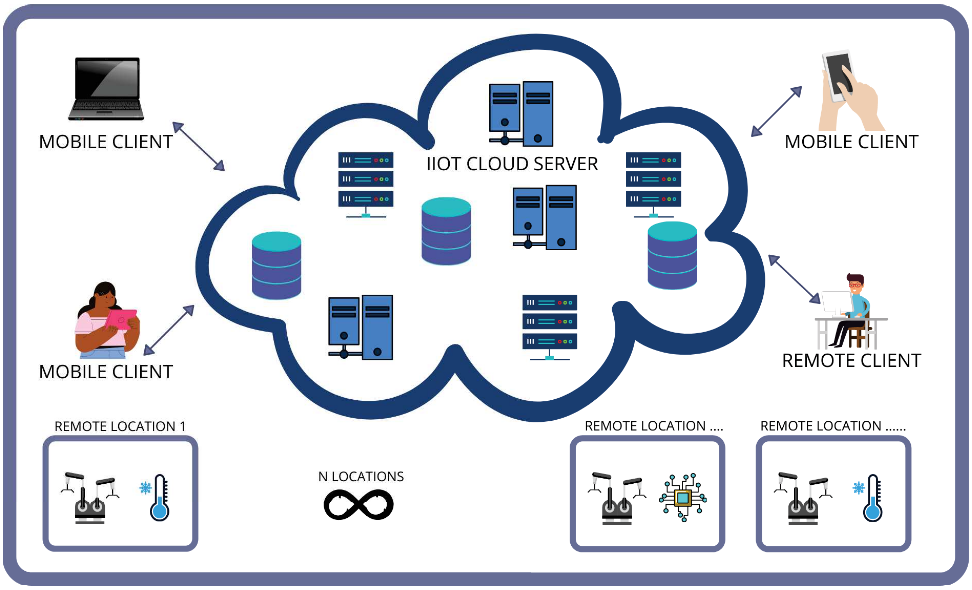
3.1 ENABLING TECHNOLOGIES

The scope of this segment is to put the specific technologies in the context of a 4.0 industrial environment. The technologies were selected based on their recurrence of appearance in the SLR execution. When possible, the respective architectures were demonstrated through schematic figure of the whole concept – in a broad sense – or in a specific schematic applied manner, focusing on their boundaries crossing point. The consumer applied use cases were disregarded, given the nature of industrial orientation of this research.

3.1.1 SCADA

SCADA, or Supervisory Control and Data Acquisition, is an industrial system which aims to concentrate and manage the control of a determined set of machinery and had on its first conceptualization, the implementation based almost entirely on hardware, which was customary proprietary technology(SAJID; ABBAS; SALEEM, 2016). With the advent of the fourth industrial revolution, as all of the communication side became integrated to the machinery themselves, now it is a software-centered solution. The Fig. 7 demonstrates the application of SCADA oriented to IoT.

Figure 7 – The SCADA contextualized into IoT schematics



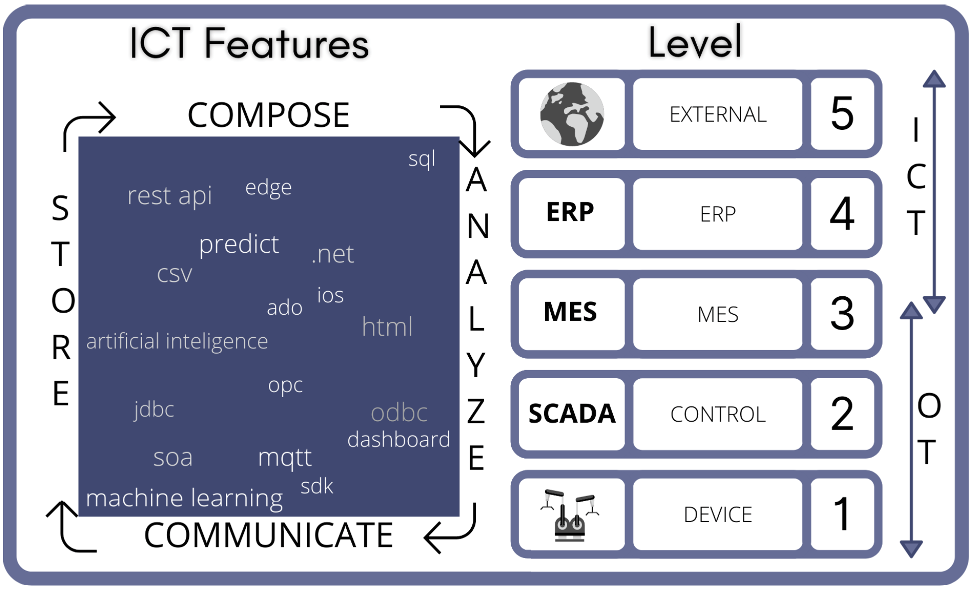
Source: Self authorship (2021).

With that major transition, the concept became part of a broader solution, and it is now situated by the interconnecting segment between OT, IACS, and ICPS(SCURTU et al., 2020) which will be briefly explained and graphically represented in the next sections.

3.1.2 OT / IACS

Industrial Automation Control Systems is the terminology used to assign aggregation of devices and techniques focused on the industrial automated environment(GOTO; YOSHIE; FUJIMURA, 2017) through the application of OT, Operational Technology. The points where OT and IACS are exactly the point of interest of this study. The related repertoire of procedures and technological resources are quite intrinsically connected, and in some cases they might even be overlapped. At that moment is when the I4.0 comes in place. By integrating those technologies and extracting more than they could ever offer individually. The Fig. 8 illustrates the fields where ICT and OT are related, and where the SCADA is inserted in the IACS context.

Figure 8 – The IT and OT relations

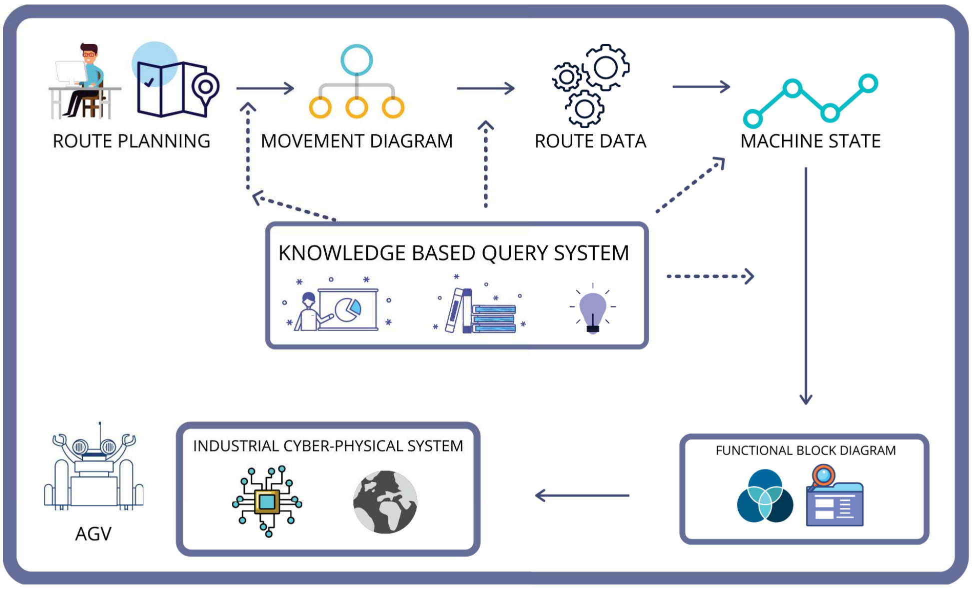


Source: Self authorship (2021).

3.1.3 Industrial Cyber-Physical Systems

The capacity of a digital system to interact with a variable in the physical ambient or process that it is located is one of the characteristics that defines the CPS – Cyber-Physical Concept (LEE, 2008). The concept has emerged on 2006 and since then has been a merging point, where the diverse technologies involved converge. In order to make possible the interaction from the physical environment to a cyber-environment, multiple technological resources have to be put in action in a synergistic manner. For instance: computer vision can be an option for data acquisition from an operator's industrial tablet in the physical ambient, which will then link to the intended information over a QrCode, referenced to a cloud storage web service that would then request a read from a sensor connected using Lorawan protocol. Finally, with this sensor reading, the production system is able to be self-configure itself to optimized parameters according to the specific conditions at that moment in time. The very same flow is able to follow both directions. In the case of the system's stock count being full of a determined variant of product, the system can request the arrangements on the physical side to be done. By application of MDE, the ICPSs' modelling and standardization phase has yielded divers techniques(LI, L. et al., 2019). The Fig. 9 exemplifies an AGV routing scenario model, which takes in consideration both the system desired (ideal) route, the 'real time' barriers that might be encountered, the historic data and the machine itself data (battery status, for example).

Figure 9 – The ICPS flow



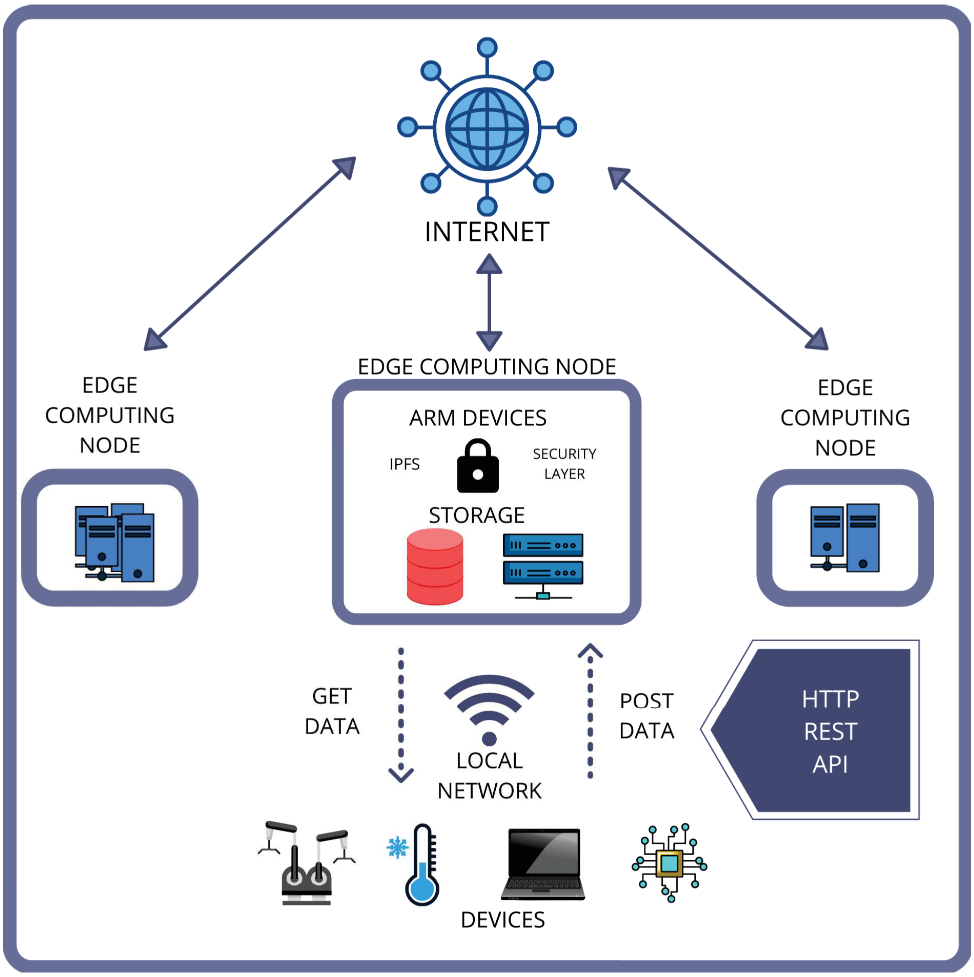
Source: Self authorship (2021).

As far as related events, advancements, the Industrial Cyber-Physical Systems Center (iCyPhy)(INDUSTRIAL..., 2020) through the Department of Electrical Engineering and Computer Sciences(EECS..., 2020) from the University of California at Berkeley(HOME..., 2020) is an pioneer consortium initiative that have the intention to converge the academia along with the industry by evolving the knowledge through researches on most diverse study fields related to CPS. Those research topics are defined from common interest in such a way both the sponsors, researchers and the scientific community gain from it. ICyPhy has held conferences since 2012. IEEE has a dedicated committee for especially for that area, called the IEEE-IES Technical Committee on Industrial Cyber-Physical Systems(IEEE..., 2020).

3.1.4 M2M / D2D

Machine-to-Machine, or M2M (and D2D) are conceptual paradigms in which the communication occurs from a device directly to another device, without the need for external (human) intervention(FROIZ-MÍGUEZ; FRAGA-LAMAS; FERNÁNDEZ-CARAMÉS, 2020). At a first glance its importance might be underrated, but actually the concept has gained importance as basis to more in-depth solutions and paradigms. The Fig. 10 bellow demonstrates the from M2M paradigm.

Figure 10 – The D2D schematics



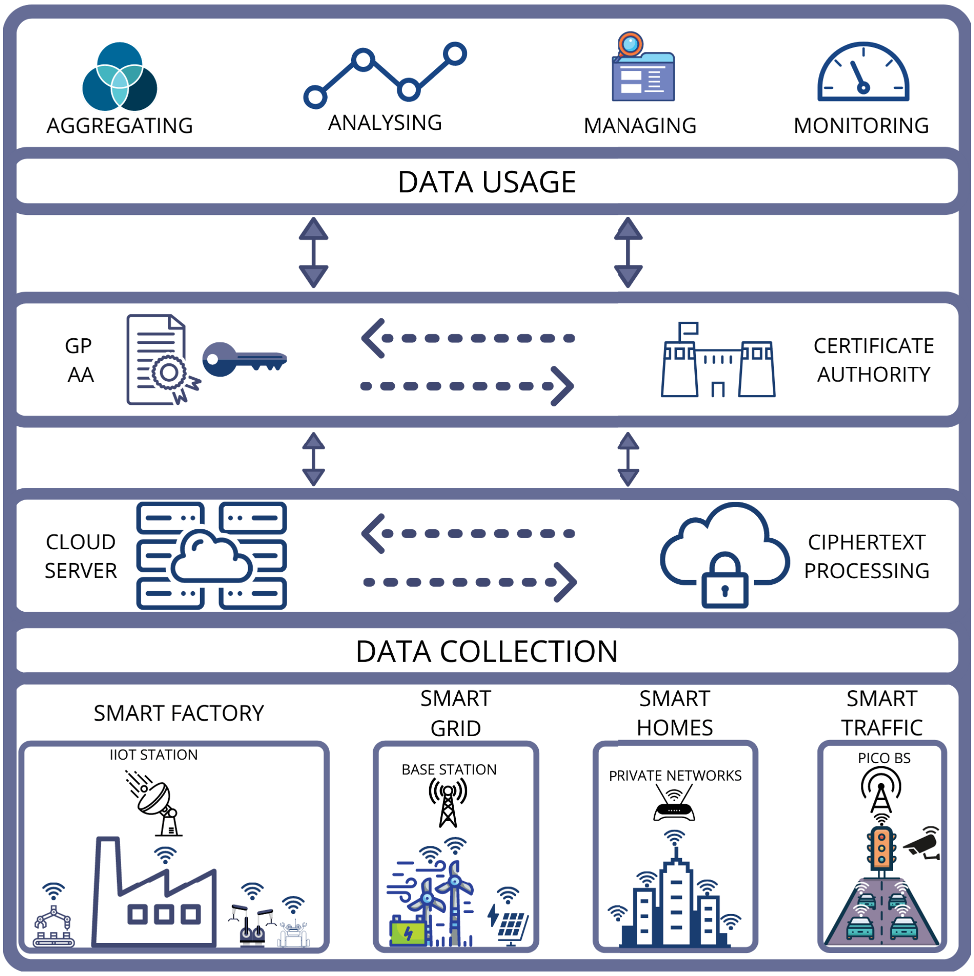
Source: Self authorship (2021).

The begin of D2D is related to telemetry and sensing still in a simplex transmission mode. Along with the usage and applications increase, came the technology evolution translating into full duplex high speed variants and ultra-low power focused devices (with M2M). The major differences between D2D to M2M are that the first is hardware oriented, versus the second being software oriented, meaning that D2D can happen on more basic electronic level, while M2M relies on a software level to operate, and as such is technology-independent(HAUS et al., 2017). It can be linked as base to IoT (ESFAHANI et al., 2019), and ubiquitous computing(GHAVIMI; CHEN, 2015).

3.1.5 IIOT

The IoT in a simplistic analysis is a virtual segment of network where the devices can stabilish connection between themselves and devices from other layers. The IIot, or Industrial IoT is the replication of the IoT capabilities into the IACS context(SIOW; TIROPANIS; HALL, 2018). The methods themselves create a whole new range of possibilities, those being from the information flow, up the amount of data accessible. The industrial version differs mainly in a sense of security and reliability concerns from the consumer version. The Fig. 11 represents an IIoT framework model using the proposed encryption protocol (ZHANG et al., 2020), including additional security practices into the traditional IoT. Between any exchange of data is added one or more caution measures, such as the use of internal certificates and cyphering approaches, aiming to increase the overall safety and reliability levels.

Figure 11 – An IIoT architecture example towards smart-smart city capabilities

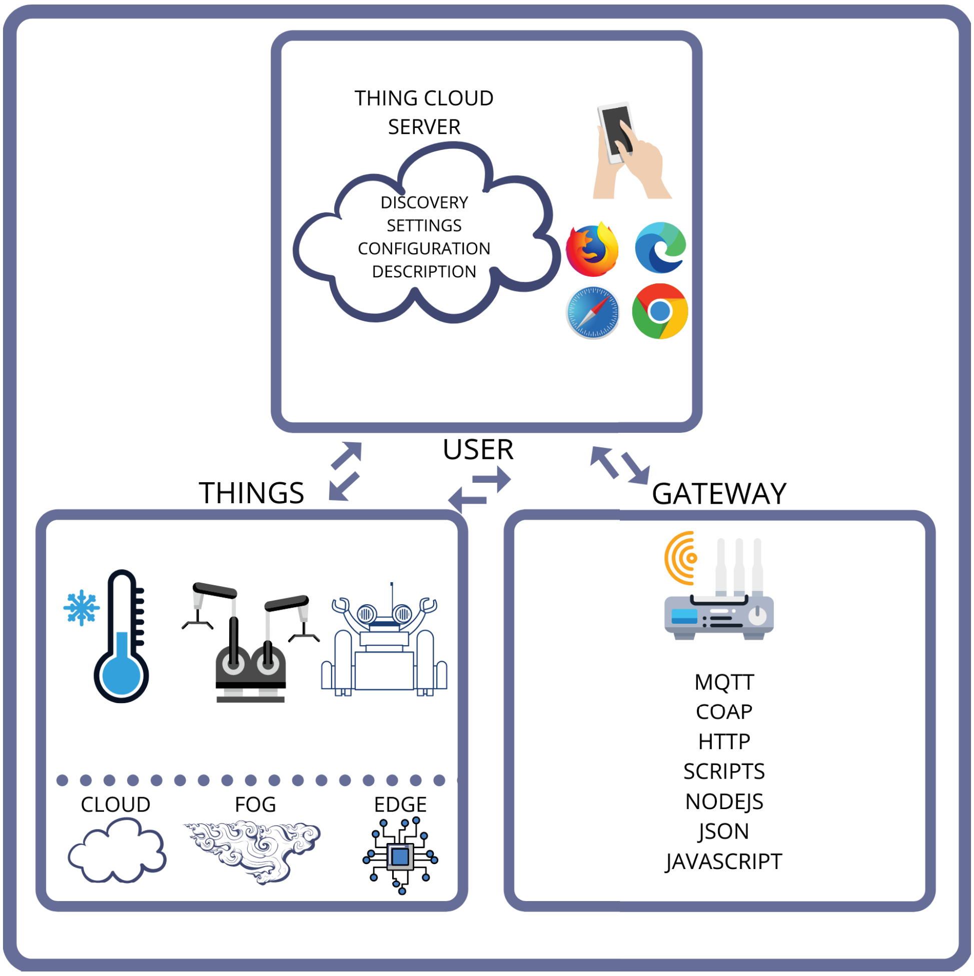


Source: Self authorship (2021).

3.1.6 WoT

From the challenges brought by the use of IoT in larger scales, some points to be improved came up. Especially related to standardization, whether hardware and software related. Based on that, a multidisciplinary consortium contributed in the same manner that led us to use the internet WWW, by a standard, the W3C. The World Wide Web Consortium(W3C. . . , 2020) has been working with a large community in order to establish standards along with some of the major industrial stakeholders from the industry and academia as well. Given the size and complexity of the demand, the W3C created the Web of Things concept. It consists on the consortium's effort translated into groups of work and interest whom aim to design a universal and complete standard protocol to improve and empower the IoT as whole, regardless of its manufacturer, geographic location or application(MURAWAT et al., 2020). The Fig. 12 demonstrates the WoT architecture allowing multiple I4.0 enabling technologies to interact.

Figure 12 – A WoT usage example and data flow

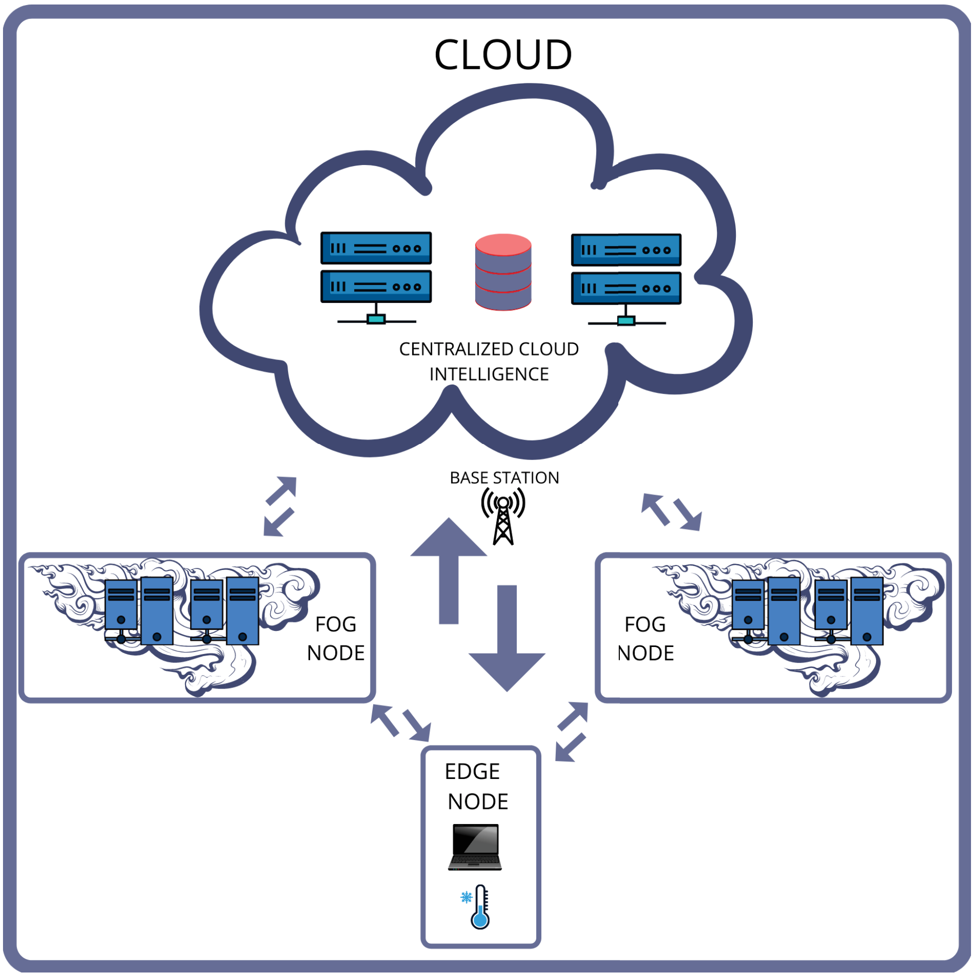


Source: (MURAWAT et al., 2020).

3.1.7 Cloud Computing

Cloud computing emerged as a paradigm that was originally for picture sharing, and as the utilization gained more uses, it was explored into other fields(QU et al., 2020). The cloud computing contributes to the industry digitization when it allows to centralize data centers, and distribute resources in a scalable and flexible fashion. In the Fig. 13, the analysis of the cloud computing and its explorations, such as centralized intelligence model put into the industrial structure context.

Figure 13 – An example of Cloud schematics

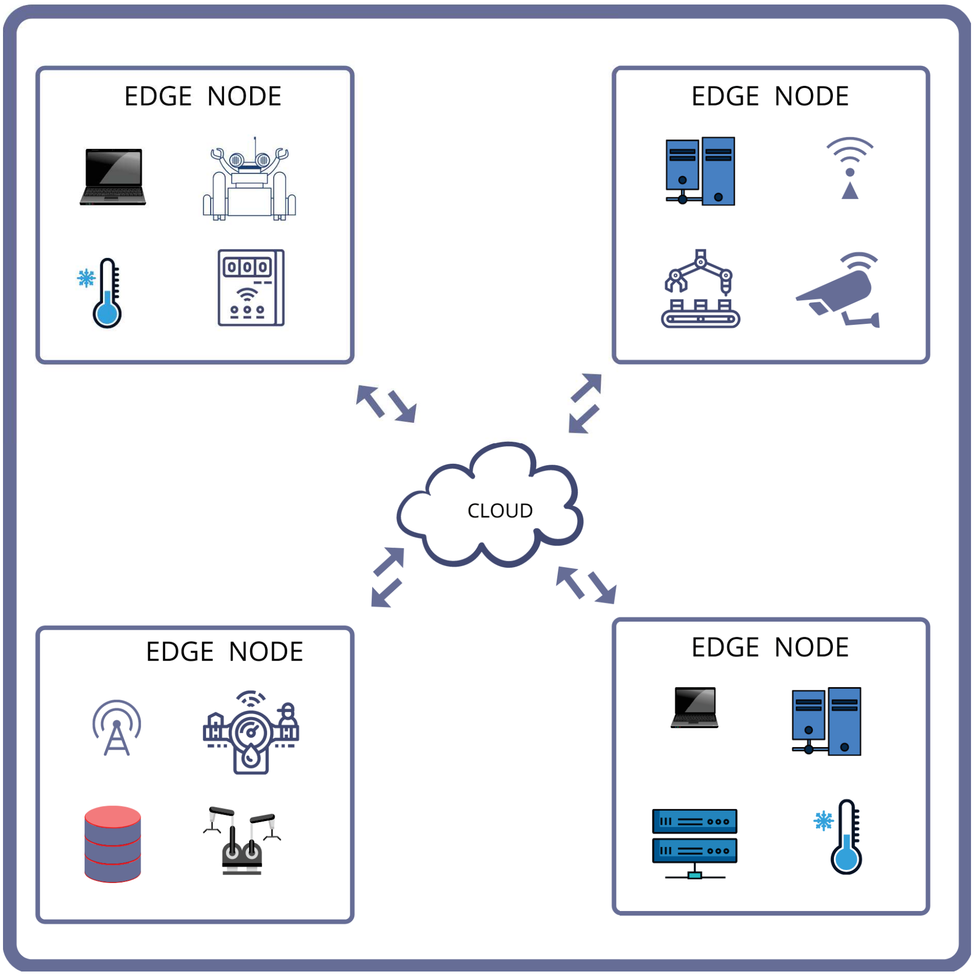


Source: Self authorship (2021).

3.1.8 Edge Computing

With the advancement and exploration of multiple computing paradigms, the edge computing concept came up to define the most popular paradigm. Consisting on the simplest and direct kind: when the data entry and processing happen both on the same level and layer. With a distributed resources layout, edge computing provides low-latency network response and high-reliability which are key factors in several applications(ASIM et al., 2020). The Fig. 14 illustrates that the EC cell can also be part of a cloud computing cell that is in a higher hierarchy level. This is how it empowers other technologies and gain importance related to the fourth industrial revolution.

Figure 14 – Edge computing cells



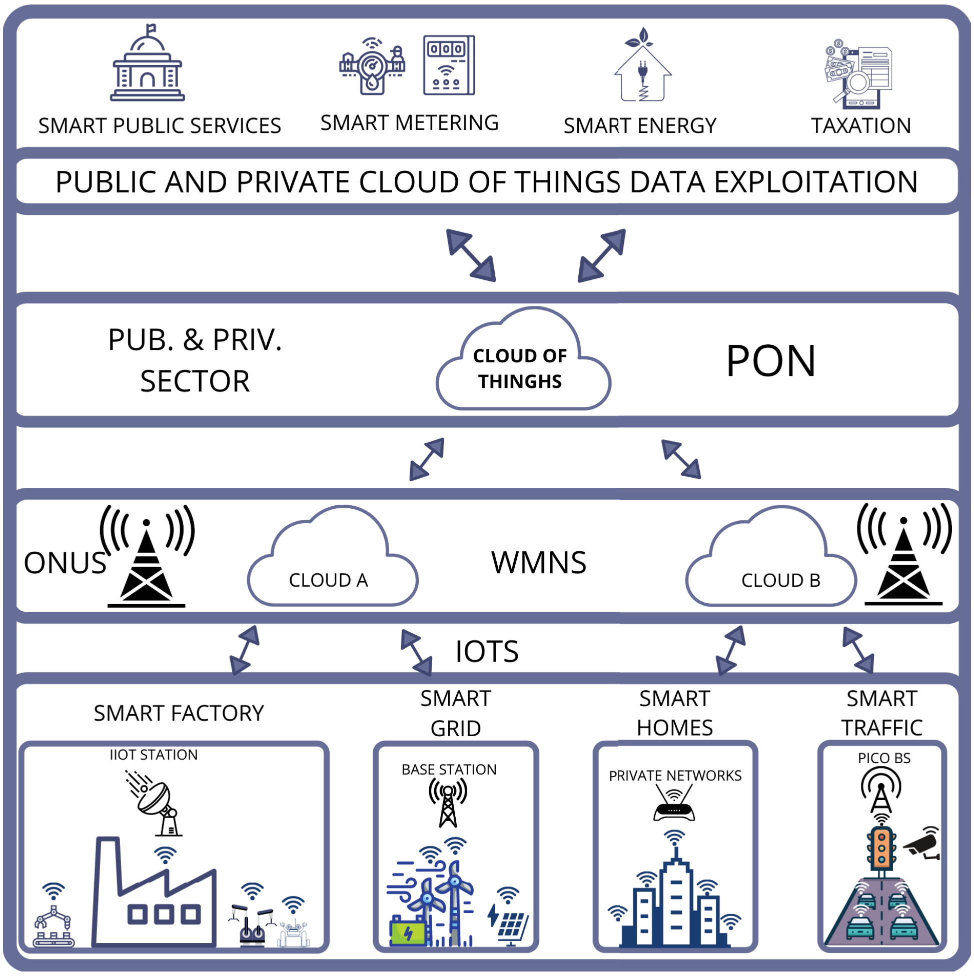
Source: Self authorship (2021).

3.1.9 CoT

Once the devices are connected through IIoT, they might also in addition, be connected to the internet, and as such, from that raises the possibility to connect them to a cloud. Which by itself brings new possibilities as well. The most significant of them being the ability to unite different groups of IIoT, into one larger and decentralized meeting point. For instance, the cloud eliminates the geographic barriers from two plants from belonging to the same manufacturer, by allocating the devices in their private cloud.

Turning with that all of them, independently on how many different locations they might be physically located, available in one unified platform. That's what defines Cloud of Things, making it as a manner to integrate multiple internet of things, whether they are public, private, independently if they are locally or globally accessed or located. Despite the fact that there are still a vast number of challenges to be addressed, such as heterogeneity (NING et al., 2019), ultimately it will potentiate the unfolding and outspreading of a number of combined and derived technologies, such as smart-cities and smart-traffic. The Fig. 15 illustrates the mixed nature architecture of a cloud of things. The combination and transverse composition of MANs, LANs, EC nodes, IoT nodes, smart sensors, WiFi, among other technologies liable to be employed in a smart-city, smart-community or smart-factory prototype.

Figure 15 – A contextualization of cloud of things architecture in a vast community

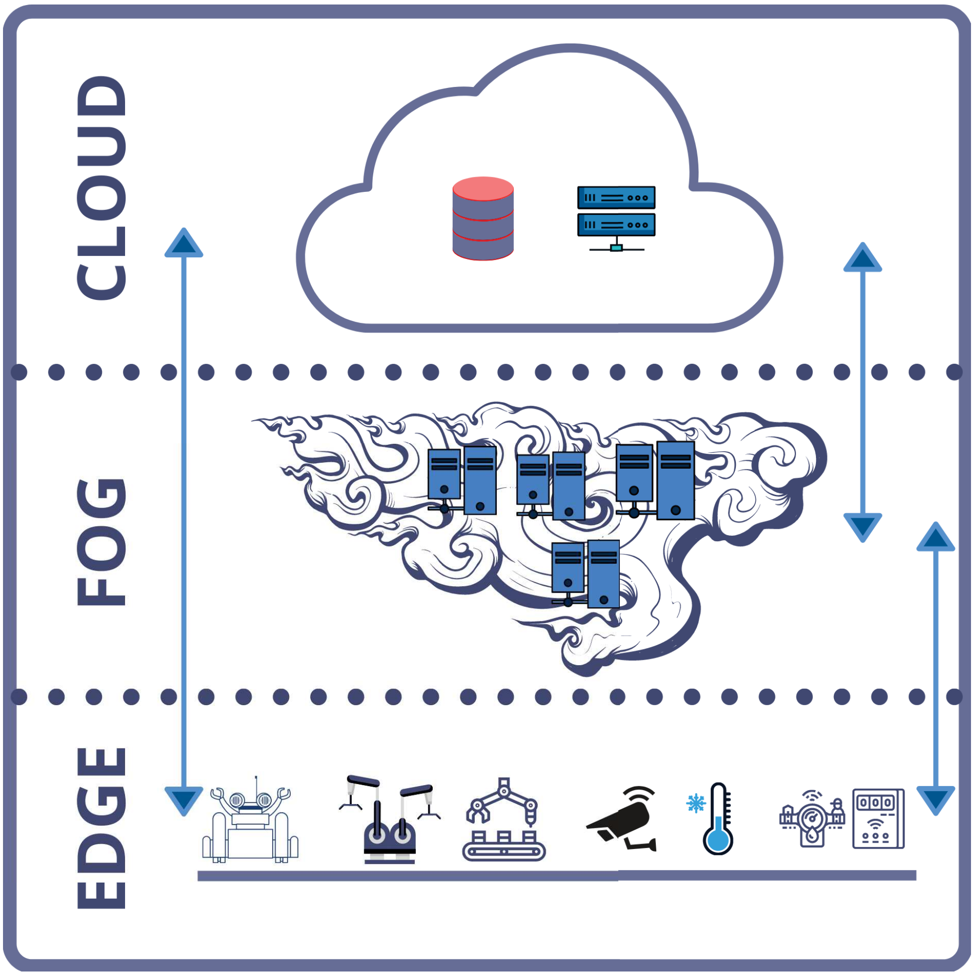


Source: Self authorship (2021).

3.1.10 Fog Computing

The fog computing is a computing paradigm that can be considered as a layer hierarchically between the edge computing layer and the cloud computing layer(DAHIYA; DALAL, 2018). And as such, bringing the cloud of things to operate in an optimal manner both locally and remotely by operating focused on the transitioning of data and processing. This is where comes from the range of applications in the smart industry scenario, where often there is need for low latency data access along with great processing power. The Fig. 16 illustrates the fog layer.

Figure 16 – Fog computing layer illustrated

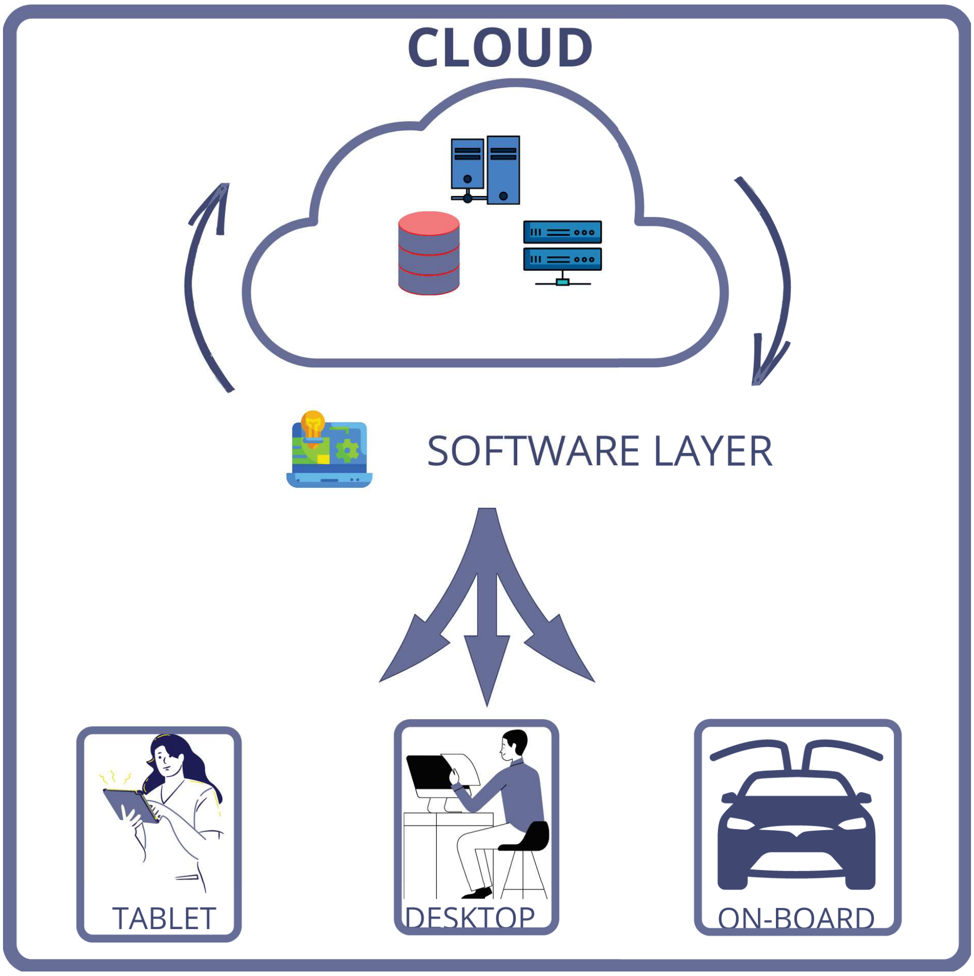


Source: Self authorship (2021).

3.1.11 Ubiquitous Computing

With the flexibility gained from the mixing the three computing paradigms, several solutions become viable. One of them is the ability to transit between devices while operating on the same network or even process. That is the concept of ubiquitous computing, also called pervasive computing(MUKHAMETOV, 2020). From ubiquitous computing comes the possibility to explore Industrial Cyber-Physical Systems and digital twin systems. The flexibility and capability to have interactions in a multi-platform and complimentary manner gives the I4.0 methodologies a high amount of freedom to work with. The Fig. 17 provided by the figure demonstrates the wide range of devices and systems from which the ubiquitous computing take advantage from.

Figure 17 – Ubiquitous computing contextualized

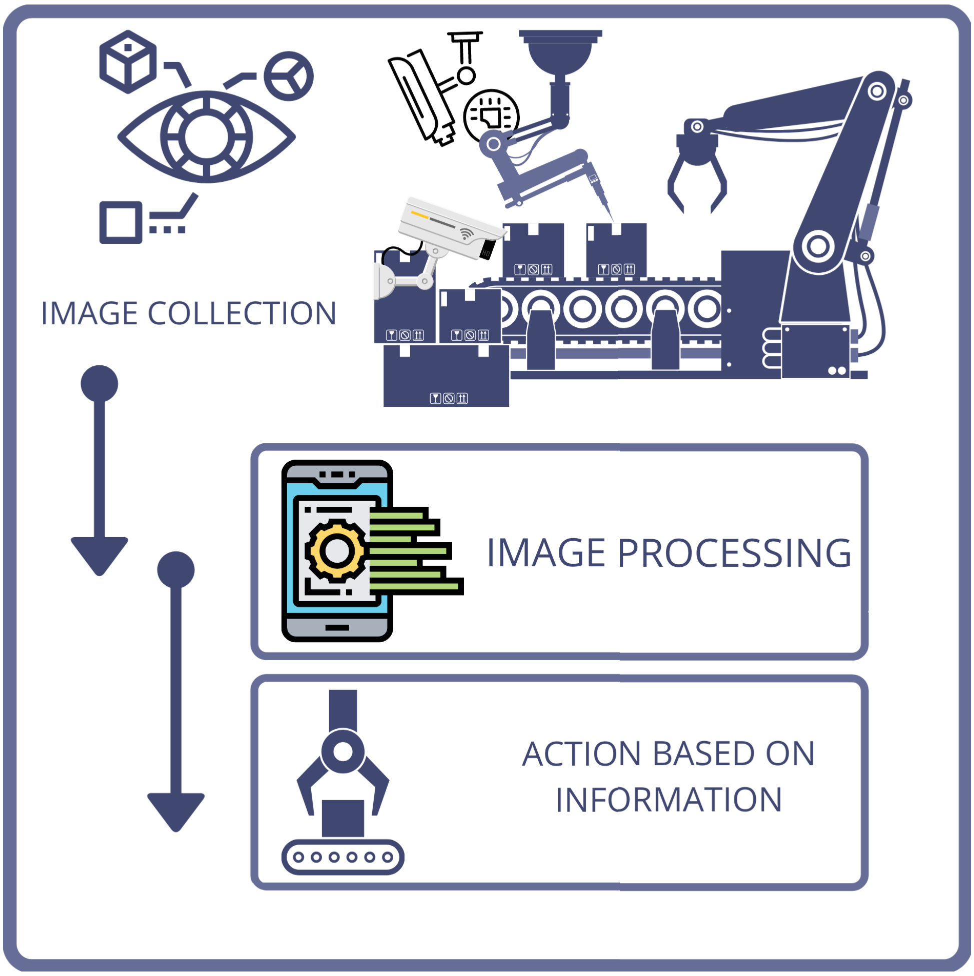


Source: Self authorship (2021).

3.1.12 Computer Vision

Despite the fact that Computer Vision is not a recent concept, its advancements have made possible several combinations of technology related to the fourth industrial revolution, such as the ICPS, the QRCode, AR, in varied uses related to automation, security and augmentation. With the ability to process images or videos, the computer vision system can be trained to specific tasks by the utilization of models. Adding artificial intelligence techniques to the system gives them a great potential, frequently explored by I4.0(VILLALBA-DIEZ et al., 2019). The Fig. 18 illustrates the application of computer vision and deep learning in a cyber-physical system.

Figure 18 – Computer vision applied along with AI

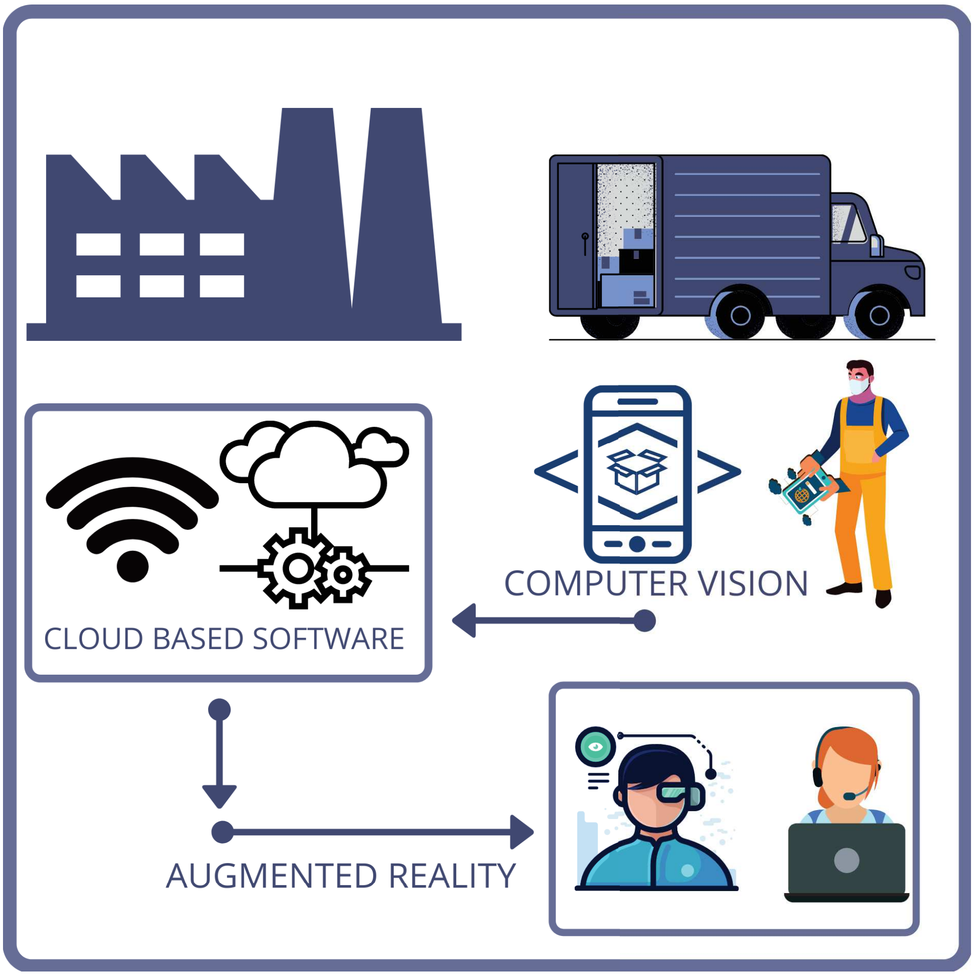


Source: Self authorship (2021).

3.1.13 Augmented Reality

As mentioned in the previous section the augmented reality explores a combination of technologies including computer vision, ICPS and artificial intelligence(LIU et al., 2017). Its application on the industry is often related to training, maintenance, and prototyping, and also when combined to other empowering technologies it can result in more complex projects, like a complete IACS, or near reality physic simulators. With the Fig. 19, is possible to have a representation of how is contextualized an augmented reality application through a CPS, by the use of computer vision, integrated to a cyber-twin system.

Figure 19 – The representation of augmented reality

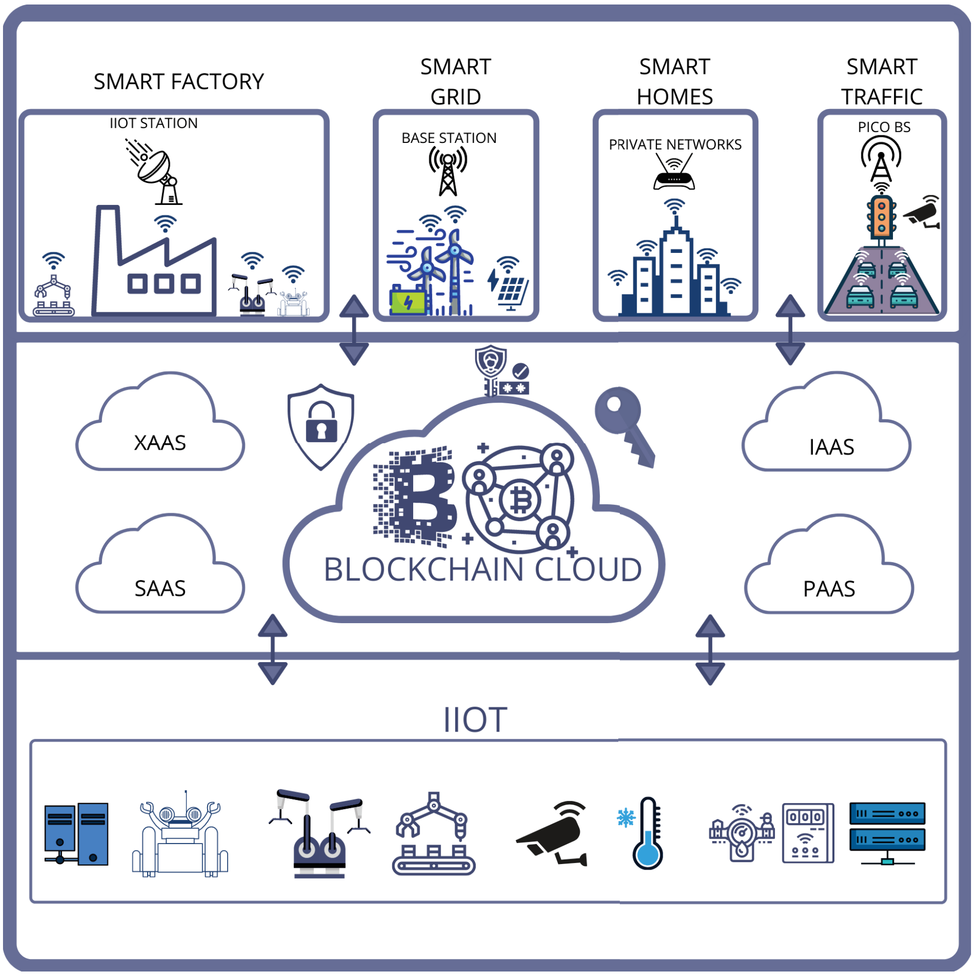


Source: Self authorship (2021).

3.1.14 Blockchain

Blockchain consists in a distributed database which has the main objective to ledge(NGUYEN, D. C. et al., 2020) by the access of its records. That being so, consolidates it as a highly versatile tool that can be applied in quite a handful of solutions. The first appearance of this technology was parallel to the cryptocurrency development. On few words, it was first described as one whole financial statement for all transactions that ever happened(NGUYEN, D. C. et al., 2020). With the propriety of holding that security information in a replicated distributed way, it could be as well used in several other applications, especially related to security authentication and its variants. In the ICT context is somewhat as if it had an inherited redundancy and clustering capability by design. That applied to the industry 4.0, means distributed and replicated layers of security, a major concern when devices may be exposed to the public internet. The Fig. 20 displays how is inserted a Blockchain as a service infrastructure, and its interaction with different public and private clouds, in addition to CoTs, according to the Nguyen proposition.

Figure 20 – A BlockChain use case between cloud, IoT and XaaS

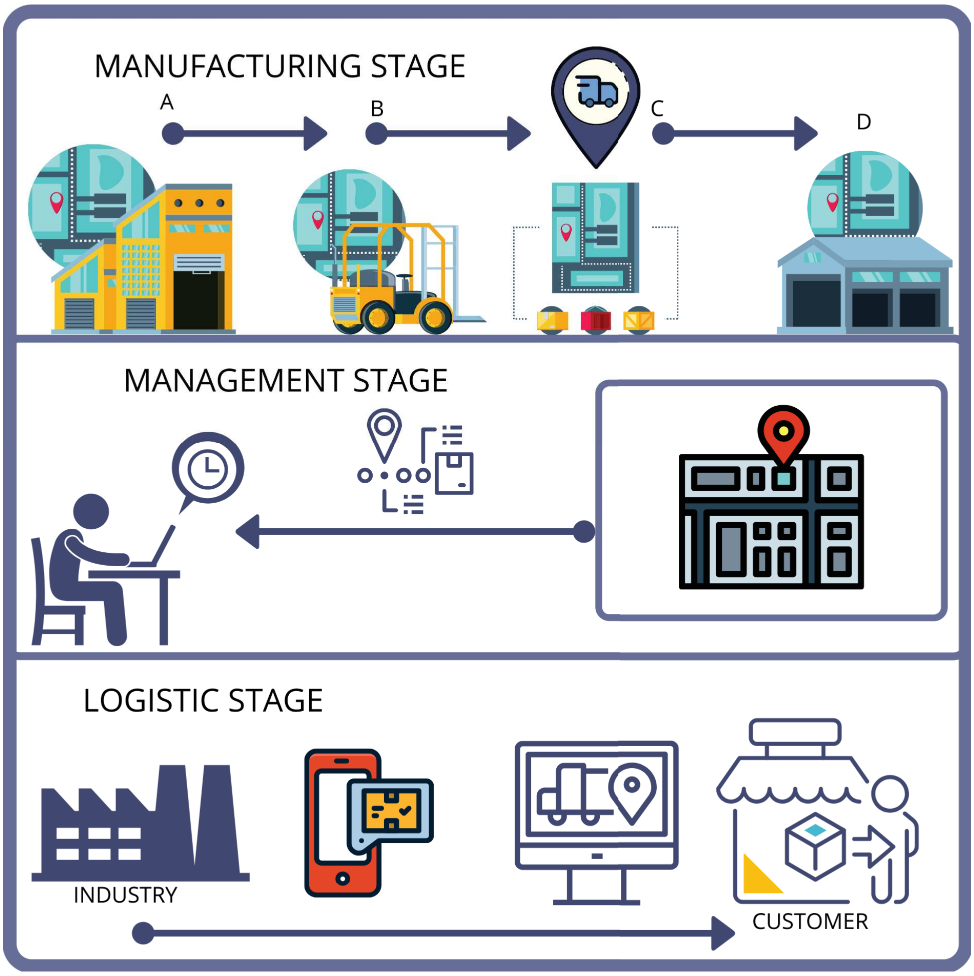


Source: Self authorship (2021).

3.1.15 RTLS

The Real Time Location System is not a new concept, but its application in large scale on industrial environments is. Along with all the needed interconnection that happens in the industry 4.0 scenario, one asset or even a product's real time location might be an advantageous information in a complex manufacturing environment. To reach that, by combining different technologies, the RTLS data can be explored in different ways, with high transverse value according to the specific need in an industrial site(HUANG et al., 2017). RFID, Lora and Bluetooth are RTLS enabling technologies, each one of them with its own particularities that will be approached in the next sections. In the Fig. 21 is possible to see the contextualization of the RTLS data flow in a complex factory.

Figure 21 – An example of industrial RTLS usage

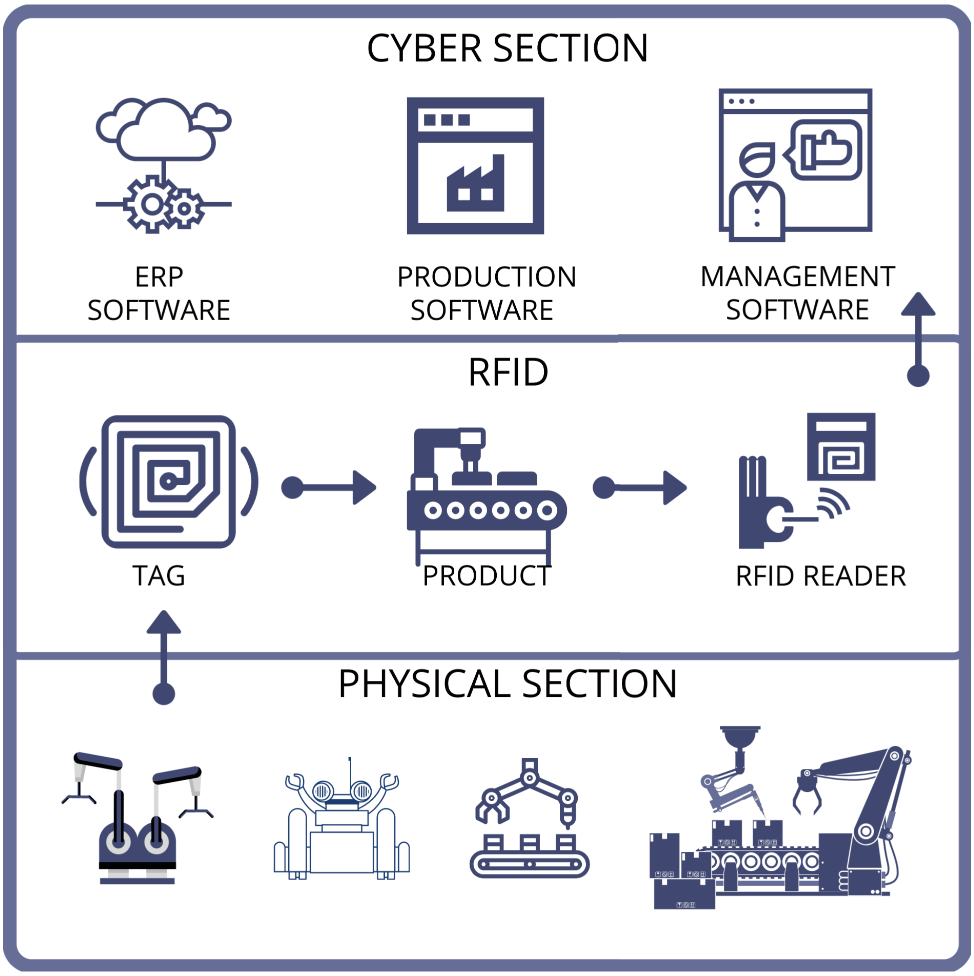


Source: Self authorship (2021).

3.1.16 RFID

Radio Frequency Identification is the technology system that explores the combination of tags and readers that communicate with no contact, by the use of radio frequency transmission. There are two kinds of tags, the difference being that the passive receives its power through the radio frequency waves, by the own radio antenna and the active uses battery. The RFID tags have a built in storage where a small amount of data is stored to be used as a key, which will then be used by another system as reference. That is why the RFID gains great importance the industry 4.0. It can be used as a transitional asset between the cyber system and the physical system(HUEBNER et al., 2013). Besides that, with a combination of readers, it can be used for RTLS or geo fencing(JIANG et al., 2018), and as low cost LS using passive tags. Another positive point is the cost. The simpler tags cost less than 0.50 USD. The Fig. 22 is a representation of a RFID system schematic data flow contextualized into a CPS.

Figure 22 – A RFID represented as part of a CPS



Source: Self authorship (2021).

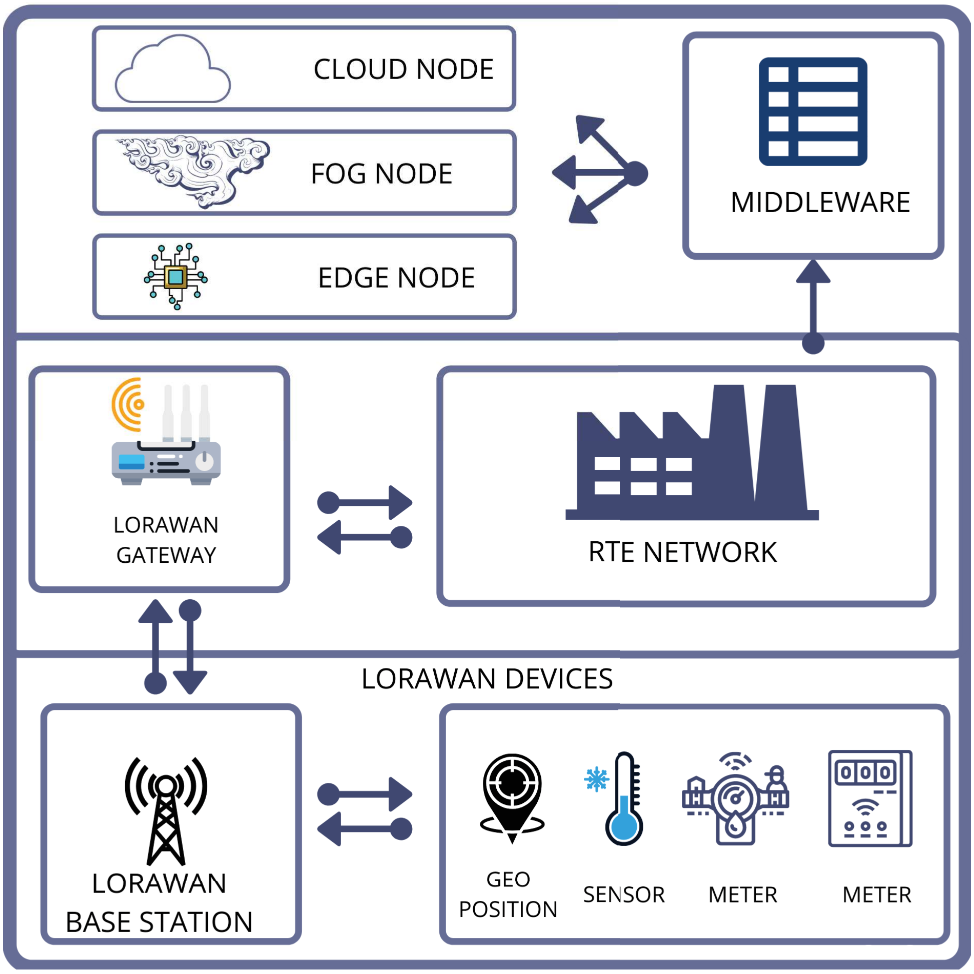
3.2 ENABLING PROTOCOLS

In an analogous way to the technologies, hereby will be presented the enabling protocols. The scope of this segment is to put the specific protocols in the context of a 4.0 industrial environment. When possible, the respective architectures were demonstrated through schematic figure of the whole concept – in a broad sense – or in a specific schematic applied manner. With that, focusing on their boundaries crossing point, given the nature of industrial orientation of this research:

3.2.1 Lorawan

Lorawan is a LPWA (Low Power Wide Area) wireless type of protocol. In practical terms, low power meaning its battery can last for years, and wide area meaning it can cover kilometers of distance and with no wire connection. That is what brings a vast usage to the i4.0 applications, where it has been widely used for sensing and tracking(VITTURI et al., 2020). Not only the technical aspects, but also the public signal coverage is attractive to the industrial standards, despite to possibility to have a private network, all considered makes it a key IIoT enabling protocol. In the Fig. 23, the schematics of a Lorawan device and the manner it integrates with the cloud and RTE network, as well to other assets.

Figure 23 – An application of LORAWan

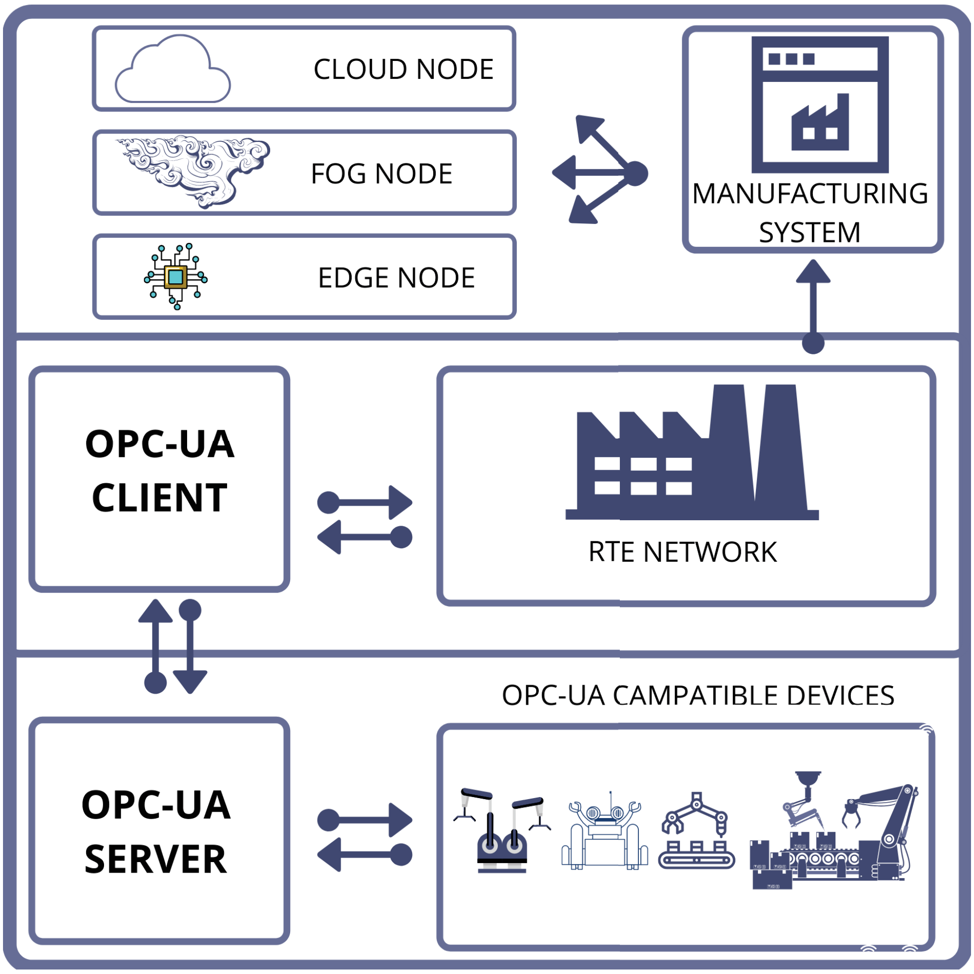


Source: Self authorship (2021).

3.2.2 OPC-UA

OPC-UA stands for Open Platform Communication - Unified Archiecture. The main role it being playing, in the sense of by I4.0 contribution is IIoT and M2M communication through a standardized fashion, includes high grade security and uses a robust client/server mode of communication, compatible to multiple platforms(MELO; GODOY, 2019). The use of the protocol has a wide adoption among manufacturers which made it become the official industrial standard communication protocol for industrial machine to machine interoperability. The Fig. 24 represents the protocol usage contextualizing OPC-UA client and server model.

Figure 24 – The schematics of an OPC-UA controller

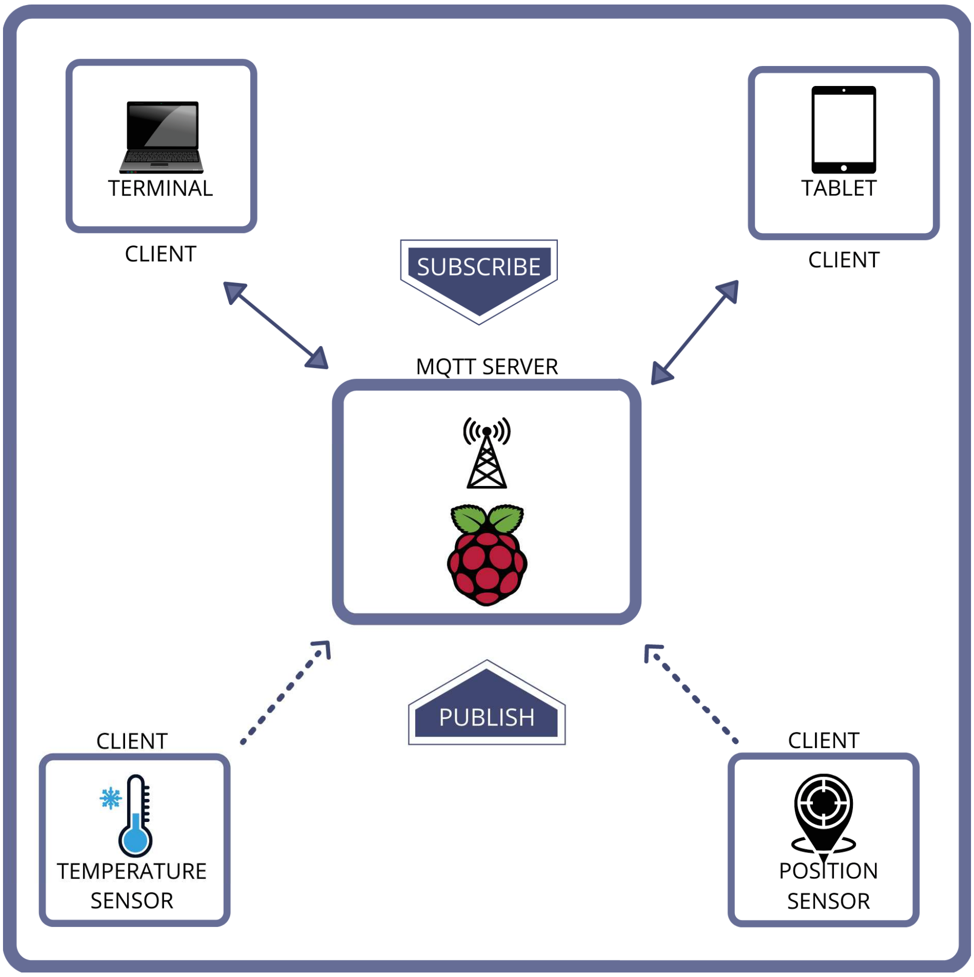


Source: Self authorship (2021).

3.2.3 MQTT

Message Queue Telemetry Transport or MQTT, is analogous to the OPC-UA, but specifically designed for telemetry and other low resources devices and uses with low bandwidth and high latency environments(PATEL; DOSHI, 2020). With a client/server mode of operation, and lightweight operation, has various uses in the I4.0 field, focusing the low cost devices communication. The schematics and roles over MQTT data flow are illustrated using an raspberry device in the Fig. 25.

Figure 25 – A MQTT message exchange schematics

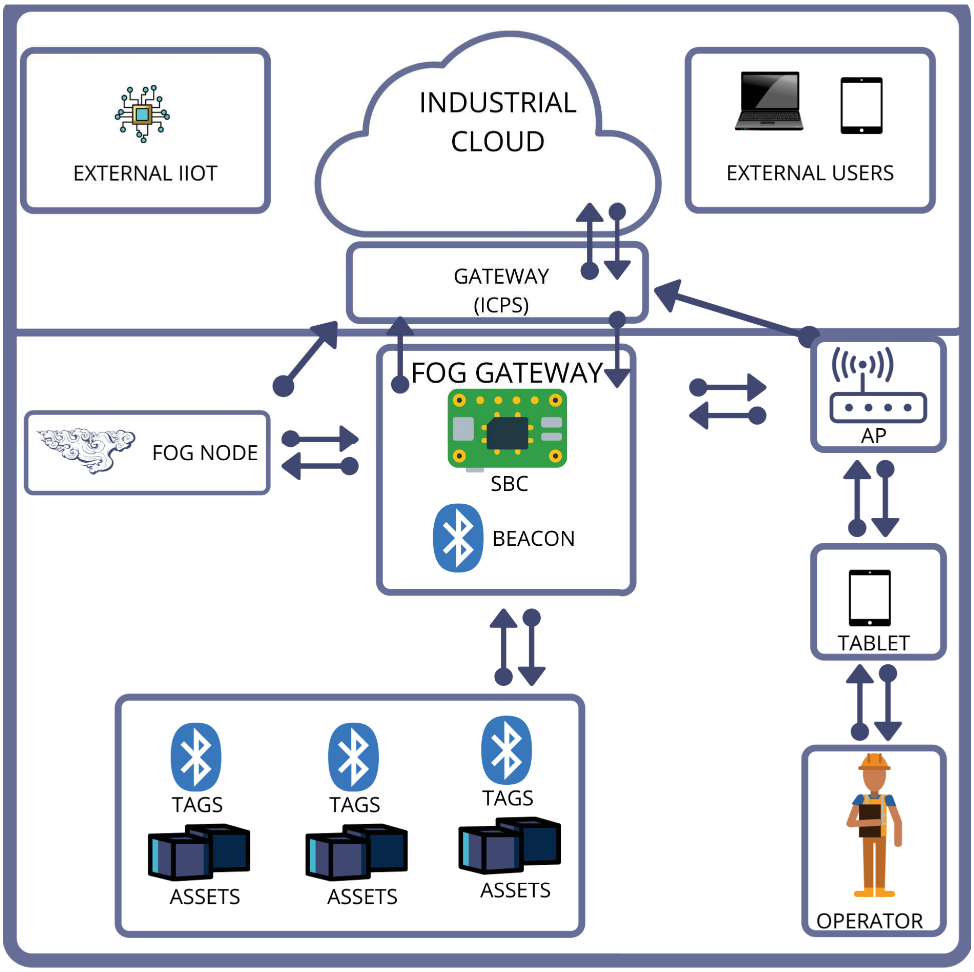


Source: Self authorship (2021).

3.2.4 Bluetooth

Despite being well known for its consumer uses, since the implementation of the LE – Low Energy – function, and mesh network on version 4.0 and 4.1 respectively, Bluetooth gained a great potential for industrial exploration. With low power capabilities it is possible to reduce power consumption in up to 80% and with mesh function it is possible to use it for RTLS and asset tracing(FRAGA-LAMAS et al., 2020). Both characteristics makes it very attractive for IIoT applications. In that subject it will be presented the structure of an experiment that took plane in Spain, consisting on creating a whole ICPS based on Bluetooth Beacons for tracking parts in a fog node, further connected to a cloud. In the Fig. 26, the Navarria's (Spain), city port Bluetooth application scheme is shown.

Figure 26 – An industrial use case of BLE in Spain

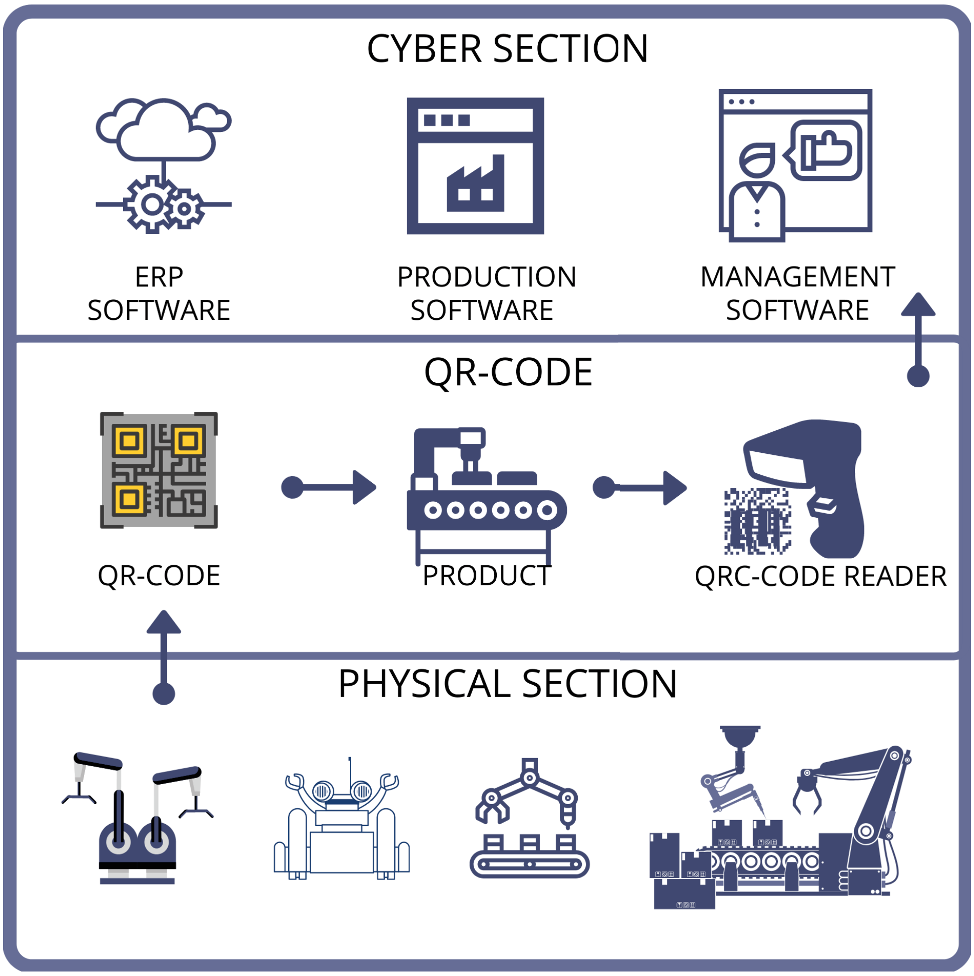


Source: Self authorship (2021).

3.2.5 Qrcode

QRCode is a bi-dimensional barcode which represents a code that can be referenced to a system, a geographic position, a weblink and even personalized. The reading can be done through computer vision or optical reader. Its relation to the fourth industrial revolution, is considered as an enabling technology. The QRCode may act as a trigger which referencing to an AR system(TENG; WU, 2012), and also being part of an ICPS. The proposition of an QR-Code referenced ICPS system is well represented in the Fig. 27, where the code read will transition to the cyber segment.

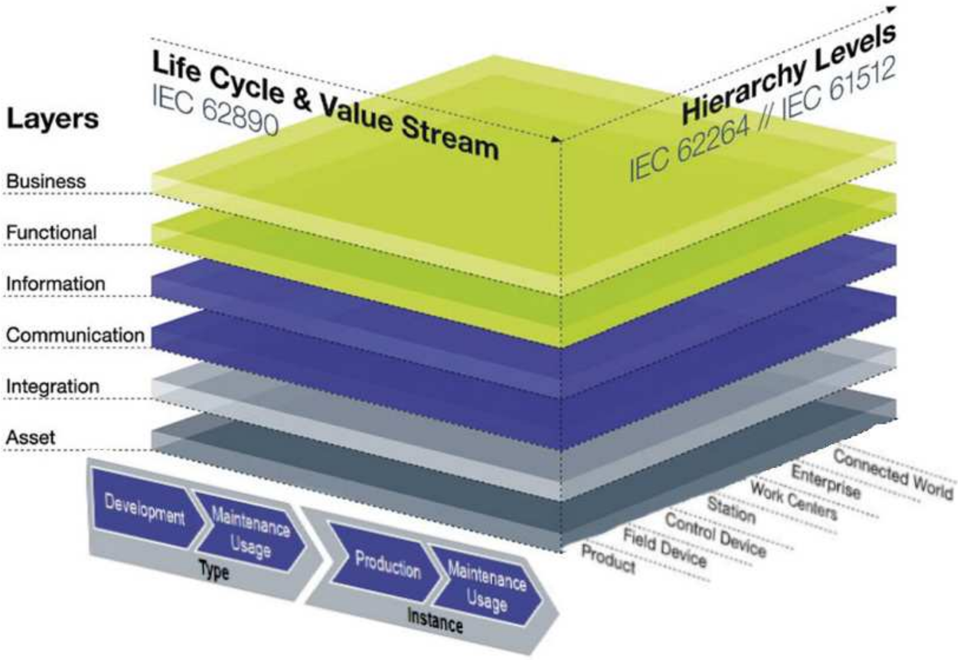
Figure 27 – QR-Code usage as a trigger into ICPS



Source: Self authorship (2021).

3.3 THE REFERENCE ARCHITECTURE MODEL FOR INDUSTRY 4.0

Figure 28 – The RAMI Dimensions



Source: (MELO; GODOY, 2019).

The Reference Architecture Model for Industry 4.0 – RAMI4.0 is a Service Oriented architecture proposal, composed by a set of standards, practices and references (RAMI. . . , 2021) that along with a major stakeholders association, the German Electrical and Electronic Manufacturers Association (ZVEI)(THE. . . , 2021) have been outlining through the years. In addition, in 2020 the initiative was aligned with the IIC (Industrial Internet Consortium)(THE. . . , 2021), which represents all the American Industrial Internet standards, what empowered even more the RAMI 4.0 in terms of reach and adoption.

The model is represented in a three-dimensional graph, where the layers are co-related, as illustrated by the Fig. 28. Each dimension and sub-dimension will be characterized in the next subsections.

3.3.1 Hierarchy Axis

Based on the International Electrotechnical Commission (TECHNICAL. . . , 2021) standard 62264 and International Electrotechnical Commission standard 61512, it is segmented in hierarchical levels, which categorize the level where the asset acts according to its condition into the system, although the exchange of information between different levels does not occur in a traditional cascade manner. It might occur in a transverse way or even bypassing the hierarchical order represented by the Table 5.

Table 5 – The hierarchy axis

Order	Stage
1st	Product
2nd	Field Device
3rd	Control Device
4th	Station
5th	Work Centers
6th	Enterprise
7th	Connected World

Source: Self authorship (2021).

3.3.1.1 Product Level

On this level the products themselves are considered, which is one of the first things to draw attention as a noticeable difference from the third industrial generation, by considering the final product as part of the system. The reason for that comes from the need for the manufactured good to interact with the manufacturing process as a whole, what might happen in an early stage, as prototyping, or even in the final stages, such as the recycling, by the good's end of life. From its inception to the point it ceases to exist, the item must be traceable. An example of usage would be a software update made OTA.

3.3.1.2 Field Device Level

The devices used as infrastructure to support and ancillary any segment of the manufacturing process are operating on the field device level. Most of the devices interacting on this level consisting on sensors, meters, scanner, have their data collected and can be used for decision making or action triggering. A thermometer is an example, frequently used in order to monitor the production temperature, and subsequently exchange data with the control level, by keeping it in a specified range. Field level interactions are often between control, station and work center levels.

3.3.1.3 Control Device Level

A layer where the asset's properties are dedicated to supervise and monitor, such as human machine interfaces, or SCADA related devices. This layer is usually related to the enterprise level, sending data, and at the same time to field level operation devices, gathering data.

3.3.1.4 Station Level

This level represents interactions related to the core asset's purpose on an industry: when they are utilized for the production itself. Might be related to modules that compose a complex system (work center level) or a single piece system as well. This layer may receive inputs from multiple layers while giving output to multiple layers simultaneously.

3.3.1.5 Work Center Level

The work center level represents actions applicable to a group of assets with a common purpose, or jointly dedicated to production. Like the station level, has multiple inputs and outputs, and usually multiple stations on its composition.

3.3.1.6 Enterprise Level

It holds the interactions done by the assets when they are not oriented to the direct production itself, but to the processes around it, as orders and other administrative guided activities. Frequently exchanges data with all of the other levels, usually gathering more data than sending back. It is related to the core business management with a great impact on the overall result.

3.3.1.7 Connected World Level

It is the level used by the factory interactions with the external world. By external world, it could be a supplier, a client or even a subsidiary. For instance, the supply chain can be automatically reached to deliver raw material or to produce elements requested by the production line accordingly to the need. Its connection is viable to all of the other layers, upon necessity.

3.3.2 Life Cycle and Value Stream Axis

The life cycle axis is where the processes, or services, relate to the assets current life cycle status. From the concept development to the maintenance of an old model, it is possible to relate, trace and reference its trail within the manufacturing stages. Based on the International Electrotechnical Commission standard 62890, it is segmented according to the Table 6.

Table 6 – The Life Cycle Axis

Order	Stage
1st	Type: Development
2nd	Type: Maintenance / Usage
3rd	Instance: Production
4th	Instance: Maintenance / Usage

Source: Self authorship (2021).

The status are classified between type and instance, in a total of four stages:

3.3.2.1 Type: Development

During the conceptualization of the product, the life cycle may assume the construction, simulation or prototype status when it comes to development type. Activities and assets related to research and development will be classified in this category.

3.3.2.2 Type: Maintenance and Usage

As far as the maintenance or usage type, activities such as software updates, maintenance cycles or even instruction manuals are concentrated within this status. Actions in this class must be related to the product itself, not the factory maintenance.

3.3.2.3 Instance: Production

The production instance refers to the action of manufacturing, to fabricate the product itself. It is the instance which is supposed to be supported by all the others actions and processes, once it is of primary importance and the most critic status to the factory.

3.3.2.4 Instance Maintenance and Usage

The maintenance usage instance occurs when the activity is related to the manufacturing maintenance itself. Status like recycling and servicing are covered by this status.

3.3.3 Layer Axis

All the properties and attributes that classify the asset itself are positioned and segmented in six layers. The layer axis represents the asset. Asset being the object of interaction to the smart manufacturing system. From the identification, to its capabilities, specification, integration before the whole system, and even how it relates to processes and the business itself, all the that dictates how the asset can transition and interact within the other assets is defined on its six architectural layers. They are divided according to the Table 7.

Table 7 – The Layer Axis

Order	Stage
1st	Asset
2nd	Integration
3rd	Communication
4th	Information
5th	Functional
6th	Business

Source: Self authorship (2021).

3.3.3.1 Asset

The layer related to the physical device itself is the asset layer. It is the only layer that refers exclusively to the physical world. It takes place regarding the unique identification of the asset, which will be carried on into digital world layers. That being considered, the asset layer also takes part on the security aspect of the model.

3.3.3.2 Integration

It is the layer used to transition between the physical world to the cyber world. It uses a combination of technologies as a digitalization tool, acting as a link between the asset layer into the communication layer through the Asset Administration Shells, that are a form of software that aims to standardize the fashion that the devices interact among themselves and before the manufacturing system.

3.3.3.3 Communication

The communication layer consists on the infrastructure layer responsible for the asset data exchange and access. It is the first exclusively digital layer, and aims to enable the exchange of data and interactions with a multitude of devices and manufacturers. Several protocols and techniques are explored by this layer, such as OPC-UA, Modbus, REST and MQTT. From IIot devices, servers and edge computers, the data must flow in an heterogeneous environment. It can be analyzed in an analogous way to the OSI Layers, receiving information from the first physical layer (integration) and delivering data until the last (application) layer, through OPC-UA, for instance.

3.3.3.4 Information

The information layer is composed by the asset data itself contextualized into the I4.0 *lingua franca*. The syntax and vocabulary matching the description of the virtual standard. It is related to the asset identification and the asset's respective available service. Whether it routes ultimately to the cloud, edge, or fog, it is composed by the data which will enable transitions between assets in different layers and as such enabling the flow and interaction between the system as a whole.

3.3.3.5 Functional

The functional layer is where the assets capability to execute actions is treated and defined. Its functions are established in a manner it can be easily compared to others and analyzed according to its particularities, once they follow the standard professed by the model.

3.3.3.6 Business

Is the layer where the process the asset is related to is defined according to the organization specifications and business needs. It is the most higher level among the layers and its usage has a business and processes oriented nature. In this specific layer, it is possible to link to which part of the business the asset is aligned with.

3.4 RESULTING TECHNOLOGIES

Analogous to the several enabling technologies, and with the combination and convergence of the diverse techniques previously explored on Section 3.1 and Section 3.2, it is reached a point where is possible to explore a new cybernetic level of information as an outcome. From now on referred to, as Resulting Technologies. The core being the Digital Twin technology, it will be presented on the following sub-section.

3.4.1 Digital Twin

The Digital Twin can be described as a near real-time software reproduction of a designed set of equipment's state. For that to be possible, it is required that the assets can communicate among themselves and exchange data with internal and external networks. A key factor in the intelligent manufacturing systems(LI, M. et al., 2020), will provide the necessary means to implement other data science tools, such as preemptive data analytic models, and real-time automated decision based on artificial intelligence.

The software layer that is responsible for the virtual representation, enables reactions and predictions in a incomparable manner. The response time is drastically reduced and with that, the negative impact of undesired occurrences can either be completely avoided or exponentially reduced.

The RAMI 4.0 digital twin approach is called Asset Administration Shell, or AAS(ASSET. . . , 2021), and its ultimate goals is to set a standardized, interchangeable and universal way of communication between the assets. The AAS implementation is the ultimate goal when complying to the architecture model.

3.4.1.1 The RAMI 4.0 Asset Administration Shell

The expected outcome of the Reference Model adoption is the exploration of the Digital Twin technologies, which is represented by the AAS in the RAMI 4.0(ASSET. . . , 2021).

Each asset has its respective information referenced on its own asset administration shell. It is a software layer with the intent to operate in a standardized manner between different assets from different manufacturers.

By the interactions of this assets AAS comes the possibility to converge the data and gather information in a very synergistic fashion. With the use of the three axes crossing, the map can be represented in a clear and versatile manner, comprehending the full scope of an industry procedure, allowing the enterprise to ultimately reach the Industry 4.0 resources – or consequences, such as digital twin, real-time automated decision and predictive maintenance.

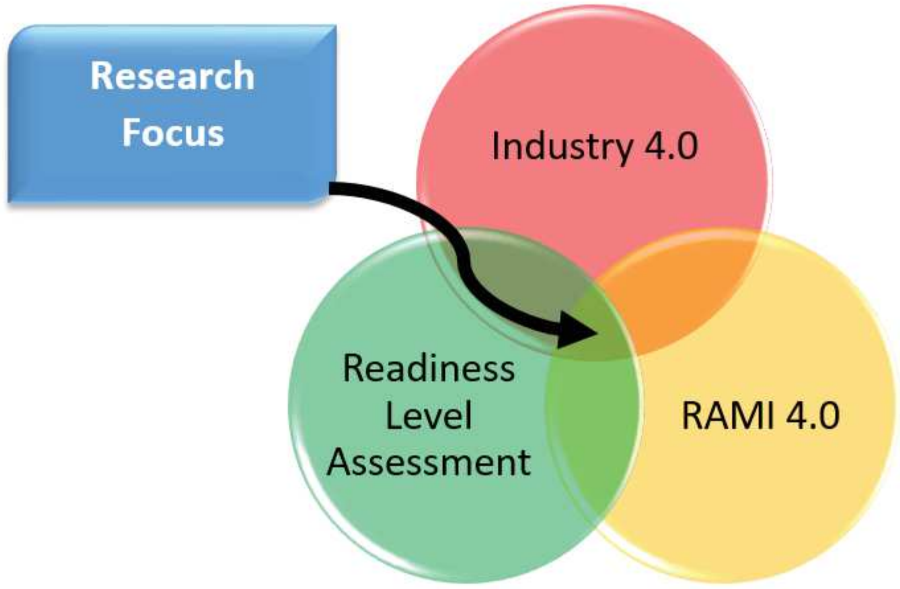
To describe in a broad manner, the resource consists on a software interface representing the real world interaction between the assets where the communication flow is based on file exchanges through an API in a peer-to-peer basis.

4 READINESS ASSESSMENT METHOD BASED ON THE RAMI 4.0

In addition to Germany, the RAMI 4.0 has been elected by a vast number of countries, such as Japan, China, Australia, Holland, France and Italy to be the nation official standard.(DOWNLOADS. . . , 2021). Not only that fact, but also taken in consideration to the broad adoption, the interoperability (ARCHITECTURE. . . , n.d.) provided by the alignment with the Industrial Internet Consortium, makes it a very promising scenario. As a consequence, comes a demand for assessing the current situation in order to implement the model. That gap is to be explored with the assessment proposition.

With the realization of the gap in the literature, alignment to the concentration area, and the scope of this research objective, hereby is delineated the area of interest. Overall, it is related to developing a readiness level assessment to be applied in the industrial field. The focus of the research is the crossing path between the 3 fields of study, what could be stated as: A readiness assessment method for industry 4.0 according to the RAMI 4.0 reference model. The Fig. 29 represents the research focus and area of interest.

Figure 29 – Focus of research



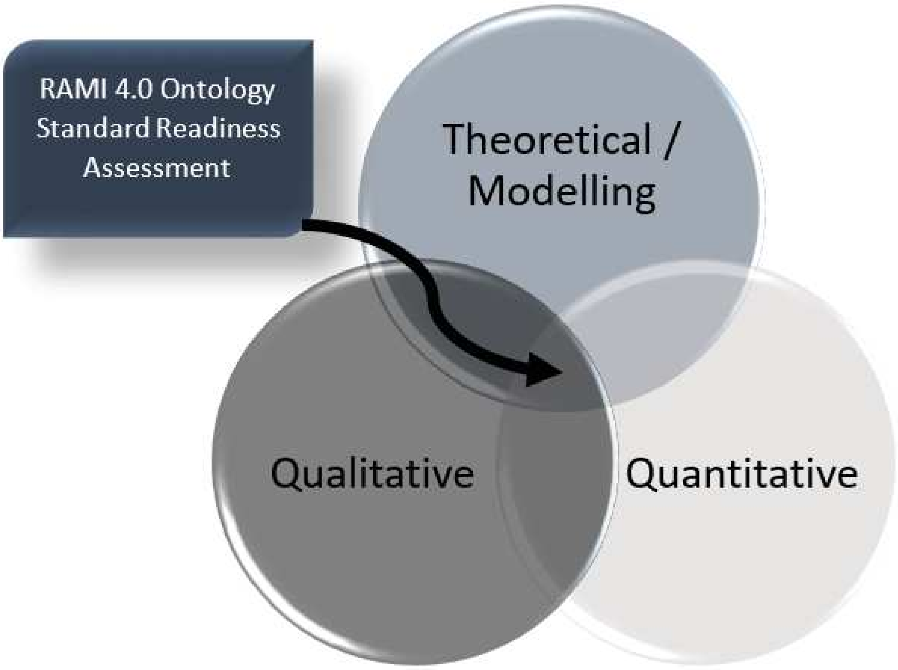
Source: Self authorship (2021).

4.1 ASSESSMENT PROPOSAL

The assessment method will consist on a readiness assessment questionnaire model. The readiness will be measured taken in consideration the assessed organization compliance to the already defined standards according to the RAMI 4.0 architecture model. It is segmented in the very same way as the reference architecture model, a three axis structure which will be described with its respective standards from ISO(ISO. . . , 2021), IEC(TECHNICAL. . . , 2021), and RFC(RFCS. . . , 2021). The compliance to the referenced standards will be considered in order to evaluate the readiness level, through the accounting of one point for each standard application compliance.

As illustrated by the Fig. 30, the main advantage of this model besides its simplicity, is that the nature of the evaluation is qualitative, quantitative while oriented by an architectural model at the same time.

Figure 30 – The combined nature of this assessment approach



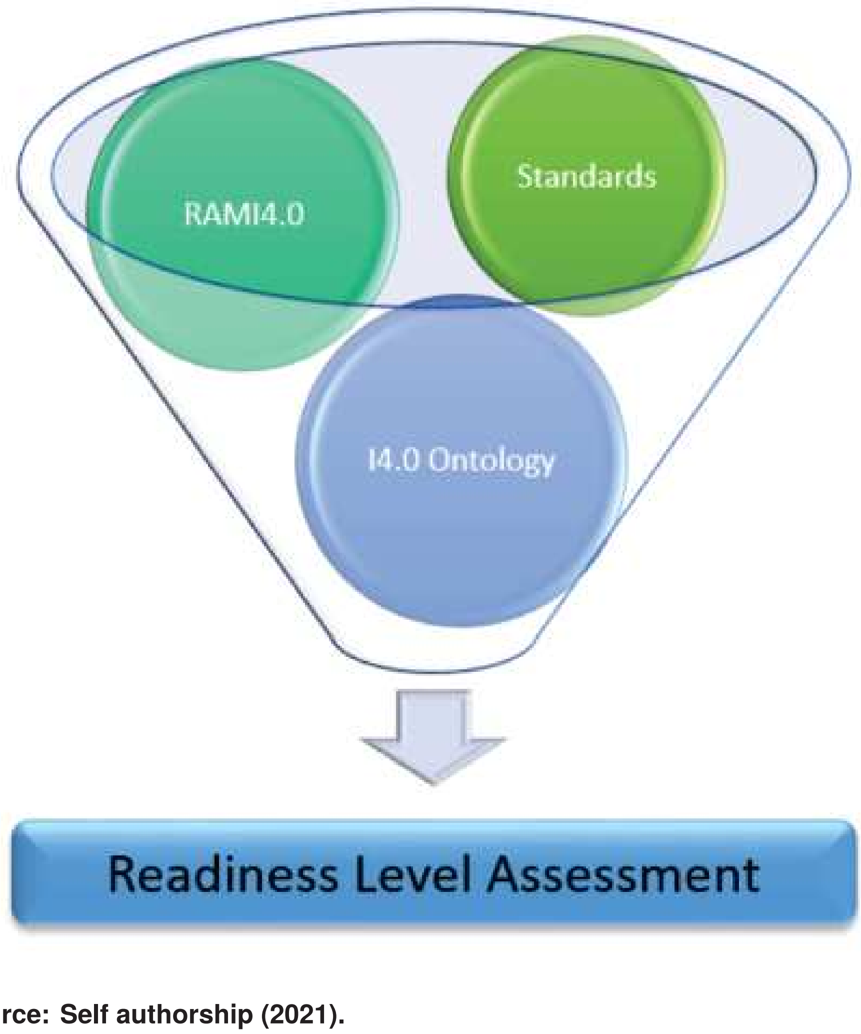
Source: Self authorship (2021).

4.1.1 Experimental segment

The experimental segment of this study will consist on the application of the postulated readiness level assessment method. The grounds for the readiness model were outlined by the RAMI standards compliance. The orientation will follow both qualitative and quantitative aspects and metrics according to the RAMI 4.0 ontology designed by (BADER et al., 2020). Based on the proposed developed method, the assessment will be executed on an automotive industrial plant with the objective to validate the experiment.

As represented by Fig. 31, the core theme of this assessment is a combination between the RAMI 4.0, its ontology and with that, gathered, classified and identified according to the RAMI 4.0 segment they represent, based on Bader et al ontology study(BADER et al., 2020), all resulting in a readiness level assessment.

Figure 31 – Assessment Scheme



Source: Self authorship (2021).

4.1.1.1 Overview of the questionnaire

The questionnaire consists on the gathering of the definition of adherent or not adherent to each one of the 142 standards applications. Based on the collected data, the result is compiled. The result compilation takes in consideration that each of the norm application corresponds to one point, and, as the same norm can be related to, and hence, applied to multiple axis/sub axis, each norm has its value calculated proportionally to the number of times it is applied, as presented and detailed in Table 9. For cases of multiple plants from the same industrial complex, multiple questionnaires can be executed and even (weight)averaged - as proposed on the Section 4.1.3. In accordance to the specificity of the institution's need, it is also possible to give a differed weight to each axis.

4.1.1.2 Distribution of standards application (and points) per RAMI axis, level and layer

The Table 8 contains the standard count, and hereby points, per dimension and sub dimension.

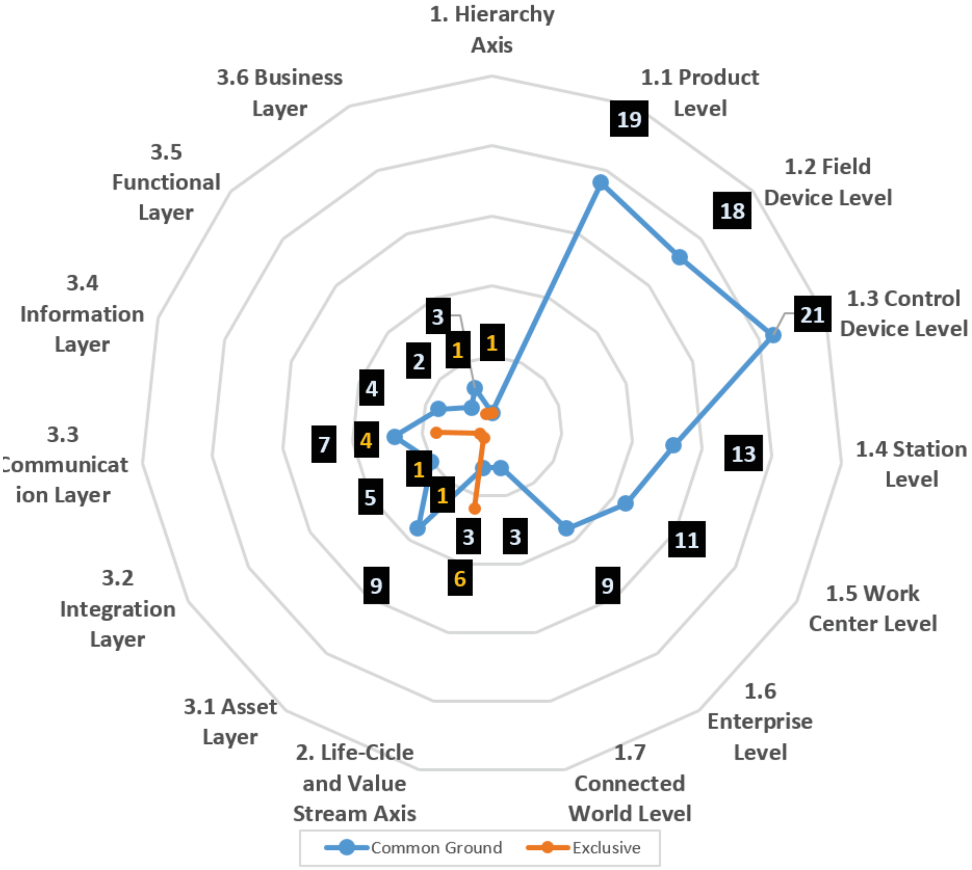
Table 8 – Number of Standards Application by RAMI 4.0 Segments

Dimension / Sub-Dimension	**Common Ground**	**Exclusive**	**Overall**
1. Hierarchy Axis	1	1	2
1.1 Product Level	19		19
1.2 Field Device Level	18		18
1.3 Control Device Level	21		21
1.4 Station Level	13		13
1.5 Work Center Level	11		11
1.6 Enterprise Level	9		9
1.7 Connected World Level	3		3
2. Life-Cycle and Value Stream Axis	3	6	9
3.1 Asset Layer	9	1	10
3.2 Integration Layer	5	1	6
3.3 Communication Layer	7	4	11
3.4 Information Layer	4		4
3.5 Functional Layer	2		2
3.6 Business Layer	3	1	4
Total Points	128	14	142

Source: Self authorship (2021).

The standards application, and hereby questionnaire points, is represented by the Fig. 32, where the total of points can be observed according to the axis/sub-axis they are inserted.

Figure 32 – Standards application dispersion



Source: Self authorship (2021).

Each standard might be related to more than one segment, and in such a case, this standard adherence will result in one point for each segment it is related to, what is demonstrated in more details on the categorization table, Table 9. The norms that are applied only one time are categorized as exclusive. The norms applied more than once are categorized as common-ground.

All the standards are detailed regarding its objective, categorization and to which axis/sub-axis they are applied contextualized to the assessment. The amount of points they sum to the questionnaire is represented, according to the number of applications. The data used for the crossing between the standards and their relation to the axis and sub-axis were based on (BADER et al., 2020) and the Standardization Council Industrie 4.0(RAMI. . . , 2021) publications.

Table 9 – Representation of the ontology based standards categorization, relation to dimensions, levels and layers with their respective questionnaire point values

Standard	Description	Category	Sub Axis Related	Points
6LoWPAN	IPv6 over IEEE802.15 as the Low Power Wan protocol	Exclusive	3.3 Communication Layer	**1**
CoAP	Constrained application protocol software architecture~	Exclusive	3.3 Communication Layer	**1**
eCl@ss	Cross-industry master-data standard for products and services(ECLASS:…, 2021)	Common Ground	1.1 Product Level; 1.3 Control Device Level; 1.4 Station Level; 1.5 Work Center Level; 1.6 Enterprise Level; 1.7 Connected World Level	**6**
IEC 29182-1	General overview for SNRA specifications related to Internet of Things	Common Ground	1.2 Field Device Level; 1.3 Control Device Level; 3.3 Communication Layer	**3**
IEC 60839 -5-2:2016	Supervised premises transceiver (SPT) alarm transmission systems~	Common Ground	1.2 Field Device Level; 1.3 Control Device Level; 2. Life-Cycle and Value Stream Axis; 3.3 Communication Layer	**4**
IEC 61131	PLC languages syntax and semantics related to industrial automation systems and integration	Common Ground	1.3 Control Device Level; 1.4 Station Level; 1.5 Work Center Level	**3**
IEC 61360	~IEC CDD commonly repository of concepts primarily used in the electrical industry	Exclusive	3.1 Asset Layer	**1**
IEC 61499	Function blocks software architecture related to industrial automation systems and integration	Common Ground	1.2 Field Device Level; 1.3 Control Device Level	**2**
IEC 61508	Functional safety of safety related systems related to industrial automation systems and integration	Exclusive	2. Life-Cicle and Value Stream Axis	**1**
IEC 61512	Batch control terms and models~	Common Ground	1. Hierarchy Axis; 1.1 Product Level; 1.3 Control Device Level; 1.4 Station Level; 1.5 Work Center Level	**5**
IEC 61784	Fieldbus industrial communication network profile related to industrial automation systems and integration	Common Ground	1.2 Field Device Level; 1.3 Control Device Level; 3.3 Communication Layer	**3**
IEC 61804	Function blocks software architecture for controlling EDDL related to industrial automation systems and integration	Common Ground	1.2 Field Device Level; 1.3 Control Device Level	**2**
IEC 61987_	Measurement and control related to industrial process	Common Ground	1.1 Product Level; 1.2 Field Device Level; 1.3 Control Device Level; 1.4 Station Level; 1.5 Work Center Level; 1.6 Enterprise Level;	**6**
IEC 62061	Requirements regarding machinery safety-related electrical control systems	Exclusive	2. Life-Cicle and Value Stream Axis	**1**

IEC 62264	Enterprise-control system integration terms and models	Exclusive	1. Hierarchy Axis	**1**
IEC 62337	Data processing, communication and presentation on condition monitoring and diagnostics of machines related to industrial automation systems and integration	Common Ground	1.2 Field Device Level; 1.3 Control Device Level; 1.4 Station Level; 1.5 Work Center Level; 1.6 Enterprise Level; 3.5 Functional Layer	**6**
IEC 62443	Security measures regarding IACS implementation related to industrial automation systems and integration	Exclusive	2. Life-Cycle and Value Stream Axis;	**1**
IEC 62453	FDT interface specification related to industrial automation systems and integration	Common Ground	1.2 Field Device Level; 1.3 Control Device Level; 1.4 Station Level	**3**
IEC 62541	OPC-UA as the M2M data exchange protocol cross platform SOA	Common Ground	1.2 Field Device Level; 1.3 Control Device Level; 1.4 Station Level; 1.5 WorkCenter Level; 1.6 Enterprise Level; 1.7 Connected World Level; 3.3 Communication Layer	**7**
IEC 62714	Standardized engineering data exchange format related to industrial automation systems and integration	Common Ground	1.1 Product Level; 1.2 Field Device Level; 1.3 Control Device Level; 3.4 Information Layer	**4**
IEC 62890	Key performance indicators definition and description related to MES~	Common Ground	1.4 Station Level; 1.5 Work Center Level; 2. Life-Cycle and Value Stream Axis	**3**
IEC TS 62832	Digital factory framework based on the general principles related to Industrial-process measurement, control and automation.	Common Ground	1.2 Field Device Level; 1.3 Control Device Level; 1.4 Station Level; 1.5 Work Center Level	**4**
ISO 1101	Geometrical product specifications. Geometrical tolerances on form, orientation and run-out using profile tolerating	Common Ground	1.1 Product Level; 3.1 Asset Layer	**2**
ISO 11898-1	Data link layer and physical signaling on CAN systems related to road vehicles	Common Ground	2. Life-Cycle and Value Stream Axis; 3.3 Communication Layer	**2**
ISO 13374	Machines condition monitoring and diagnostics related to industrial automation systems and integration	Common Ground	1.6 Enterprise Level; 3.6 Business Layer	**2**
ISO 13485	Quality management systems for medical devices	Exclusive	2. Life-Cycle and Value Stream Axis	**1**
ISO 13849	Safety-related machinery parts of control systems around industrial automation systems and integration	Exclusive	2. Life-Cycle and Value Stream Axis	**1**
ISO 14306	Standardized JT binary file related to three dimensional products definition primarily used in industry	Common Ground	1.1 Product Level; 3.1 Asset Layer	**2**

ISO 15704	Enterprise-referencing architecture and methodologies related to industrial automation systems and integration	Common Ground	1.6 Enterprise Level; 3.6 Business Layer	**2**
ISO 15746	Advanced process control and optimization capabilities related to industrial automation systems and integration	Common Ground	1.1 Product Level; 1.2 Field Device Level; 1.3 Control Device Level; 3.2 Integration Layer; 3.3 Communication Layer; 3.4 Information Layer	**6**
ISO 15926	Integration of life-cycle date for plants related to industrial automation systems and integration	Common Ground	1.1 Product Level; 3.2 Integration Layer	**2**
ISO 16739	XML file type as the BIM recognized by IFC as the industrial data sharing schema	Common Ground	1.4 Station Level; 1.5 Work Center Level	**2**
ISO 16792	Technical products documentation	Common Ground	1.1 Product Level; 3.1 Asset Layer	**2**
ISO 18629	Process specification language related to industrial automation systems and integration	Common Ground	1.1 Product Level; 1.2 Field Device Level; 1.3 Control Device Level; 3.2 Integration Layer; 3.3 Communication Layer; 3.4 Information Layer; 3.5 Functional Layer	**7**
ISO 18828-2	Procedures for production systems engineering related to industrial automation systems and integration	Common Ground	1.1 Product Level; 1.2 Field Device Level; 1.3 Control Device Level; 1.4 Station Level; 1.5 Work Center Level; 1.6 Enterprise Level	**6**
ISO 19439	Framework~ around enterprise integration modelling	Exclusive	3.6 Business Layer	**1**
ISO 19440	Constructs for enterprise modelling and architecture related to industrial automation systems and integration	Common Ground	1.1 Product Level; 1.6 Enterprise Level; 3.2 Integration Layer	**3**
ISO 22400	Key performance indicators definition and description related to industrial automation systems and integration	Common Ground	1.2 Field Device Level; 1.3 Control Device Level; 1.4 Station Level; 1.5 Work Center Level; 1.6 Enterprise Level; 1.7 Connected World Level; 3.6 Business Layer	**7**
ISO 22745-11	Terminology guidelines on the application of open technical dictionaries used in master data related to industrial automation systems and integration	Common Ground	1.1 Product Level; 3.1 Asset Layer	**2**
ISO 5459	Geometrical product specifications. General datum and datum system	Common Ground	1.1 Product Level; 3.1 Asset Layer	**2**

ISO 8062-4	Geometrical product specifications. General tolerances for castings using profile tolerating in a general datum system	Common Ground	1.1 Product Level; 1.2 Field Device Level; 1.3 Control Device Level; 3.1 Asset Layer	**4**
ISO ASTM 52915	AMF additive manufacturing file format definition primarily used in industry	Common Ground	1.1 Product Level; 3.1 Asset Layer	**2**
ISO TS 14649-201	Computerized numerical controllers data model on industrial automation systems and integration	Common Ground	1.1 Product Level; 1.2 Field Device Level; 1.3 Control Device Level; 3.1 Asset Layer; 3.2 Integration Layer	**5**
ISO/IEC 24760	IT security and privacy framework around terminology and concepts related to~ identity management	Common Ground	1.1 Product Level; 1.2 Field Device Level; 1.3 Control Device Level; 1.4 Station Level; 3.4 Information Layer	**5**
ISO/IEC 81714	Design of graphical symbols in technical documentation of industrialized products	Common Ground	1.1 Product Level; 3.1 Asset Layer	**2**
Modbus protocol	Modbus Protocol	Exclusive	3.2 Integration Layer	**1**
RFC 2616	Usage of HTTP v1.1 protocol	Exclusive	3.3 Communication Layer	**1**
RFC 7540	Usage of HTTP v2 protocol	Exclusive	3.3 Communication Layer	**1**
VDI/VDE 2182	Security measures regarding automated machines and plants related to industrial automation systems and integration	Exclusive	2. Life-Cycle and Value Stream Axis	**1**

Source: Self authorship (2021), based on (BADER et al., 2020).

4.1.2 Questionnaire Format

The questionnaire consists in collecting the information regarding compliance or not of the 49 related standards. Presenting the standards identification as the first column, and with their respective rows filled, followed by blank spaces to mark the positive or negative compliance to it. Next three columns reserved for taking notes related to the responsible for that standard during the interview, the most relevant observations and the source identification around that particular item. The following column refers to the value in points that this standard represent, and is pre-filled. This number is obtained based on the amount of sub-axis that the standard is applied to, information that has been detailed in the column "Sub Axis Related" in the Table 9. At the last column is calculated the result, which will be equal to the Standard Value in positive case, or zero, in negative case. The full assessment questionnaire can be found in Appendix A. The Table 10 illustrates the format of a blank questionnaire (first three lines only, for demonstrations purposes).

Table 10 – Blank Questionnaire Format Example

	Compliance						
Standard	Yes	No	Responsible	Observation	Source	Value	Result
6LoWPAN						1	
CoAP						1	
eCl@ass						6	
.	.	.	.	.	.	.	.
..	..	..	..	..	..	..	..
...	...		...	...	...	...	...
TOTAL						8	

Source: Self authorship (2021).

The questionnaire can be completed either by interviewing the staff in charge for the technical norms compliance at the assessed plant, or by direct filling out of the form. The Table 11 contains a fictional sample (first three lines only, for demonstrations purposes), of the completed sheet.

Table 11 – Filled Questionnaire Format Example

Standard	Compliance Yes	 No	Responsible	Observation	Source	Value	Result
6LoWPAN		X	Engineering	By Dr Smith	Dpt 14	1	**0**
CoAP		X	Projects	By Dr Stone	Dpt 27	1	**0**
eCl@ass	X		Engineering	Norm equivalency	Dpt 22	6	**6**
...	...		...	...	...	...	...
....	....	....	....	....	....	....	....
TOTAL						8	**6**

Source: Self authorship (2021).

With the completed questionnaire, the data can be crossed with the information in Table 9 to present segregated status among all the axis and sub-axis. In addition, they are also classified between common ground and exclusive types of standards.

In case of an assessment that encompasses more than one plant, it is possible to obtain a composed and/or weighted result by following the methods presented in Section 4.1.3.

4.1.3 Proposed Assessment Result Calculation and Classification

The postulated assessment may present the final readiness result both in an overall point of view, or by the common ground or even by an axis oriented point of view, according to the following sub sections:

4.1.3.1 Overall Readiness

The overall readiness can be calculated using the following equation:

$$R_{OA} = \frac{\sum(R \times W)}{\sum W} \tag{1}$$

Taken in consideration that all the axis readiness must be included in order to calculate the Overall Readiness Degree.

4.1.3.1.1 Classification

The Overall Readiness Degree is classified according to the questionnaire result as represented on the Table 12.

Table 12 – Overall classification

Questionnaire Points	Readiness Degree
0 - 28	Embryonic
29 - 56	Underdeveloped
57 - 85	Intermediate
86 - 114	High intermediate
115 - 142	Completely Ready

Source: Self authorship (2021).

4.1.3.2 Common Ground Readiness

The readiness level related to the standard that are common to dimensions, layers or levels can be calculated using the following equation:

$$R_{CG} = \frac{1}{n} \times \sum_{1}^{n} Q_{CG} \tag{2}$$

4.1.3.2.1 Classification

The Common Ground Readiness Degree is classified according to the questionnaire result as represented on the Table 13.

Table 13 – Common Ground Classification

Questionnaire Points	Readiness Degree
0 - 24	Embryonic
25 - 51	Underdeveloped
52 - 77	Intermediate
78 - 103	High intermediate
104 - 128	Completely Ready

Source: Self authorship (2021).

4.1.3.3 Hierarchy Level Axis Readiness

The readiness level related to the standards that are exclusive to the Hierarchy Level axis can be calculated using the following equation:

$$R_{HL} = \frac{1}{n} \times \sum_{1}^{n} Q_{HL} \tag{3}$$

4.1.3.3.1 Classification

The Hierarchy Level Readiness Degree is classified according to the questionnaire result as represented on the table:

Table 14 – Hierarchy Level Axis Classification

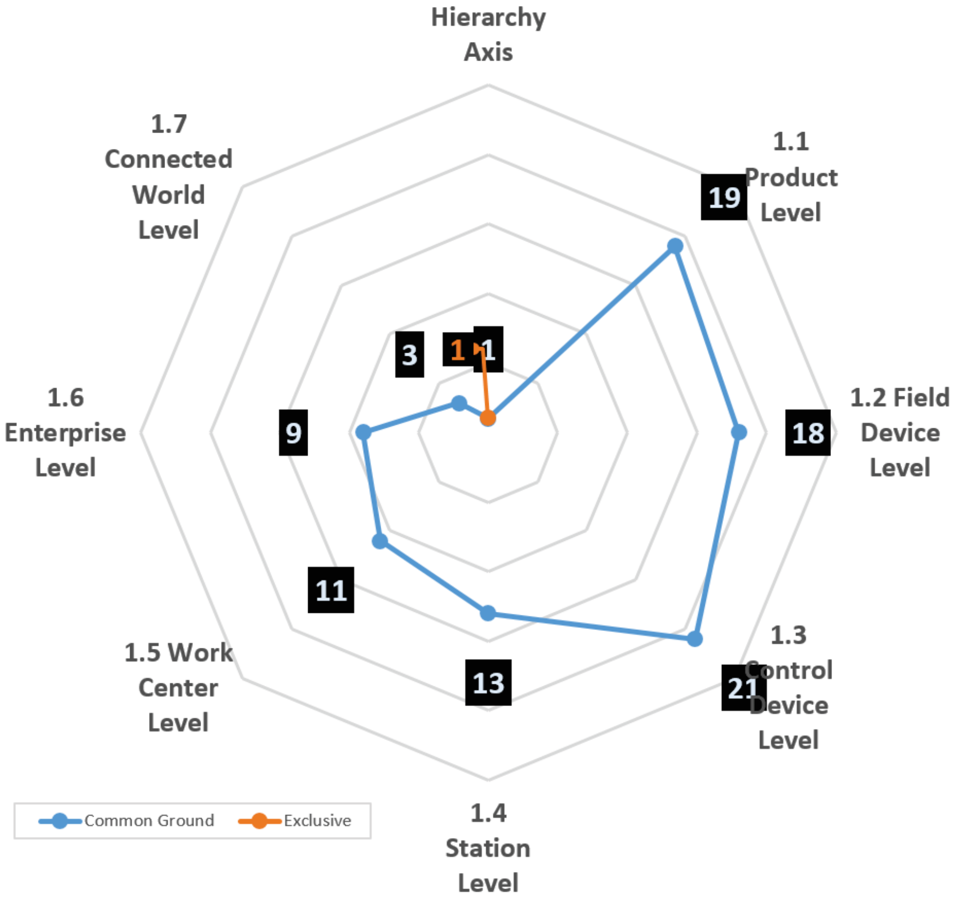
Questionnaire Points	Readiness Degree
0 - 18	Embryonic
19 - 37	Underdeveloped
38 - 58	Intermediate
59 - 77	High intermediate
78 - 96	Completely Ready

Source: Self authorship (2021).

4.1.3.3.2 Graphical Mapping

The ideal (Completely ready) graphic representation of the Hierarchy Levels Questionnaire would be presented as Fig. 33:

Figure 33 – Hierarchy Axis Standards



Source: Self authorship (2021).

4.1.3.4 Life-Cycle Status Axis Readiness

The readiness level related to the standards that are exclusive to the Life-Cycle Status Axis can be calculated using the following equation:

$$R_{LCS} = \frac{1}{n} \times \sum_{1}^{n} Q_{LCS} \tag{4}$$

4.1.3.4.1 Classification

The Life-Cycle Status Axis Readiness Degree is classified according to the questionnaire result as represented on the Table 15.

Table 15 – Life-Cycle Status Axis Classification

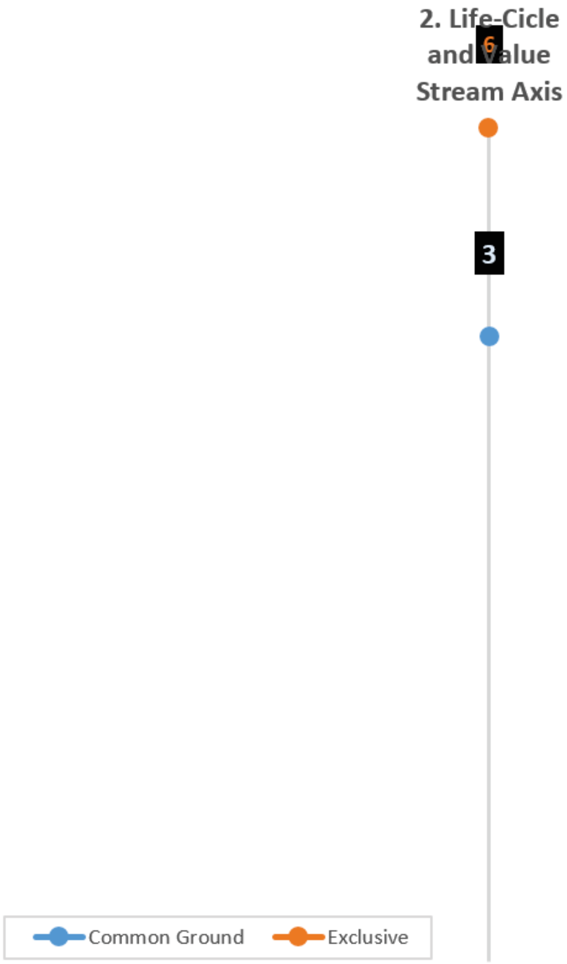
Questionnaire Points	Readiness Degree
0 - 1	Embryonic
2 - 3	Underdeveloped
4 - 5	Intermediate
6 - 7	High intermediate
8 - 9	Completely Ready

Source: Self authorship (2021).

4.1.3.4.2 Graphical Mapping

The ideal (Completely Ready) graphic representation of the Life-Cycle Status Axis Questionnaire would be presented as Fig. 34

Figure 34 – Life-Cycle Axis Standards



Source: Self authorship (2021).

4.1.3.5 Layer Axis Readiness

The readiness level related to the standards that are exclusive to the Layer Axis can be calculated using the following equation:

$$R_{LA} = \frac{1}{n} \times \sum_{1}^{n} Q_{LA} \tag{5}$$

Considering that:

4.1.3.5.1 Classification

The Layer Axis Degree is classified according to the questionnaire result as represented on the Table 16.

Table 16 – Layer Axis Classification

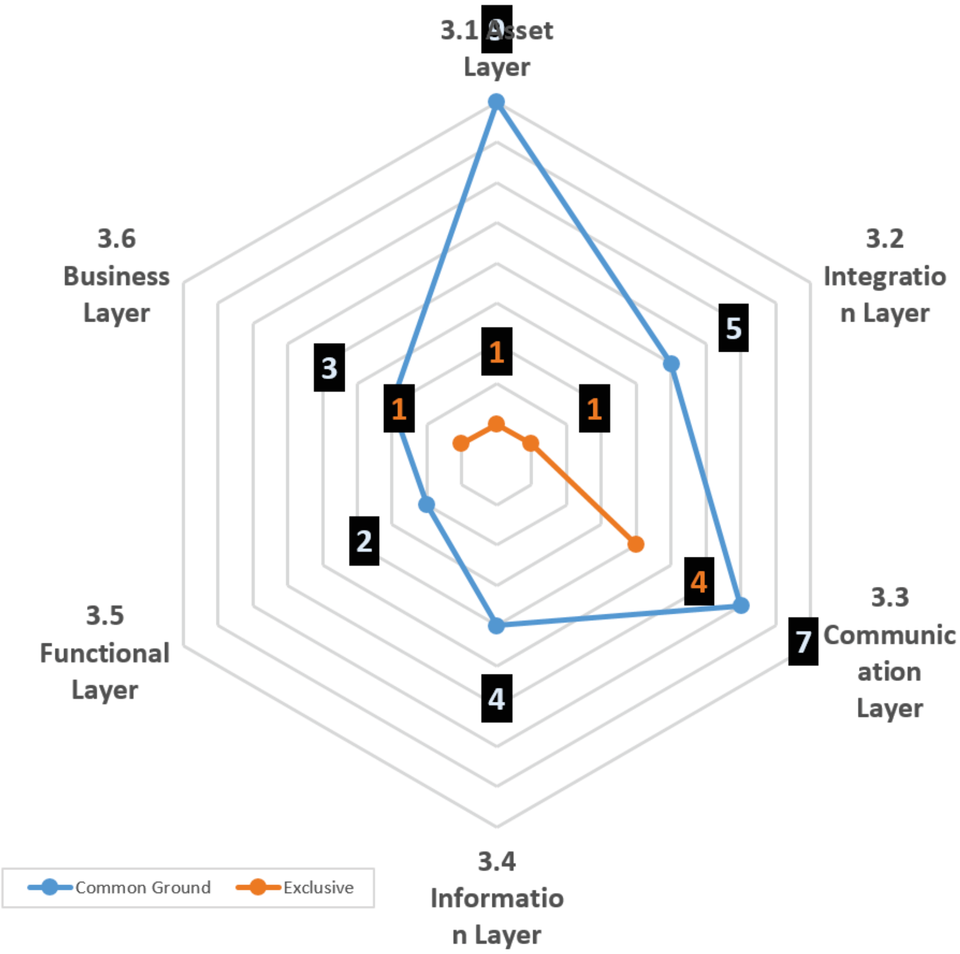
Questionnaire Points	Readiness Degree
0 - 7	Embryonic
8 - 15	Underdeveloped
16 - 21	Intermediate
22 - 29	High intermediate
30 - 37	Completely Ready

Source: Self authorship (2021).

4.1.3.5.2 Graphical Mapping

The ideal (Completely Ready) graphic representation of the Layer Axis Questionnaire would be presented as Fig. 35.

Figure 35 – Layer Axis Standards



Source: Self authorship (2021).

4.1.3.6 Equation Symbols

The symbols used on the equations are represented on the Frame 7:

Frame 7 – Equation Symbols

Symbol	Description
n	Number of Questionnaires
Q_{HL}	Points from Hierarchy Level Axis Standards Compliance Questionnaire
Q_{CG}	Points from Common Ground Standards Compliance Questionnaire
Q_{LA}	Points from Layer Axis Standards Compliance Questionnaire
Q_{LCS}	Points from Life-Cycle Status Axis Standards Compliance Questionnaire
R_{HL}	Hierarchy Level Axis Readiness
R_{CG}	Common Ground Readiness
R_{LA}	Layer Axis Readiness
R_{LCS}	Life-Cycle Status Axis Readiness
R_{OA}	Overall Readiness
W_{HL}	Hierarchy Level Axis Weight
W_{CG}	Common Ground Weight
W_{LA}	Layer Axis Weight
W_{LCS}	Life-Cycle Status Axis Weight

Source: Self authorship (2021).

5 EXPERIMENT

In this section will be described the results based on the application of the assessment at an automotive industrial complex located in Brazil, that shall remain anonymous for confidentiality reasons.

5.1 RESULTS

Table 17 – Questionnaire Results

Dimension / Sub-Dimension	Common Ground	Exclusive	Overall
1.1 Product Level	4		4
1.2 Field Device Level	2		2
1.3 Control Device Level	4		4
1.4 Station Level	2		2
1.5 Work Center Level	2		2
1.6 Enterprise Level	1		1
1.7 Connected World Level	1		1
2. Life-Cycle and Value Stream Axis	1	4	5
3.1 Asset Layer	3		3
3.2 Integration Layer		1	1
3.3 Communication Layer	2		2
Total Points	22	5	27

Source: Self authorship (2021).

The Table 17 represents the summary of the total points obtained by the questionnaire application, grouped by each axis/sub-axis.

5.1.1 Overall Readiness

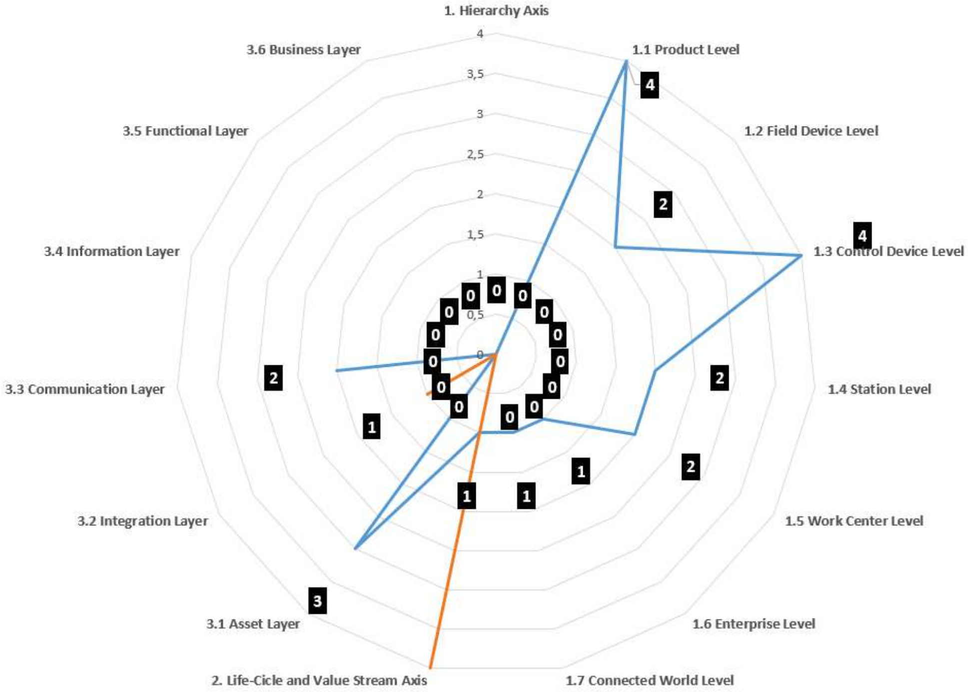
Table 18 – Overall Classification

Questionnaire Points	Readiness Degree
27	Embryonic

Source: Self authorship (2021).

The Table 18 represents the total amount of points obtained by the questionnaire application, which is referenced as the Overall Readiness, and its readiness degree according to the proposed assessment method.

Figure 36 – Resulting standards application dispersion.



Source: Self authorship (2021).

The Fig. 36 graphically represents the overall result dispersion of the standards application between each Axis/Sub-Axis.

5.1.2 Common Ground Readiness

Table 19 – Common Ground Classification

Questionnaire Points	Readiness Degree
22	Embryonic

Source: Self authorship (2021).

The Table 19 represents points that are related to multiple axis/sub-axis obtained by the questionnaire application, which is referenced as the Common Ground Readiness, and its readiness degree according to the proposed assessment method.

5.1.3 Hierarchy Level Axis Readiness

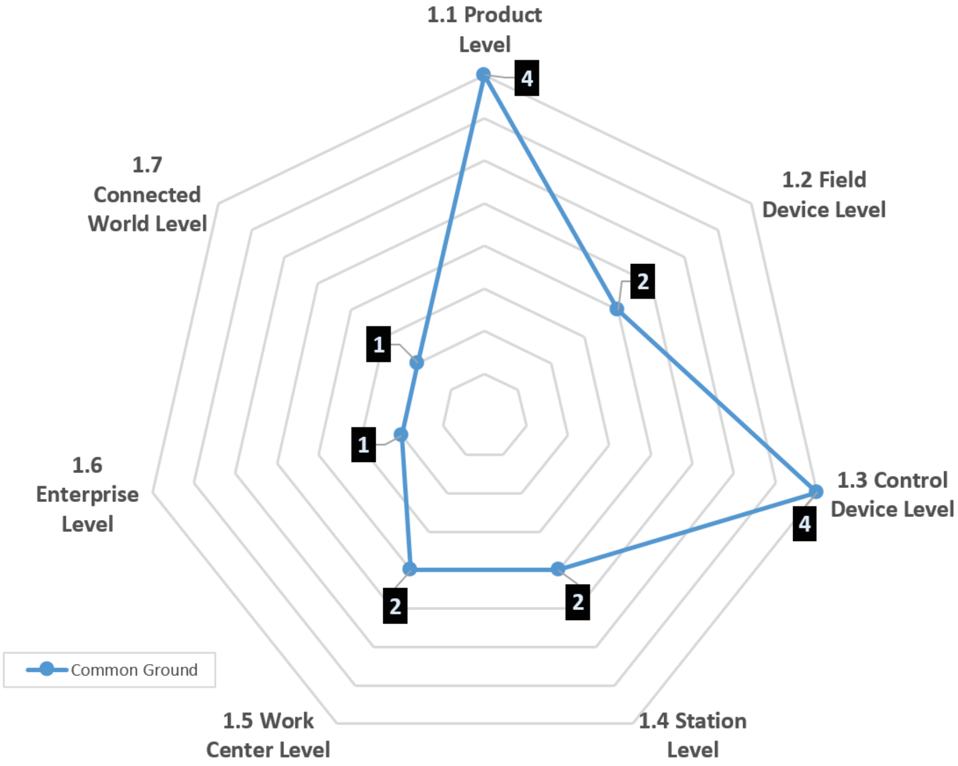
Table 20 – Hierarchy Level Classification

Questionnaire Points	Readiness Degree
16	Embryonic

Source: Self authorship (2021).

The Table 20 represents points that are related to the Hierarchy Level Axis, obtained by the questionnaire application, and its readiness degree according to the proposed assessment method.

Figure 37 – Hierarchy Axis Standards Results



Source: Self authorship (2021).

The Fig. 37 graphically represents the amount and dispersion of the standards application by the Hierarchy Level Sub-Axis.

5.1.4 Life-Cycle Status Axis Readiness

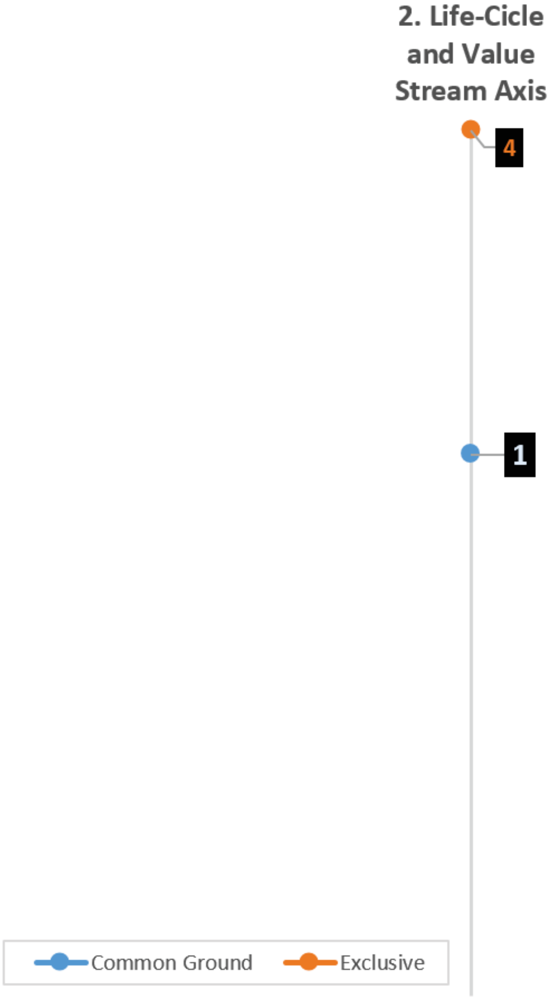
Table 21 – Life-Cycle Axis Classification

Questionnaire Points	Readiness Degree
5	Intermediate

Source: Self authorship (2021).

The Table 21 represents points that are related to the Life-Cycle Axis, obtained by the questionnaire application, and its readiness degree according to the proposed assessment method.

Figure 38 – Life-Cycle Axis Standards Results.



Source: Self authorship (2021).

The Fig. 38 graphically represents the amount and dispersion of the standards application by the Life-Cycle Sub-Axis.

5.1.5 Layer Axis Readiness

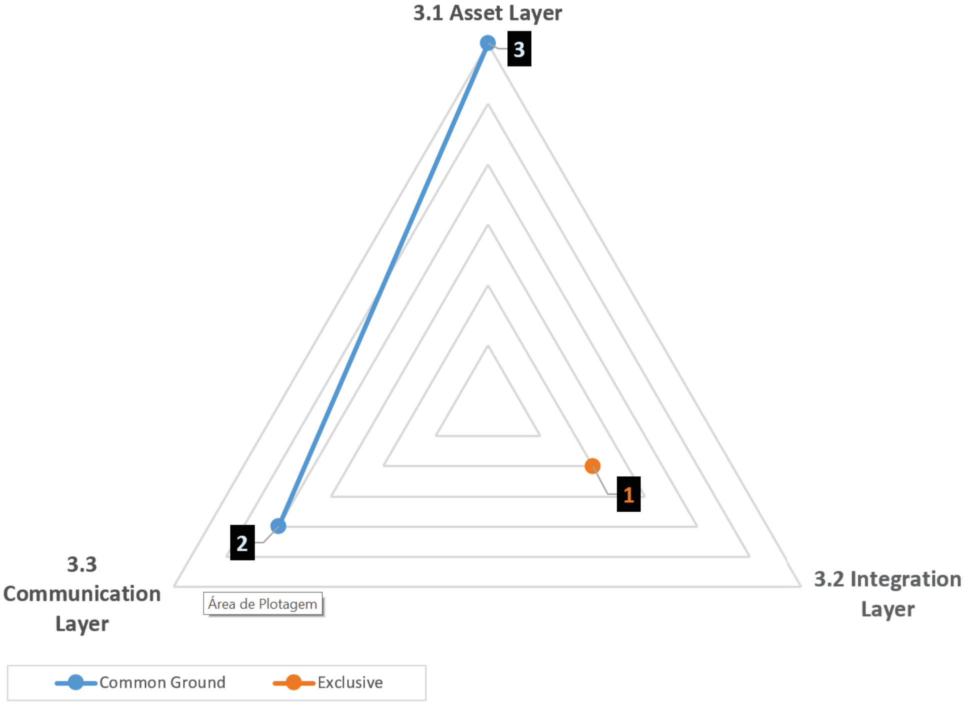
Table 22 – Layer Axis Classification

Questionnaire Points	Readiness Degree
6	Embryonic

Source: Self authorship (2021).

The Table 22 represents points that are related to the Layer Axis, obtained by the questionnaire application, and its readiness degree according to the proposed assessment method.

Figure 39 – Layer Axis Standards Results



Source: Self authorship (2021).

The Fig. 39 graphically represents the amount and dispersion of the standards application by the Layer Sub-Axis.

5.2 RESULTS DISCUSSION

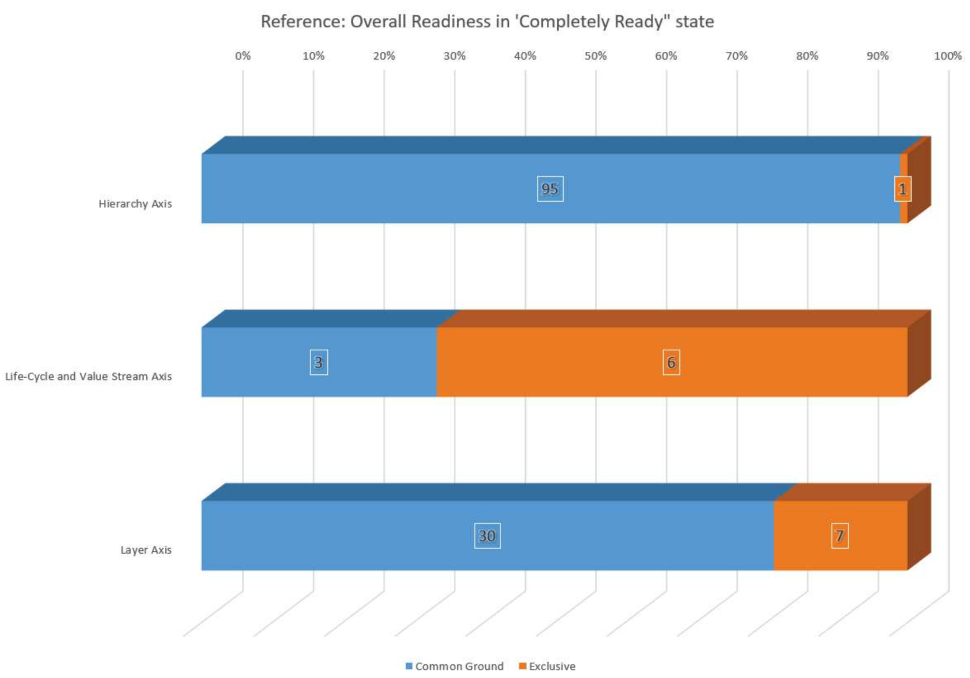
As the adoption of the I4.0 and its related technologies grow on adherence, the demand for readiness assessments accompany, creating then a very promising and fertile field of study and exploration. The experimental result gathered on the industrial plant was able to satisfactorily present to the engineering and management departments the main strengths and weaknesses of the evaluated plant and as such, defining which departments, procedures and processes should get more attention and investment in order to be better aligned not only with the RAMI 4.0 directives, but also to the I4.0 in general, prior to its implementation, what by itself is an advantage already.

With the obtained information is possible to notice precisely which are the areas that have the most potential to improve or to be explored in a broader fashion. To reach a more in-depth observation, the results from the experimental assessment for each axis/sub-axis will be graphically represented and compared to its respective 'Completely Ready' state. The latter representing the ideal readiness scenario.

5.2.1 Overall Readiness

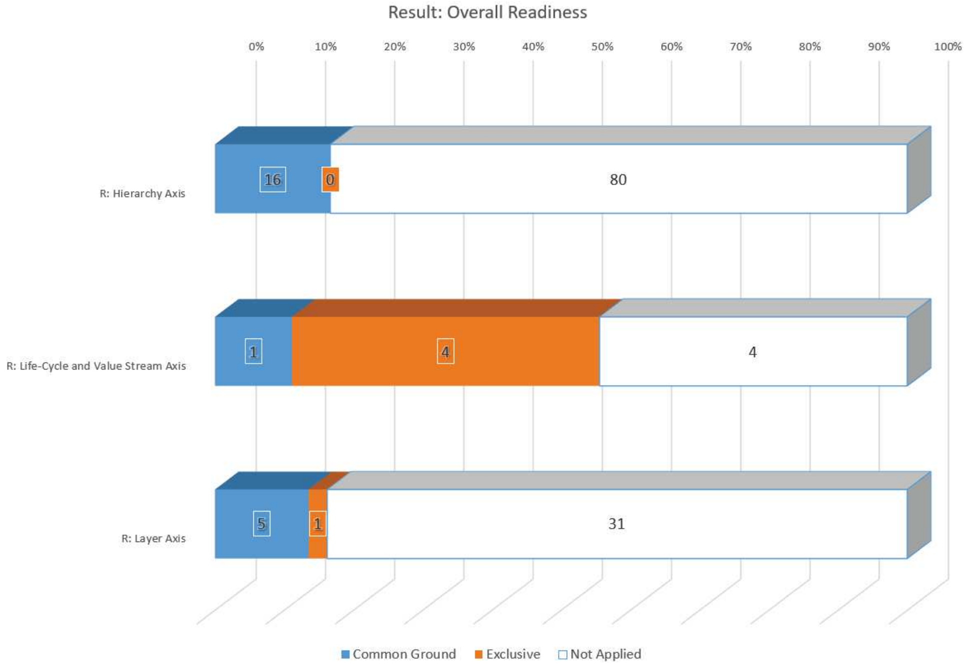
The points sum obtained from all the standards application show that there is quite a substantial amount of ground to cover in general in order to reach a ready state degree, while being equivalent to 19 percent of the possible standard application total amount, as presented on the Table 18.

Figure 40 – Reference for 'Completely Ready' Overall Readiness State.



Source: Self authorship (2021).

Figure 41 – Results for Overall Readiness State.



Source: Self authorship (2021).

Through the comparison of the optimal situation represented by Fig. 40 against the calculated result in Fig. 41 it is possible to notice the discrepancy between the 3 axis readiness, as well as the proportion from common ground to exclusive standards. Such difference will be explored with more details in the respective axis analysis.

5.2.2 Common Ground Readiness

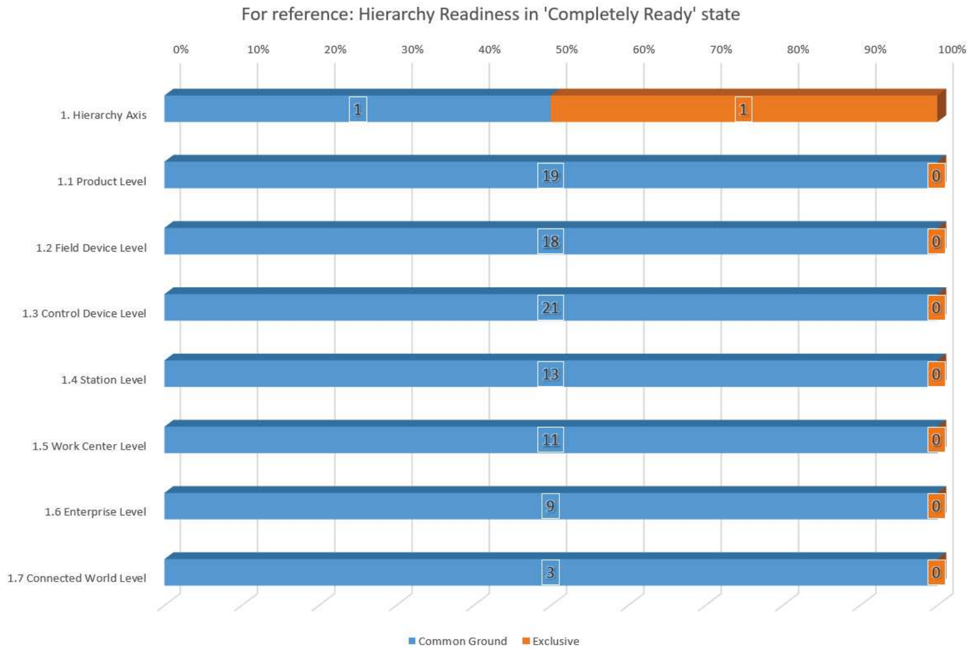
Representing the standards that are applied for multiple axis/sub-axis, the common ground readiness came up with around of 17 percent of the entirety of standards applied, as shown in Table 19. Such standards comprehend broad applications and are concentrated in the Hierarchy Level, serving as a bedrock to the smart manufacturing.

5.2.3 Hierarchy Level Axis Readiness

When it comes specifically to the standards related to the Hierarchy Level Axis, the questionnaire pointed around 17 percent of whole number of standards application, illustrated by Table 20.

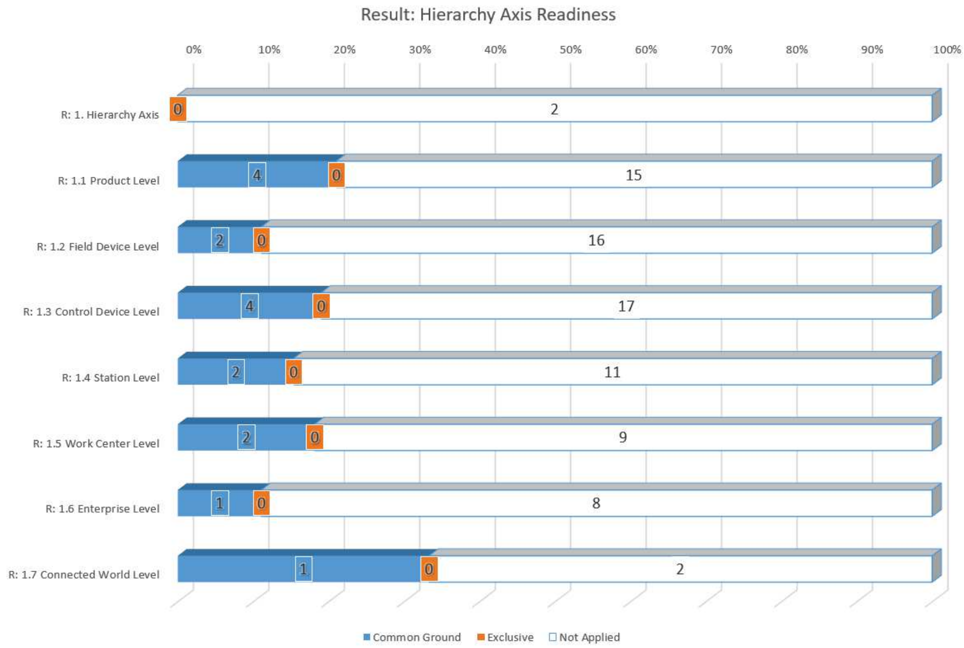
With the graphical representation in Fig. 37, becomes clear that despite the fact the Product Level and the Control Device Level sub-axis has double the average resulting norm application, the sub-axis from the Hierarchy Level axis are still way below the ready degree.

Figure 42 – Reference for ’Completely Ready’ Hierarchy Axis Readiness State.



Source: Self authorship (2021).

Figure 43 – Results for Hierarchy Axis Readiness State.



Source: Self authorship (2021).

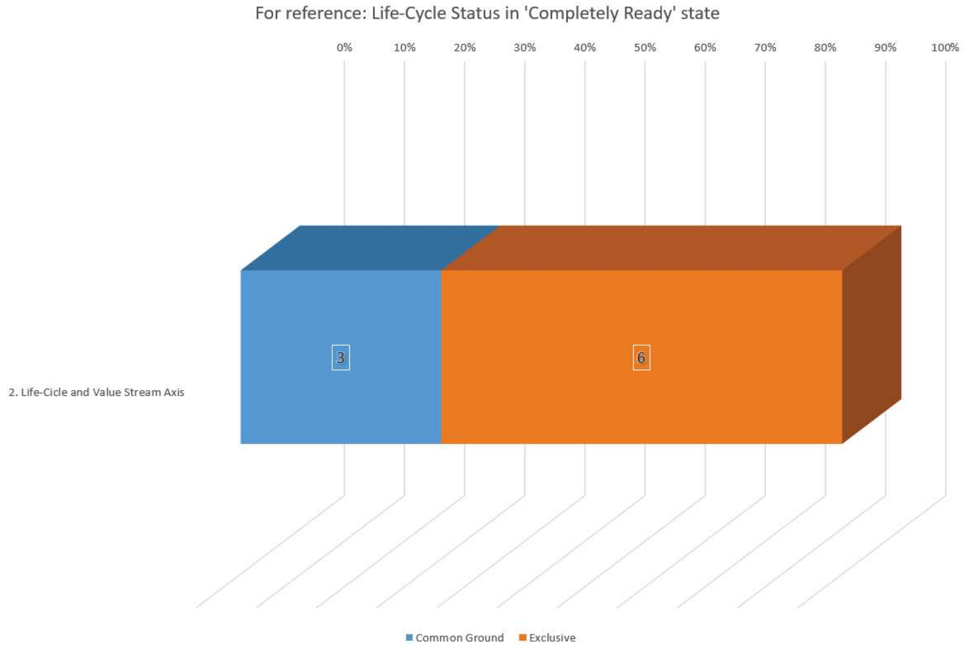
Represents the axis with the higher number of standards application, yet the axis with fewer exclusive standards. According to the involved staff during the questionnaire process, the related standards have both generalist and foundational characteristics. With the hierarchy level development, it becomes tangible to operate and transact information in a transverse manner, hence the architectural nature of the layer, at the same time it makes a sensible option to treat it as a priority in the digitization strategy.

5.2.4 Life-Cycle Status Axis Readiness

Regarding the standards application related to the Life-Cycle Status Axis readiness, the questionnaire resulted in around 55 percent of the total set of standards application, as shown in Table 21.

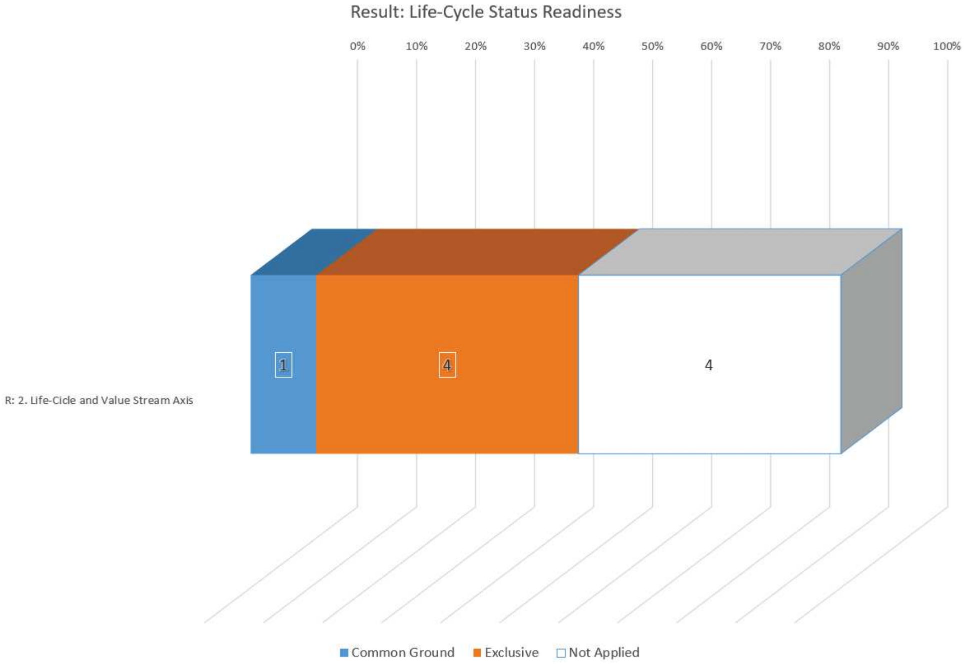
The plot in the Fig. 38 shows the axis that received the best result among the questionnaire. The Life-Cycle axis related norm application was classified as intermediate, demonstrating that the readiness level is above the average, with 55 percent of the totality compliance. With that, it represents the main strength of the evaluated plant.

Figure 44 – Reference for 'Completely Ready' Life-Cycle Status Axis Readiness State.



Source: Self authorship (2021).

Figure 45 – Results for Life-Cycle Status Axis Readiness State.



Source: Self authorship (2021).

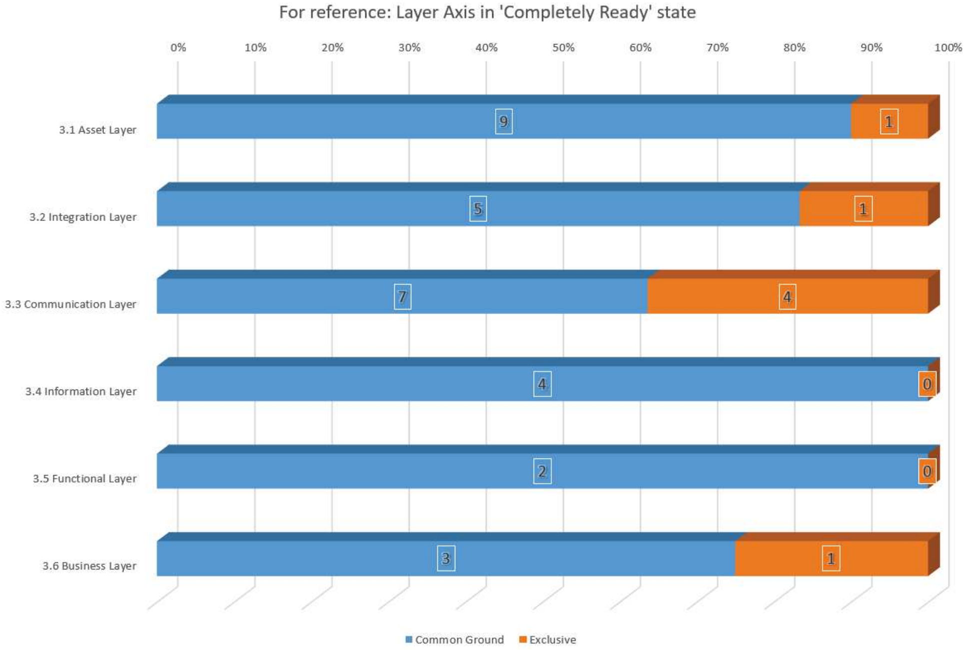
Such leap when compared among the 3 axis, according to the interviewed coordinator responsible for the plant engineering, comes from intrinsic reasons to the automotive manufacturing business. Meaning that, being vehicles long lasting assets with concerns since its conception, passing by its maintenance, and until its adequate end of life through material recycling. The life-cycle has been, as a matter of fact, part of the business model's core, what is indeed reflected in the 75% of exclusive standards compliance for this axis. Such result also reinforces the ability of the developed assessment model to diagnose the readiness level with accuracy.

5.2.5 Layer Axis Readiness

About the standards strictly around the Layer Axis, the questionnaire result came up to 16 percent of the sum of standards application, as presented in the Table 22.

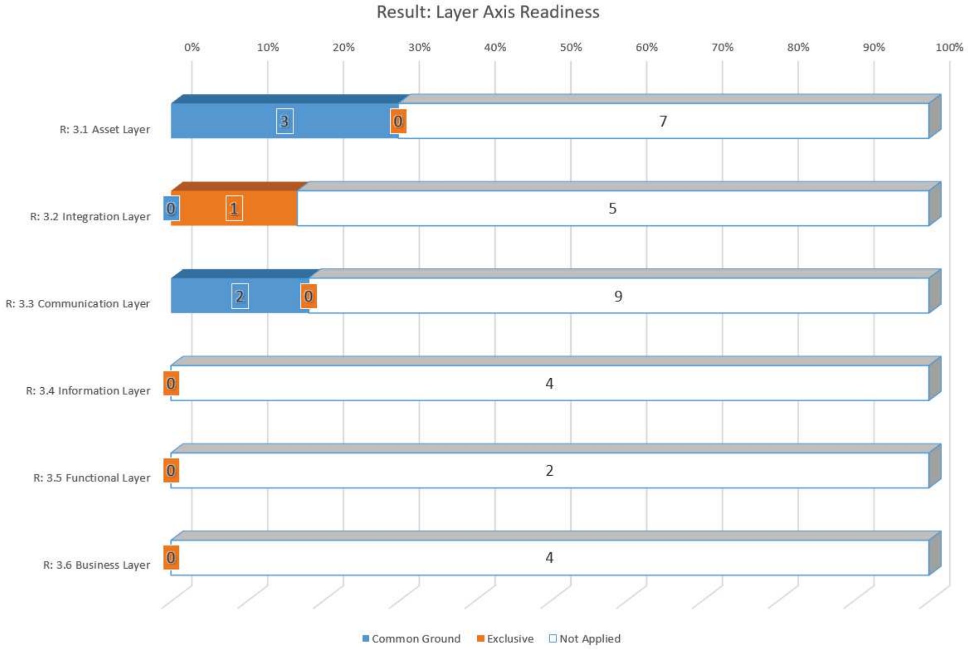
With the representation in Fig. 39 of the axis that received the lowest score on the evaluation, is possible to notice that three of the six existing sub-axis resulted to have no application of standards. With that, several points of improvement are highlighted which can now be used by the institution as a guidance to elaborate an improvement road-map.

Figure 46 – Reference for 'Completely Ready' Layer Axis Readiness State.



Source: Self authorship (2021).

Figure 47 – Results for Layer Axis Readiness State.



Source: Self authorship (2021).

Despite the present status, it is currently mapped as the one with perspective of being the recipient of large investments. The goal is to enable the company to increase the processes efficiency by the exploration of specially the Integration and the Communication layers at first, followed by Information, Functional and Business Layers.

5.2.6 Contributions

Regarding action taking based on the results, there is a clear benefit regarding the recognition of strengths and weaknesses (when compared to (PACCHINI et al., 2019)) once they are pointedly segregated by Axis/Sub-Axis and referenced to the specific standard that ought to be adhered to in order to evolve the readiness status. Another gain (considering (SCHUMACHER; EROL; SIHN, 2016) is the precision from which each axis readiness can be individually observed and a plan strategized upon.

5.2.7 Practical Implications

The assessment application was considered very efficient by by the involved staff from the plant where the the experiment was conducted. The advantages pointed were its practicality and objectiveness, follow by the cost-effectiveness and timeliness. The whole process did not demand any kind of physical presence, what was definitely a plus, taken in consideration that by the time this research was executed, there were social distancing, traveling and commuting restrictive protocols worldwide due to a pandemic.

As far as human resources, one person from the examining side, and three (for reassurance reasons) from the plant side were necessary to collect the data to run the experiment. As far as duration, it took 3 days (non-exclusive dedication) to collect the data and additional 3 days (non-exclusive) to elaborate the result report.

As limiting factors brought up, was the fact that the RAMI standards adoption is continuously under expansion, once the model itself is under development and enhancement. It implies in the possibility of updating and adding topics to the questionnaire itself, what demands revising.

With the plus side outweighing the downsides, as a a practical outcome of the assessment execution, the engineering supervisor was able to strengthen the investment road-map, and reassure that the current projects are aligned with the long-term strategies, as well as expand the exploration of the areas that are already well developed. With that, a demand for assessing two more plants is already signalized. With the industrial complex assessment expansion, the vision will be wider, allowing to have a more clear perception of the full manufacturing conglomerate and its next step towards the smart manufacturing road.

6 FINAL CONSIDERATIONS

The acceptance by the community who took part on the experiment is highly positive and points to the direction of the demand for a commercial solution in the same genre, which is very encouraging and challenging. At the current stage of this research work, it is clear that the proposed assessment brings value in the sense that the information provided by its application might potentially generate cost reduction and avoidance. The cost reduction can be obtained through the investment on the specific area in need, as pointed by the result. While the cost avoidance can happen once the precision of the result shows the exact weak spot, which once identified and treated will avoid unnecessary expenses on detecting the inefficiency symptom, but on the on the root cause instead.

The result of this research production contributed to the overall industry 4.0 readiness evaluation and measurement, more specifically concerning the information and communication technology infrastructure, taken by reference universal parameters which can be reproduced and replicated with very low impact regarding cost, time and effort. In that manner, the outcome gives the resources to situate the precise status that the subject of analysis is arranged in the gradation towards industry 4.0, making it possible to take measures precisely where they ought to be taken.

6.0.1 Future Works

During the research of this work, has become noticeable that the chosen theme for research could be expanded both vertically and horizontally. The technologies and methods themselves deserve to be explored with more depth, such as Low Power technologies and environmentally friendly methods (aligned with RAMI 4.0 axis or in addition as a sub-axis), what is yet to be considered as a primary industrial metric (or solution), hence its mostly unexplored features. In addition, other protocols have the merit and deserve to be included for analysis on the scope of a future studies.

Also, by the time of the systematic mapping execution, there were no studies concentrated on the industry 4.0 readiness assessment method based on any model that took in consideration the environmental alignment and ecological sustainability as a primordial dimension metric. The closest to the spectrum this study aims is Essakly, Wichmann e Spengler, 2019 (ESSAKLY; WICHMANN; SPENGLER, 2019) that exploit the ecological impact in the small and medium enterprises assessment, which gains quite a specific scope, while being specifically designed towards SMEs and considering specially the ecological impact as a consequence, or secondary factor from the evaluated item.

Instead of solely focusing on the avoidance of negative ecological impact, a future study scope could be to evaluate the degree of ecological alignment in an industrial business as a primary goal, along with the technological and procedural side carried by the Reference Architecture Model for Industry 4.0, regardless of its size. The intention is with those prescriptions, to explore that literature gap.

6.0.2 Limitations

The same aforementioned reason motivates to state the limitation of this research. Not all the technologies and protocols available in the market took part on the study. This work limited the options to the ones available or previously considered as a case of study in the environment subjected to its application.

The inherent nature of this work being developed around the RAMI model might be considered as a risk of bias, given other models models are not put into context, despite the fact that a substantial amount of standards mapped into this study is explored by other reference models as well.

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APPENDIX A — ASSESSMENT QUESTIONNAIRE

A.1 ASSESSMENT QUESTIONNAIRE

Here is presented the assessment sheet from the proposed readiness assessment model:

Table 23 – Blank Assessment Questionnaire

	Compliance						
Standard	Yes	No	Responsible	Observation	Source	Points	Result
6LoWPAN						1	
CoAP						1	
eCl@ss						6	
IEC 29182-1						3	
IEC 60839-5-2:2016						4	
IEC 61131						3	
IEC 61360						1	
IEC 61499						2	
IEC 61508						1	
IEC 61512						5	
IEC 61784						3	
IEC 61804						2	
IEC 61987_X						6	
IEC 62061						1	
IEC 62264						1	
IEC 62337						6	
IEC 62443						1	
IEC 62453						3	
IEC 62541						7	
IEC 62714						4	
IEC 62890						3	
IEC TS 62832						4	
ISO 1101						2	
ISO 11898-1						2	
ISO 13374						2	
ISO 13485						1	
ISO 13849						1	
ISO 14306						2	
ISO 15704						2	
ISO 15746						6	
ISO 15926						2	
ISO 16739						2	
ISO 16792						2	
ISO 18629						7	
ISO 18828-2						6	
ISO 19439						1	
ISO 19440						3	
ISO 22400						7	
ISO 22745-11						2	
ISO 5459						2	
ISO 8062-4						4	
ISO ASTM 52915						2	
ISO TS 14649-201						5	

ISO/IEC 24760	5
ISO/IEC 81714	2
Modbus protocol	1
RFC 2616	1
RFC 7540	1
VDI/VDE 2182	1

Source: Self authorship (2021), based on(BADER et al., 2020).