Industry 4.0 Readiness Assessment Method Based on RAMI 4.0 Standards

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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 and maturity levels of the institution accordingly to that scope. To achieve that, methods will be developed and applied to gather information and subsequently threaten it. Finally, the results will be confronted versus 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.

INDEX TERMS Industry 4.0, Rami 4.0, readiness evaluation method, industrial cyber-physical systems, readiness level assessment.

I. INTRODUCTION

The industrial current stage has its core mainly related to cyber-physical systems, where a contextualization of intelligent manufacturing [1] 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.

Since the emergence of the Industry 4.0 terminology in 2011 [2] 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 - RAMI4.0, gain such an importance in this scenario. Moreover, the transitioning process planning and road-mapping tools may of great hand, exactly what this research aims to cover.

The main objective of this work is to improve the overall 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.

With that in mind, 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 precise, 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.

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

Table 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 level assessment into the industry 4.0? |

Paper Structure: This work is presented in the following structure: Section 2 consists in a scoping review 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. Section 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.

Section 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.

II. SCOPING REVIEW

With the broad outlook provided by the Industry 4.0 constant transition, the execution of a scoping review shall be of grand benefit. The orientation provided by its verified information will be used as a guide to narrow this study scope. The comparative segment will be given by the elaboration of a chart from the gathered studies on the literature regarding readiness assessment methods on the industry 4.0, and as such, supporting the differences and particular characteristics motivating its development.

A. RELATED STUDIES

A substantial amount of industry 4.0 related theme presented in a form of review researches have been developed. Multiple fields of study are involved and as such, have mutual interest in gains based on its development: from IT, ICT, industrial, engineering to even administration related sciences. Several distinct points of view have been taken, such as MBSE based modeling [3], the impact that SMEs will receive from entrepreneurial standpoint [4], how do startups develop IoT systems [5], environmental Big Data [6], the facilitation of development through application of MDE in CPSs [7], solutions related to the link from ICN and IoT [8]. Still in the IoT field and specifically its challenges [9], the synergy between Internet of Things and cloud computing [10], deployment and orchestration for IoT [11], and also the study of industrial smart energy grids [12] (regardless of its environmental adequacy manufacturing guidance) as well as on industrial WSN [13]. Notwithstanding their high-grade and depth content, the vast majority, however, diverge from this work’s proposed research questions and objectives. The points of view of the studies compared are represented in 1. Despite the variety broadness of exploration, by the time the search was executed on the selected digital academical libraries (ACM, IEEEExplore, 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 [14], interoperability in IoT [15] and [16], the mapping on modelling languages [17], and in a sense of the infrastructure technologies, the survey in an analytic approach [18] and the
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FIGURE 1. Studies points of view variation.

analysis framework by Boyes et Al [19]. Taking the gathered info in consideration regarding the specially increasing pace in the past 5 years, an opportunity raises to explore. Given as the representation in 1, the SLM studies fall into 4 broad classes, from which this study intend to explore reference and infrastructure models.

B. REVIEW METHOD
This mapping will be conducted considering as a north a combination of the research method conducted by [20], given its completeness and [3] 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.

C. REVIEW QUESTIONS
The questions were defined in order to guide the expected outcome from the review. 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 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.

D. 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 [21] and [3], shown on the 2.

TABLE 2. Digital libraries publications.

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

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 3 the string versions are shown.

TABLE 3. Search strings.

| String                      | Complete String                        |
|-----------------------------|----------------------------------------|
| R-STR1                      | (“fourth industrial” OR “industry 4.0”) AND (“assess**” OR “evaluat*” OR “measur*” OR “matur*”) AND (“approach” OR “method” OR “model”) |
| R-STR2                      | (“fourth industrial” OR “industry 4.0”) AND (“assessment” OR “evaluation” OR “maturity”) AND (“approach” OR “method” OR “model”) |
| R-STR3                      | (“fourth industrial” OR “industry 4.0”) AND (“assess* approach” OR “assess* method” OR “assess* model” OR “evaluat* approach” OR “evaluat* method” OR “evaluat* model” OR “measur* approach” OR “measur* method” OR “matur* approach” OR “matur* method” OR “matur* model”) |

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.

E. 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 4 specifies the rules.

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
TABLE 4. Exclusion / Inclusion Rules.

| Rule Type   | Condition                                                                 |
|-------------|---------------------------------------------------------------------------|
| Exclusion   | Research not available for access online through CAPES or UFPR proxy;     |
|             | Scope unrelated to this work proposal; Publication date prior to 2016;     |
| Inclusion   | Approach on industry 4.0 infrastructure related technologies;              |
|             | Approved and reviewed in journal or conference;                           |

TABLE 5. 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      |
|       | Screening Phase 2: Removal of newsletters, mini reviews and publications that did not endorse online access |
| Third | Screening Phase 3: In depth analysis of scope relation                      |
| Fourth| Removal of inaccessible papers according to the defined access methodology |

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

F. SCREENING STAGE RESULT ANALYSIS

Based on the studies that remained as result of the screening, it was possible to notice at least 3 distinct categories, which are illustrated in the 2, and will be explored in the following paragraphs.

1) MODELING RELATED STUDIES

Aiming to represent the physical infrastructure according to the chosen model, such as [22] and [23]. Hence they remain out of the objective of this study, those works were excluded from the selection.

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 [24] and [25] 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 2.

3) METHOD PROPOSITION STUDIES

The remaining category of study, representing assessment, maturity and readiness levels, were analyzed, despite the fact that 13 were theme aligned selected works ([26], [27]) could not be accessed through the proposed manner on section 4, so they were also excluded. After the final screening, the result was composed by [28]–[44].

G. SCREENING QUANTIFICATION

The evolution of studies quantity through all of the screening stages is now represented in the 6:

| 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  |

H. 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:

1) QUESTION 1: WHAT ARE THE MOST FREQUENT KEYWORDS ASSOCIATED TO INDUSTRY 4.0 ASSESSMENT?

The keywords that were used more frequently in the selected studies were (in the appearance order):

- Manufacturing
- Maturity Model
- Production Engineering Computing
- Digital Transformation
- Industries

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) QUESTION 2: WHAT COUNTRIES ARE LEADING THE SCIENTIFIC CONTENT PRODUCTION AROUND THE INDUSTRY 4.0 MATURITY ASSESSMENT?

The 3 represent countries with the highest academic production rates on the study field. The area dimension is proportional to the country production.

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 [45] on the I4.0 initiative, there is already a standard under development and perfectly aligned with the Industrie 4.0 Platform Working Groups’ [46] premises. That itself is a great step forward. The partnership began with the Singapore government along with TuV [32] 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 II-F, the evaluation criteria are represented by 4. The classification will be explored in the following items.

a: QUALITATIVE EVALUATION APPROACHES

The studies that take in consideration primarily qualitative specifications and characteristics to make the assessment are shown in the 7, as comparative table exploring the nuances among them.

b: QUALITATIVE AND QUANTITATIVE EVALUATION APPROACHES

The studies that take in consideration both qualitative and quantitative characteristics to make the assessment are compared in the 8.

c: THEORETICAL AND MODELLING EVALUATION APPROACHES

The studies that take in consideration theoretical and modelling characteristics to make the assessment are compared in the 9.

4) CONTEXTUALIZATION

Taken the obtained information from the scoping review as a north, 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 [2] 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 10.

Source: International Society of Automation [47]

The 5 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.

a: ENABLING TECHNOLOGIES AND PROTOCOLS

The scope of this segment is to put the specific technologies in the context of a 4.0 industrial environment. When possible, the respective architectures were demonstrated through
TABLE 7. Assessments oriented primarily on qualitative data.

| Title                                                                 | Authors                                | Date   | Focus                               | Differential                        | Misc.                                |
|----------------------------------------------------------------------|----------------------------------------|--------|-------------------------------------|-------------------------------------|--------------------------------------|
| Leveraging industry 4.0 — A business model pattern framework         | J. Welling, M. Stöcker, M. Kowalkiewicz, M. Bohm, 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. Lim, 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    | A. Eassakly, 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. Müller, and B. V. Wahrens | 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 itself               | Consolidation of different model     | Based on a systematic mapping         |
| Industry 4.0 in Practice-Identification of Industry 4.0 Success Patterns | Jörg. Puchan, A. Zeitang, and I.-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. Jenderney 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           |

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.

- **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 [48]. 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 synergic 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 QR code, 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 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.

- **IIoT** The IoT in a simplistic analysis is a virtual segment of network where the devices can establish connection between themselves and devices from other layers. The IIoT, or Industrial IoT is the replication of the IoT capabilities
TABLE 8. 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. Jazene, 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. Pacchini, and G. Munnolo | Dec. 2019 | Readiness from an 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. Schmacher, T. Nemeth, and W. Shin | 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. Pacchini, and G. Munnolo | Jan. 2019 | Measure 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. Schmacher, S. Erol, and W. Shin | Jan. 2016 | Assets and strategy                       | 3 step and 9 dimensions                           | Most cited and pioneer work                                        |

TABLE 9. 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 | Jan. 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. Piscching, 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                        |

into the IACS context [18]. 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 figure represents an IIoT framework model using the proposed encryption protocol [49], 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 ciphering approaches, aiming to increase the overall safety and reliability levels.

• OT / IACS

Industrial Automation Control Systems is the terminology used to assign aggregation of devices and techniques focused on the industrial automated environment [50] 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.

• OPC-UA

OPC-UA stands for Open Platform Communication - Unified Architecture. 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 [51]. 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.
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 [52]. With a client/server mode of operation, and lightweight operation, has various uses in the I4.0 field, focusing the low cost devices communication.

All those messaging technology advancements enabled the transition to stateless messaging models, such as RESTful web services. Such models bring viability to highly independent informational exchanges. That translating into the usage of tokens for authentication, resulting in transparent environment scalability, and in addition to be in accordance to the ubiquitous computing premises. The very same kind of soil preparation must be done to allow the technology migration from diverse engaged areas [53], while still allowing interoperability with the legacy scenarios, to better suit the transition.

**b: THE REFERENCE ARCHITECTURE MODEL FOR INDUSTRY 4.0**

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 [55] that along with a major stakeholders association, the German Electrical and Electronic Manufacturers Association (ZVEI) [56] have been outlining through the years. In addition, in 2020 the initiative was aligned with the IIC (Industrial Internet Consortium) [57], 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 6. Each dimension and sub-dimension will be characterized in the next subsections.

**Hierarchy Axis**

Based on the International Electrotechnical Commission [58] 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:

--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.

--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.

–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.

–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.

–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.

–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.

–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.

–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:

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

–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.

–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.

–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 critical status to the factory.

–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.

–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 13.

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

–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.

–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.
–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.

–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.

–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.

–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.

C: RESULTING TECHNOLOGIES

With the convergence of the diverse enabling technologies, it is reached a point where is possible to explore a new cybernetic level of information.

• 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 [59], 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 an 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, 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.

–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 [60].

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.

III. READINESS ASSESSMENT METHOD BASED ON THE RAMI 4.0

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 7 represents the research focus and area of interest.

A. ASSESSMENT METHODOLOGY

The assessment will take in consideration the most relevant topics regarding the fourth industrial revolution, which must be oriented according to the Reference Architecture Model.
for Industry 4.0 (RAMI 4.0). The research encompasses the presentation of the developed experiment proposal application in real world industrial production environment, which shall be detailed in the next session.

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 [61]. 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 8, 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 [61], all resulting in a readiness level assessment.

1) ASSESSMENT METHODOLOGY
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 [62], IEC [58], and RFC [63]. 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 9, 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.

a: OVERVIEW OF THE QUESTIONNAIRE FORMAT
The questionnaire consists on the gathering of the definition of adherent or not adherent to each one of the 142 standards. 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 15. For cases of multiple plants from the same industrial complex, multiple questionnaires can be executed and even (weight)averaged - as proposed on the III-A2. In accordance to the specificity of the institution’s need, it is also possible to give a differed weight to each axis.

b: DISTRIBUTION OF STANDARDS APPLICATION PER RAMI AXIS, LEVEL AND LAYER
The 14 contains the standard count, and hereby points, per dimension and sub dimension.
| 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      |
| eCII@ss       | Cross-industry master-data standard for products and services [61]           | Common     | 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     | 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     | 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     | 1.3 Control Device Level; 1.4 Station Level; 3.3 Communication Layer | 3      |
| IEC 61360     | –IEC CDD commonly repository of concepts primarily used in the electrical industry | Ex exclusive | 3.1 Asset Layer                                      | 1      |
| IEC 61499     | Function blocks software architecture related to industrial automation systems and integration | Common     | 1.2 Field Device Level; 1.3 Control Device Level; 2. Life-Cycle and Value Stream Axis | 2      |
| IEC 61508     | Functional safety related systems related to industrial automation systems and integration | Common     | 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 61512     | Batch control terms and models--                                           | Common     | 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     | 1.2 Field Device Level; 1.3 Control Device Level; 3.3 Communication Layer | 3      |
| IEC 61804     | Function blocks software architecture for controlling EDDL                   | Common     | 1.2 Field Device Level; 1.3 Control Device Level; 2. Life-Cycle and Value Stream Axis | 2      |
| IEC 61987     | Measurement and control related to industrial process                        | Common     | 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-Cycle 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     | 1.2 Field Device Level; 1.3 Control Device Level; 1.4 Station Level; 1.5 Work Center Level; 1.6 Enterprise Level; 3.3 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     | 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     | 1.2 Field Device Level; 1.3 Control Device Level; 1.4 Station Level; 1.5 WorkCenter Level; 1.6 Enterprise Level | 7      |
| IEC 62714     | Standardized engineering data exchange format related to industrial automation systems and integration | Common     | 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 MBS--        | Common     | 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     | 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     | 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     | 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     | 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 | Common     | 1.1 Product Level; 3.1 Asset Layer                  | 2      |
| ISO 14306     | Standardized JT binary file related to three dimensional products definition primarily used in industry | Common     | 1.6 Enterprise Level; 3.6 Business Layer            | 2      |
| ISO 15704     | Enterprise-referring architecture and methodologies related to industrial automation systems and integration | Common     | 1.6 Enterprise Level; 3.6 Business Layer            | 2      |
TABLE 15. (Continued.) The standards categorization, relation to dimensions, levels and layers with their respective questionnaire point values.

| Standards                                                                 | Categorization | Axes/Sub-Axes                                                                 | Points |
|--------------------------------------------------------------------------|----------------|-------------------------------------------------------------------------------|--------|
| 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; 3.5 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; 1.4 Station Level; 1.5 Work Center Level; 1.6 Enterprise Level | 6      |
| ISO 19439: Framework– around enterprise integration modelling            | Exclusive      | 3.6 Business Layer                                                            |        |
| 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 tolerancing 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 24780: 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                                                         | 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      |
| VDE/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      |

The standards application, and hereby questionnaire points, is represented by the 10, where the total of points can be observed according to the axis/sub-axis they are inserted.

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, 15. 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:

2) PROPOSED ASSESSMENT RESULT CALCULATION
The postulated assessment may present the final readiness result both in an overall point of view, or by the common

| Questionnaire Points | Readiness Degree   |
|----------------------|--------------------|
| 0 - 28               | Embryonic          |
| 29 - 56              | Underdeveloped     |
| 57 - 85              | Intermediate       |
| 86 - 114             | High intermediate  |
| 115 - 142            | Completely Ready   |
ground or even by an axis oriented point of view, according to the following sub sections:

**a: OVERALL READINESS**
The overall readiness can be calculated using the following equation:

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

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

- Classification
  
The Overall Readiness Degree is classified according to the questionnaire result as represented on the table:

**b: COMMON GROUND READINESS**
The readiness level related to the standards that are common to dimensions, layers or levels can be calculated using the following equation:

$$R_{CG} = \frac{1}{n} \times \sum_{i} Q_{CG}$$  \hspace{1cm} (2)

- Classification
  
The Common Ground Readiness Degree is classified according to the questionnaire result as represented on the table:

**c: 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:

$$R_{HL} = \frac{1}{n} \times \sum_{i} Q_{HL}$$  \hspace{1cm} (3)

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

**d: 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:

$$R_{LCS} = \frac{1}{n} \times \sum_{i} Q_{LCS}$$  \hspace{1cm} (4)

- Classification
  
The Life-Cycle Status Axis Readiness Degree is classified according to the questionnaire result as represented on the table:

- Graphical Mapping
  
The ideal graphic representation of the Life-Cycle Status Axis Questionnaire would be presented as:

**e: LAYER AXIS READINESS**
The readiness level related to the standards that are exclusive to the Layer Axis can be calculated using the following equation:

$$R_{LA} = \frac{1}{n} \times \sum_{i} Q_{LA}$$  \hspace{1cm} (5)

- Classification
  
The Layer Axis Readiness Degree is classified according to the questionnaire result as represented on the table:

- Graphical Mapping
  
The ideal graphic representation of the Layer Axis Questionnaire would be presented as:
TABLE 18. 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 |

TABLE 19. Life-Cycle Status Axis Classification.

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

FIGURE 12. Life-Cycle Axis Standards.

TABLE 20. Layer Axis Classification.

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

Considering that:

- Classification
  The Layer Axis Degree is classified according to the questionnaire result as represented on the table:

- Graphical Mapping
  The ideal graphic representation of the Layer Axis Questionnaire would be presented as:

3) EQUATION SYMBOLS
The symbols used on the equations are represented on the following table:

| Symbol | Description                                      |
|--------|--------------------------------------------------|
| n      | Number of Questionnaires                         |
| Q_HL   | Points from Hierarchy Level Axis Standards       |
| Q_CG   | Compliance Questionnaire                         |
| Q_LA   | Points from Layer Axis Standards                 |
| Q_LCS  | Points from Life-Cycle Status Axis Standards     |
| R_HL   | Hierarchy Level Axis Readiness                   |
| R_CG   | Common Ground Readiness                          |
| R_LA   | Layer Axis Readiness                             |
| R_LCS  | Life-Cycle Status Axis Readiness                 |
| O_A    | 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                    |

FIGURE 13. Layer Axis Standards.

TABLE 21. Equation symbols.

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

The 22 represents the summary of the total points obtained by the questionnaire application, grouped by each axis/sub-axis.

A. OVERALL READINESS
The 23 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.

The 14 graphically represents the overall result dispersion of the standards application between each Axis/Sub-Axis.

B. COMMON GROUND READINESS
The 24 represents points that are related to multiple axis/sub-axis obtained by the questionnaire application, which is
TABLE 22. 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      |

TABLE 23. Resulting overall classification.

| Questionnaire Points | Readiness Degree |
|----------------------|------------------|
| 27                   | Embryonic        |

FIGURE 14. Resulting standards application dispersion.

TABLE 24. Resulting Common Ground Classification.

| Questionnaire Points | Readiness Degree |
|----------------------|------------------|
| 22                   | Embryonic        |

TABLE 25. Resulting Hierarchy Level Classification.

| Questionnaire Points | Readiness Degree |
|----------------------|------------------|
| 16                   | Embryonic        |

TABLE 26. Resulting Life-Cycle Axis Classification.

| Questionnaire Points | Readiness Degree |
|----------------------|------------------|
| 5                    | Intermediate     |

FIGURE 15. Resulting Hierarchy Axis Standards.

TABLE 27. Resulting Layer Axis Classification.

| Questionnaire Points | Readiness Degree |
|----------------------|------------------|
| 6                    | Embryonic        |

D. LIFE-CYCLE STATUS AXIS READINESS

The 26 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.

E. LAYER AXIS READINESS

The 27 represents points that are related to the Layer Axis, obtained by the questionnaire application, and its readiness degree according to the proposed assessment method.

The 16 graphically represents the amount and dispersion of the standards application by the Life-Cycle Sub-Axis.

The 17 graphically represents the amount and dispersion of the standards application by the Layer Sub-Axis.

referred as the Common Ground Readiness, and its readiness degree according to the proposed assessment method.

C. HIERARCHY LEVEL AXIS READINESS

The 25 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.

The 15 graphically represents the amount and dispersion of the standards application by the Hierarchy Level Sub-Axis.
FIGURE 17. Resulting Layer Axis Standards.

V. 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 [65]. 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.

A. RESULTS DISCUSSION
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.

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 23.

Through the comparison of the optimal situation represented by 18 against the calculated result in 19 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.

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 24. Such standards comprehend broad applications and are concentrated in the Hierarchy Level, serving as a bedrock to the smart manufacturing.

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 25.

With the graphical representation in 15, 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.

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.
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 26.

The plot in the 16 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.

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) 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 27.

With the representation in 17 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.

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.

B. CONTRIBUTIONS
Regarding action taking based on the results, there is a clear benefit regarding the recognition of strengths and weaknesses (when compared to [34]) 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 [39]) is the precision from which each axis readiness can be individually observed and a plan strategized upon.
C. PRACTICAL IMPLICATIONS

The assessment application was considered very efficient by the involved staff from the plant where 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 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.

D. 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. In alignment with [66], the proposed assessment can be explored as a tool to define the road-map for each specific case of study, taken in considerations its particularities, objectives and limitations.

The practical results analysis demonstrated that several efficiency improvements can be done in different areas. Whether broadening the standards adoption in general, or even in specific areas, such as automation compliance, might define the strategies for enhancement, always aligned with the business needs.

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 experiment execution, there were no studies concentrated on the industry 4.0 readiness
assumption 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 et al. [29] 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 especially 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.

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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