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Research Article

Digital transformation in maintenance: interoperability-based adequacy aiming smart legacy systems

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Abstract

Paper aims: The Industry 4.0 movement highlights the importance of information and communication technologies and the two main reasons for this are advances in digitalization and automation. However, organizations trying to implement technologies face several barriers in their systems. These barriers are intensified in legacy systems, tightly coupled to organizational processes. Thus, to overcome these barriers, an adequacy strategy was structured, and detailed in the context of interoperability.

Originality: This article proposes a digital transformation framework focused on interoperability in maintenance systems.

Research method: Aiming to make legacy systems work together with cyber-physical systems, the proposed framework suggests its suitability based on strategic decisions, using Multicriteria Decision Making (MCDM) methods.

Main findings: The framework outputs demonstrate that people are the main drivers of digital transformation and that the strategies proposed by it are coherent with the actual development of both cases, proven in a new interview one year apart from its application.

Implications for theory and practice: Real industrial cases demonstrate that the framework can guarantee interoperability while facilitating strategic decisions to implement technologies in legacy maintenance systems. In the end, the legacy system, which will interoperate with the new technologies, is called Smart Legacy System.

Keywords

Industry 4.0. Legacy system. Interoperability. Maintenance system. Multicriteria decision making.

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1. Introduction

Companies pursuing higher quality and efficiency are incorporating Information and Communication Technologies (ICTs) into their processes and management systems. Among them are Cloud Computing, Big Data and Analytics (BDA), the Industrial Internet of Things (IIoT), and Artificial Intelligence (AI). Technology has always been a key driver of change in the industry, leading businesses to become increasingly digital and intelligent (Mahraz et al., 2019; Tedeschi et al., 2018; Vilarinho et al., 2017; Xu et al., 2018). Additionally, corporate decision-makers (DMs) look at these digital technologies as having a strategic role. This strategy, recently grounded in the Fourth Industrial Revolution, is based on the creative combination of technology and the market (Deloitte, 2019; Huawei, 2017; Lee et al., 2018; Mahraz et al., 2019; Mergel et al., 2019). Highlighting

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this scenario, the movement of Industry 4.0 (I4.0), or smart manufacturing (Liao et al., 2018), has encouraged organizations to upgrade their systems and processes through the implementation of ICTs. This movement is referred to as Digital Transformation (DT).

Legacy systems (Brooke & Ramage, 2001) are preferable to be digitally transformed, as they no longer meet the needs of the business environment. In comparison with cyber-physical systems, legacy systems are a piece of equipment natively lacking external communication capabilities (Tedeschi et al., 2018). The term “legacy” defines a device’s capability and not the age of the equipment (Pieper, 2011). However, these systems still play an important role in modern manufacturing. They are a core piece of hardware and/or software that continues to be used, while it is supplanted by more modern systems.

Yet, in manufacturing, the lack of adequacy of legacy systems leads to a lack of integration with new systems, processes, and business strategies. Further, integrating digital devices and platforms into existing legacy systems raises the issue of interoperability. Indeed, when updating existing systems, one may cause interoperability problems like incompatibilities between communication protocols, misalignment between information meaning, etc. Hence, as a result of such complexity, the formulation of an assertive DT strategy becomes a necessity (Weichhart et al., 2021).

Aiming at better performance, DT projects have enabled the application of new technologies in systems. Still, decisions regarding implementation are not simple. They involve criteria whose relationships are complex. A strategy should be defined in a way that legacy systems might still exchange useful information to ensure competitiveness (McKinsey & Company, 2018; Deloitte, 2018).

This present work tries to solve this problem by proposing a framework that allows organizations’ DMs to be able to define a strategy for legacy system adequacy. Interoperability is a concept that intertwines the problems perceived in such a scenario. Therefore, the framework focuses on answering conjointly—Q1: “Is it possible to adequate a legacy system or does it need to be replaced?”; and if the necessity to adequate overlaps the other, it becomes necessary to answer Q2: “What is the best strategy to adequate a maintenance legacy system when implementing I4.0 technologies to it?”. A legacy system not replaced but embedded with cyber-physical characteristics is presented here as a Smart Legacy System (SLS).

To answer these research questions, two multinationals were assessed. A legacy maintenance system was chosen in each organization, extending this work to a literature review on the most applicable I4.0-maintenance technological solution. The structure of the paper is as follows. The theoretical background, including the main concepts, is presented in Section 2. Section 3 elaborates and defines the proposed DT framework and the data gathered on the specificities of the maintenance systems. Then, the contribution is evaluated through two case studies in Section 4. Finally, Section 5 discusses the findings, and Section 6 concludes this work.

2. Theoretical background and related works

First, this section details legacy systems, as they are the artifacts to be improved if needed. Next, DT is presented as a scenario in which those systems are adequate. Then, Interoperability will be the bias adopted for building the framework. Finally, a SLS is described as the result of following the framework’s steps. Figure 1 illustrates these relations.

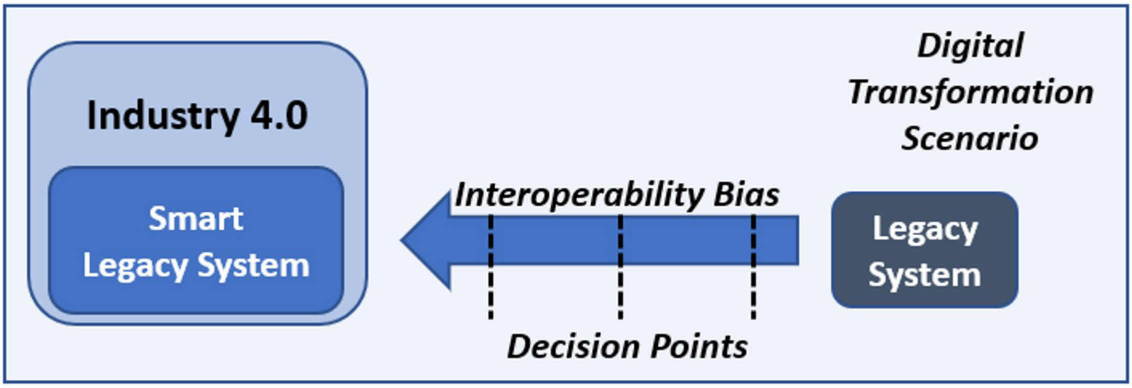

Figure 1. Research domain.

Regarding smart manufacturing, there are still many concrete results given by consultancy reports and whitepapers. Such consultancies have the manufacturing industry as a client, not only the object of study. In this sense, their data can provide a holistic overview of DT in manufacturing. As regarded by Bokrantz et al. (2017), the future of industrial decision support touches upon multiple aspects that are rarely encompassed holistically by any empirical scientific study. To better relate the present study to existing knowledge, it is relevant to consider both the artifacts in the literature and whitepapers.

2.1. Legacy systems

Legacy systems can be characterized as an organizational environment resisting modifications because it is business-critical. Conversely, they cannot provide data by a third-party application (Auvray, 2018; Johnson & Suhaib, 2009; Pieper, 2011). This leads to the lack of interoperability with I4.0 systems. Nevertheless, legacy systems are not strictly undesirable. Its data can provide valuable historical process insights, and many subsystems can depend on them (e.g., securing interconnectivity between a large range of devices that are long out of support) (Batlajery et al., 2014; European Union Agency for Cybersecurity, 2019; Liu et al., 1998). However, legacy systems cannot adequately consume I4.0 characteristics because of their inflexibility. In a smart industry, they do not support deterministic decision-making in stochastic environments and do not provide sufficient communication and exploitation of data for collaborative activities. This implies a loss of scale and lack of integration with ICTs, which could improve performance.

Indeed, addressing the communication between legacy and modern systems is a complex task. In this way, a literature review was performed under legacy systems references, highlighting traits such as (1) low IT integration, (2) high cost to maintain, (3) obsolete by the organization strategy, (4) monolithic, or hard to modify, (5) does not keep up with business changes, (6) lack communication capabilities, (7) its underlying process has changed, (8) heterogeneous—cannot exclude software from process tools, hardware, people, expertise, and data (Batlajery et al., 2014; Brooke & Ramage, 2001; Crotty & Horrocks, 2017; Kaiser et al., 2005; Maeda et al., 2017; Ramage, 2000; Ransom et al., 1998; Tedeschi et al., 2018). These traits are key to understanding how to overcome barriers in the attempt to modernize them.

2.2. Digital transformation

DT is mostly associated with the need to use new technologies to stay competitive in the Internet age. It is seen as a disruptive or incremental change process, entirely dedicated to the creation of value. Organizations are impacted technologically by social media, mobile, analytics, or embedded devices; organizationally by changing processes or creating new business models; and socially by enhancing customer experience and employee tooling (Stjepić et al., 2020). Regarding I4.0 as the state of the art, optimization investments are not always well embraced since many DT projects may only generate impactful income in the long run (Bokrantz et al., 2017; Ruschel et al., 2017).

To propose a reliable portrait of an assertive DT project, it is necessary to master perspectives that impact all business processes, support processes, and organizational design. Such perspectives can be defined as (i) the use of technology to radically improve performance or reach of enterprises, and the creation of new business opportunities through the use of digital data and technology; (ii) a way to rebuild business models following the needs of customers by using new technologies; and (iii) a phenomenon related to new consumer uses and unique objects that directly impact current business models and organizations (Boulton, 2019; CBI, 2017; Huawei, 2017; Mahraz et al., 2019; Morakanyane et al., 2017; Pini, 2019; Xu et al., 2018).

This study focuses on DT, the transformation of the whole process that grasps a legacy system: people, expertise, skills, hardware, data, and business processes. In this way, it is crucial to align the entire organization with a digital strategy. In addition, legacy system modernization and new technology must be proposed. This initiative can occur across its activities, from financial judgments to brand strategies, by making faster and more accurate decisions (Huawei, 2017; Mergel et al., 2019; Weichhart et al., 2021).

2.3. System interoperability in Industry 4.0

This research highlights the importance of interoperability in the I4.0 context. It is argued that interoperability concepts are closely related to I4.0, as systems need to communicate quickly and in a high level of flexibility to reach smart (sometimes predictive) responses toward their organization's processes.

Interoperability is frequently defined as the ability of two or more systems to exchange information, understand, and use the exchanged information (IEEE 90). It was mainly a technical issue to be addressed when coupling multiple systems. Later on, until nowadays, other perspectives of interoperability are proposed. Research and practitioner work has begun to explore aspects such as conceptual and organizational (Panetto et al., 2016; Vernadat, 2010). Indeed, frameworks such as the European Interoperability Framework (EIF) (Han et al., 2017) and the Framework for Enterprise Interoperability (FEI) (Chen et al., 2007) and (Chen & Daclin, 2006), and ISO 11358 2011 describe in detail the interoperability aspects and main barriers to effective interoperability.

The studies here support the concept of interoperability based on the FEI (ISO 11358 2011) defined in the INTEROP Network of Excellence (INTEROP NoE) project. Furthermore, the research work proposed by Naudet et al. (2010) and Silva Serapião Leal et al. (2019) were also considered as they provide ontologies (i.e., formal knowledge representation) for describing the domains of enterprise interoperability and interoperability assessment.

Objectifying the adequacy of legacy systems to Industry 4.0, analyses due to interoperability can provide guidelines. The layers described in FEI are easily contextualized with the architecture layers from the Reference Architectural Model Industrie 4.0 (RAMI 4.0) (Plattform Industrie 4.0, 2015). The RAMI 4.0 model describes the enterprise layers from I4.0 as business, functional, informational, communication, integration, and asset. A semantic analysis of these two frameworks suggests that the first four layers described in RAMI 4.0 can be related to the FEI model. Figure 2 represents this relationship.

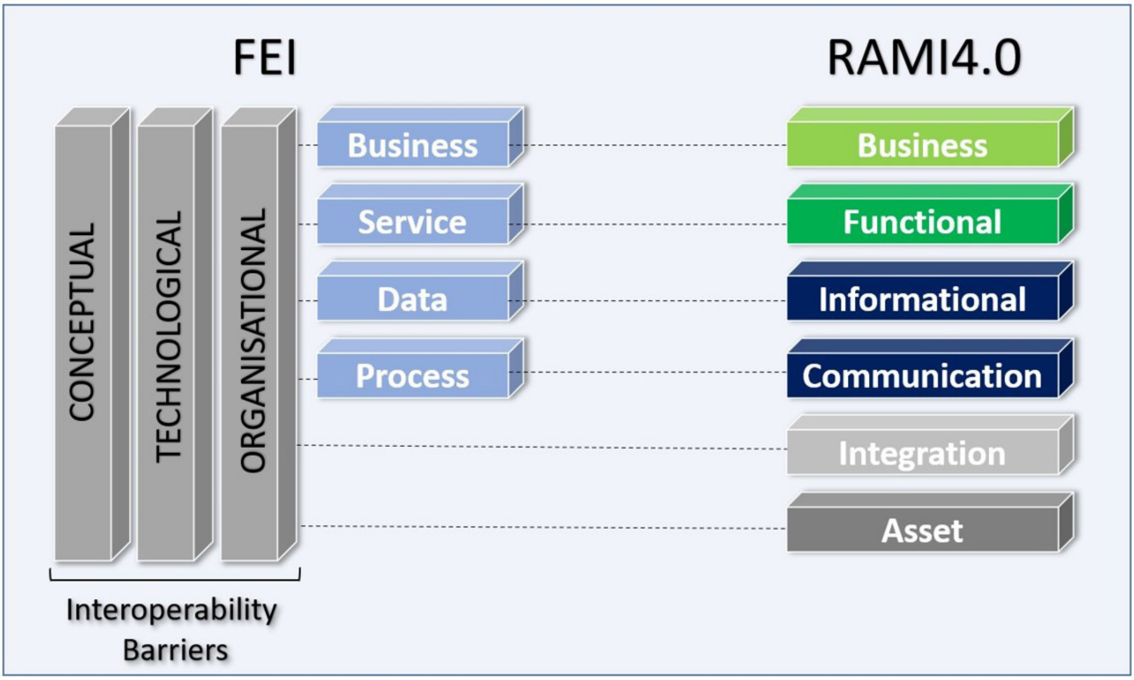

Figure 2. FEI and RAMI4.0 relationship.

Interoperability barriers represent incompatibilities that obstruct the sharing of information and prevent exchanging services; developing interoperability means developing knowledge and solutions to remove the incompatibilities (Chen & Daclin, 2006; Ullberg et al., 2009). Interoperability assessments can be performed to identify the existing and potential barriers. They can help identify the root causes of interoperability barriers and identify potential solutions (Silva Serapião Leal et al., 2019).

2.4. Smart legacy systems

From the architecture and organizational structure to products, services, business models, customers, and suppliers, Industry 4.0 is about companies integrating ICTs horizontally and vertically, and consequently, modifying their manufacturing systems. Therefore, DT involves the use of digital capabilities and technologies to impact different aspects of an organization to create value (Interactive and Reserved, 2018; Liere-Netheler et al., 2018; Morakanyane et al., 2017).

With this impact in mind, the present proposal states that an intelligent way to approach DT in manufacturing is by gradually embedding digital capabilities into legacy systems. They are by trait a key to organizations' business goals, although, in most cases, they cannot be changed drastically. This transformation will, most of the time, require a complex reengineering/adaptation action, digitalizing systems' local information into relevant and accessible data. For this adaptation, the term Smart Legacy System was presented in a previous paper (Ramos et al., 2020, p. 4). There, it is understood that:

> Legacy systems lack on some technological-capabilities level, but because they are important to the organization business, I4.0 capabilities (i.e., empower by ICTs) must be embedded on them. In that way, they can be called smart legacy systems, enabling them to be more digitally interoperable, facilitating the synergy towards the processes in which they participate.

2.5. Decision-making methods

An MCDM approach can be suitable for solving complex problems, such as system selection or technology implementation. This approach can be developed using a set of different methods. They allow the aggregation and consideration of numerous (often conflicting) criteria in order to choose, rank, sort, or describe a set of alternatives to aid a decision process (Roghanian & Alipour, 2014). There is no single method considered the most suitable for all types of decision-making situations, and it has also been acknowledged that several methods can be potentially valid for a particular decision-making situation (Kabir & Sumi, 2014; Di Matteo et al., 2016). This is the case for the DT framework presented. Since it deals with critical decisions considering an overall strategy, we propose a set of three different methods, one for each of the three framework steps.

Different criteria must be considered along with the interest of a group of experts or DMs (Hashemi et al., 2018). For assertive decision support, the present work focuses on the definition of appropriate criteria from (Keeney & Gregory, 2004). Such work approaches the problem of poor criteria choice, presenting both theory and guidelines for identifying five appropriate attributes. Moreover, all criteria for each step in this work were characterized using a subjective measure scale (Jahedi & Méndez, 2014) declared that subjective measures can be classified as specific and general subjective measures. Specific-subjective measures are derived from survey questions that ask about well-defined concepts that can be observed in principle. General-subjective measures are derived from questions that ask about broad concepts such as the level of interoperability barriers. The proposed framework's decision models are built with general subjective measures, understanding that they can effectively capture changes in both the explicit and implicit components of the variable being measured.

2.5.1. Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) developed by Saaty in 1977 (Saaty, 1987) as a multi-attribute decision support tool uses a multilevel hierarchical structure of objectives, criteria, sub-criteria, and alternatives. A flexible method, AHP, uses a hierarchical structure to present a complex decision problem by decomposing it into several smaller subproblems.

It is generally implemented in four stages: (1) decomposition of a decision problem and construction of a hierarchical model of criteria and decision variants affecting the solution of the problem; (2) pairwise comparison of the criteria (9 points scale), and generating the vector of weights for individual criteria; (3) pairwise comparison of decision variants to individual criteria, and generating the local weight vectors for those variants concerning those criteria; and (4) determination of the vector of global preferences of decision variants, arranged in relation to the contribution of variants in achieving the objective of the ultimate decision problem (Gudienė et al., 2014; Di Matteo et al., 2016; Vinodh et al., 2014). Readers interested in a more detailed description of the mathematical foundations and calculations used in the method in question can be found in the references (Podgórski, 2015; Zentes et al., 2011).

2.5.2. ELECTRE TRI

An outranking method, Elimination and Choice Expressing Reality (ELECTRE) was created by Roy (1968). The ELECTRE methods evolved over several versions: I, II, III, IV, IS, and TRI (Alencar et al., 2010). The ELECTRE TRI version used in the present work is a sorting multicriteria method designed to assign a set of actions, objects, or items to categories (i.e., this method allocates alternatives to predetermined categories). Such categorization may be proposed by a pessimistic (e.g., indicated for situations in which caution is required or there is a scarcity of resources) and optimistic (e.g., indicated for cases where it wants to encourage actions that have particularly attractive or exceptional qualities) interpretation of comparisons (Fontana & Cavalcante, 2013; Hashemi et al., 2018; Di Matteo et al., 2016).

Analysts using this method must determine the values of various parameters (the profiles that define the boundaries between categories, weights, and thresholds), which are used to construct a model from the DM preference (Trojan & Morais, 2012).

2.5.3. PROMETHEE II

Preference Ranking Organization Method of Enrichment Evaluation (PROMETHEE) was developed by Brans & Brans in 1982 and further extended in Brans & Mareschal (2005). It belongs to the methods of partial aggregation, also called outranking methods. One of the outranking methods, it closely coincides with the human perspective and determines the preferences among multiple decisions. Several versions of the PROMETHEE method have been developed, such as PROMETHEE I (partial ranking), in which the preference structure for each criterion is based on pairwise comparisons, where these preferences may vary between 0 and 1; PROMETHEE II (complete ranking), which shows a complete ranking of the alternatives; and others, outside the scope of the present work (Kabir & Sumi, 2014; Santos et al., 2017; Temiz & Calis, 2017).

The framework's final step deals with the technologies that best suit a legacy system's needs, and several criteria have to be considered in this selection process. Therefore, PROMETHEE II is suitable for this concept selection. The mathematical model in PROMETHEE is relatively easy for DMs to understand. Hence, the criteria are pairwise compared according to the DMs' preferences to generate local scores. These local scores are then aggregated to a global score, which leads to the PROMETHEE I or II ranking (Roghanian & Alipour, 2014; Temiz & Calis, 2017).

3. Digital transformation framework

The proposed three-step DT framework was conceived to answer two distinct research questions: Q1 and Q2. The first question is answered by the framework's Step 1 analysis concerning the feasibility of a legacy system to be optimized. The second question regards steps 2 and 3, concerning which functions should be optimized first, and which I4.0 technology may better suit such functions. In this work, legacy systems were analyzed in the context of maintenance. Thus, Step 2 addresses the specificities of the maintenance system functions. Finally, Step 3 depends on the outputs from the previous step, suggesting suitable technologies. A legacy system adequate to operate along with cyber-physical systems will achieve the status of the SLS.

The three-step analysis is characterized by a 4.0 DT – Feasibility, Classification and Implementation (4.0DTFCI) framework, due to the key decision points it supports. It is represented by Figure 3 on an Integration Definition for Function Modeling (IDEF0) process view (Presley & Liles, 2015).

Each step represented in Figure 3 is detailed in the next subsections.

3.1. Feasibility to upgrade (step 1)

To better understand and validate different outcomes for a legacy system, Step 1 encompasses the combination of two diagnostic techniques presented in the references (Cimitile et al., 2001; Ransom et al., 1998). The combination of these references suggests whether legacy systems can (i) be replaced by other modern systems, (ii) if they should be ordinarily maintained, (iii) or if they are less (iv) or more capable of undergoing re-engineering. The AHP method was used to answer research question Q1, ensuring if it is feasible to digitally transform a legacy system. Specifically, it is used to analyze which action is the most feasible to be executed regarding two essential forces: technical importance and business value. Figure 4 illustrates this concept.

Technical Importance (TI) represents the system's accessibility by other adjacent systems. A high TI suggests that stopping the system may harm processes, as it is strongly coupled with other systems. Quadrant 1 indicates that the system can be replaced without many issues. Quadrant 2 indicates that the system is strongly coupled with others and economically does not justify optimization.

The other force that impacts the legacy system's outcome analysis is the Business Value (BV). Quadrant 3 represents the system prone to upgrade, but in a cautious execution, as it is strongly coupled with other

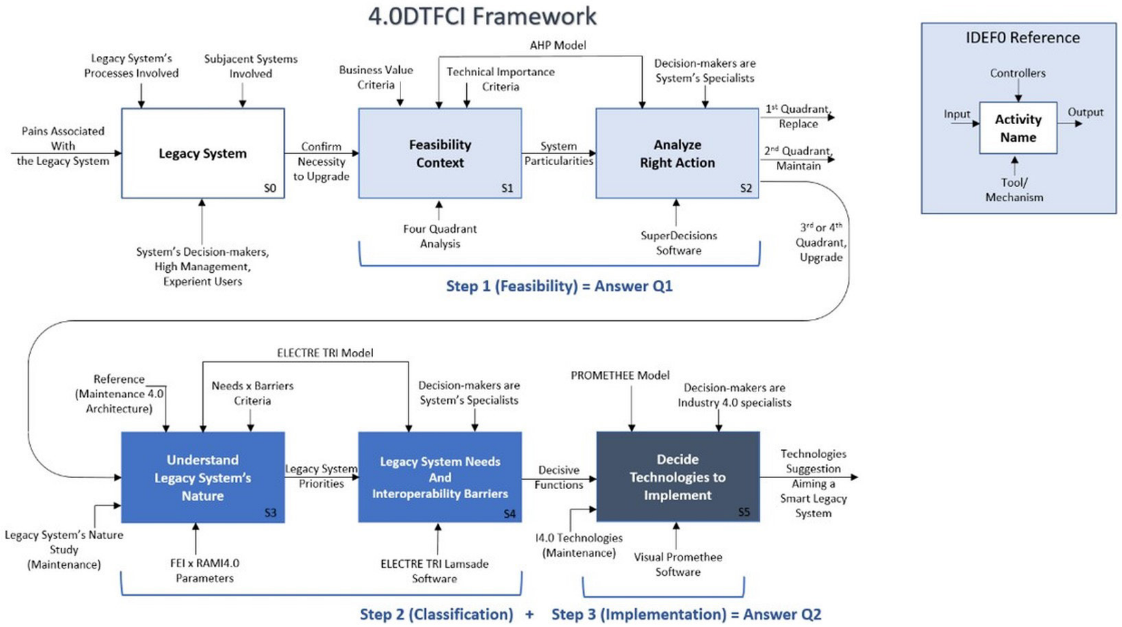

Figure 3. 4.0DTFCI Framework.

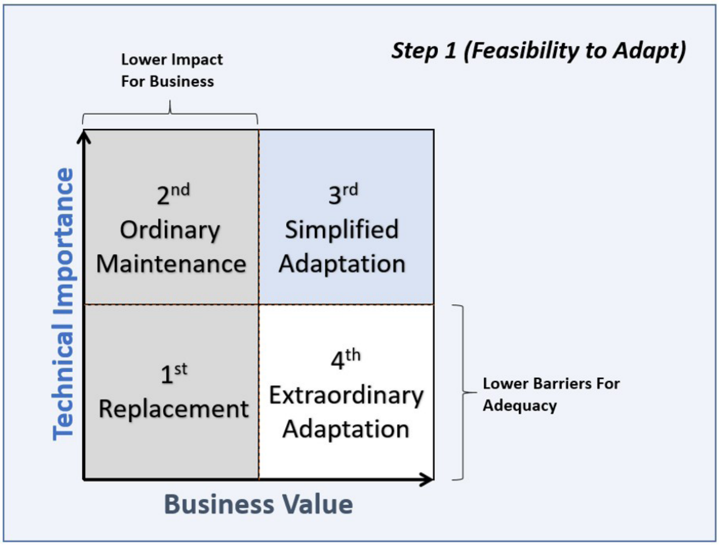

Figure 4. Legacy system's outcomes.

systems. Thus, the optimal outcome is quadrant 4, because BV is high and TI is low. Meaning, the legacy system could receive a more complex change without presenting many technical issues, while it is also business-critical. The AHP model used for this analysis is shown in Figure 5.

In summary, if the AHP method points out quadrants 3 or 4, it means that the legacy system is prone to becoming an SLS. This is a necessary condition for the framework to continue its steps.

3.2. Classifying decisive functions (step 2)

Now, the ELECTRE TRI method is applied, which highlights the most decisive functionalities of the legacy system. Thus, this decision point demands comprehension of the legacy system's nature (e.g., warehouse, quality,

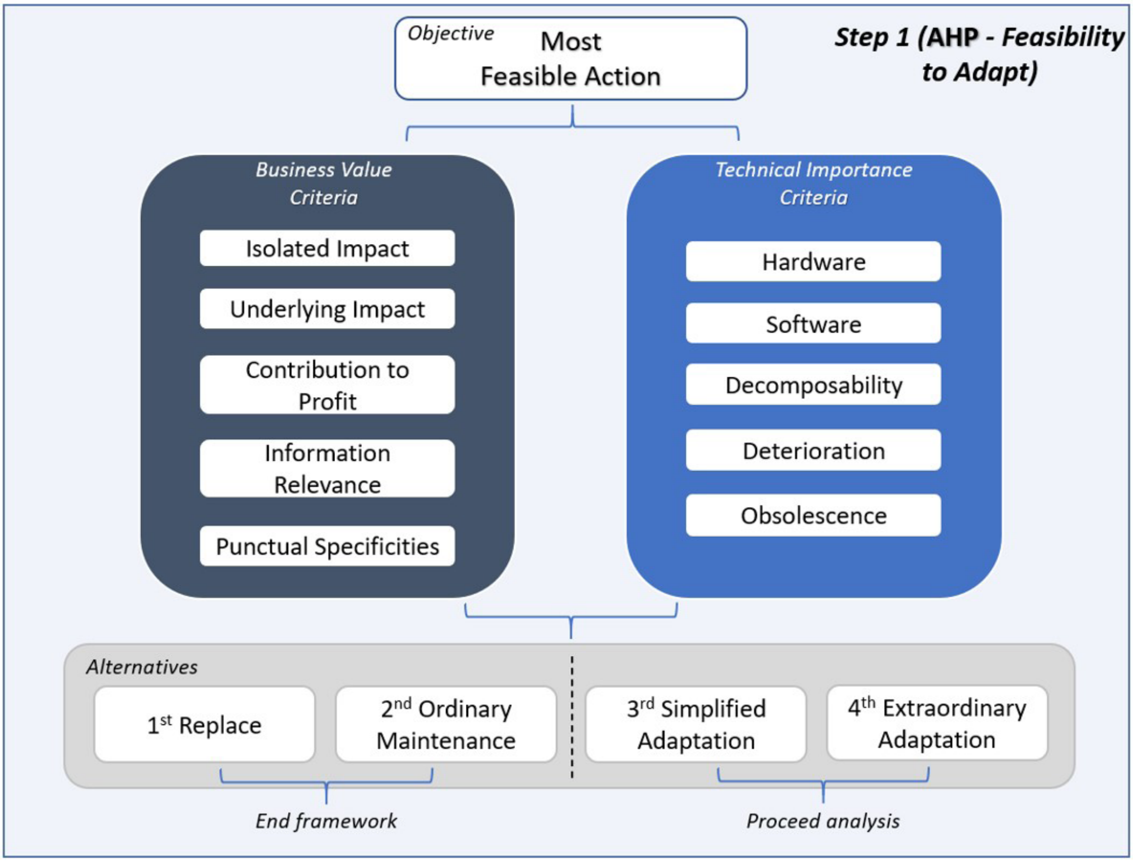

Figure 5. AHP Model for the Step 1 Analysis.

supply chain, etc.). The present work focuses on legacy systems in the context of maintenance. Therefore, a referential Maintenance 4.0 architecture, presented in Section 3.2.1, contextualizes maintenance systems in I4.0.

Under the referential architecture, 32 functions would be essential for a maintenance system to operate in a fully I4.0 environment. Nevertheless, to achieve an SLS status, the strategy is to implement only decisive functions. This is because companies' budgets do not always cover expenses to implement all functions simultaneously. Therefore, decisive functions comprehend the best-classified ones using two distinct sets of criteria:

i) System's needs: Expresses what is wanted to be implemented in the legacy system (i.e., criteria to be maximized).

ii) Interoperability barriers: Expresses what can be implemented in the legacy system (i.e., criteria to be minimized).

A forced implementation of many functionalities could impair the performance of the system, generating interoperability incompatibilities, a paradigm in which "not everything wanted to implement is possible." Figure 6 illustrates the decision model.

The system's needs criteria focus on trying to reach the I4.0 performance; meanwhile, interoperability barriers criteria intend to limit what can be done. At the end of this step, the decisive 4.0-functions are understood to be implemented in legacy systems. The next step proposes the I4.0 technologies to achieve these functions. Although, before that, it is important to understand the origin of referential architecture.

3.2.1. Maintenance-4.0 architecture

According to Lopes et al. (2016), industrial maintenance has been recognized as a function with a significant impact on the global results of industrial companies and whose efficiency usually has a high potential for improvement. Maintenance is currently seen as a complex management process that combines several factors, such as production, quality, environment, risk analysis, and safety. According to Sipsas et al. (2016), insufficient

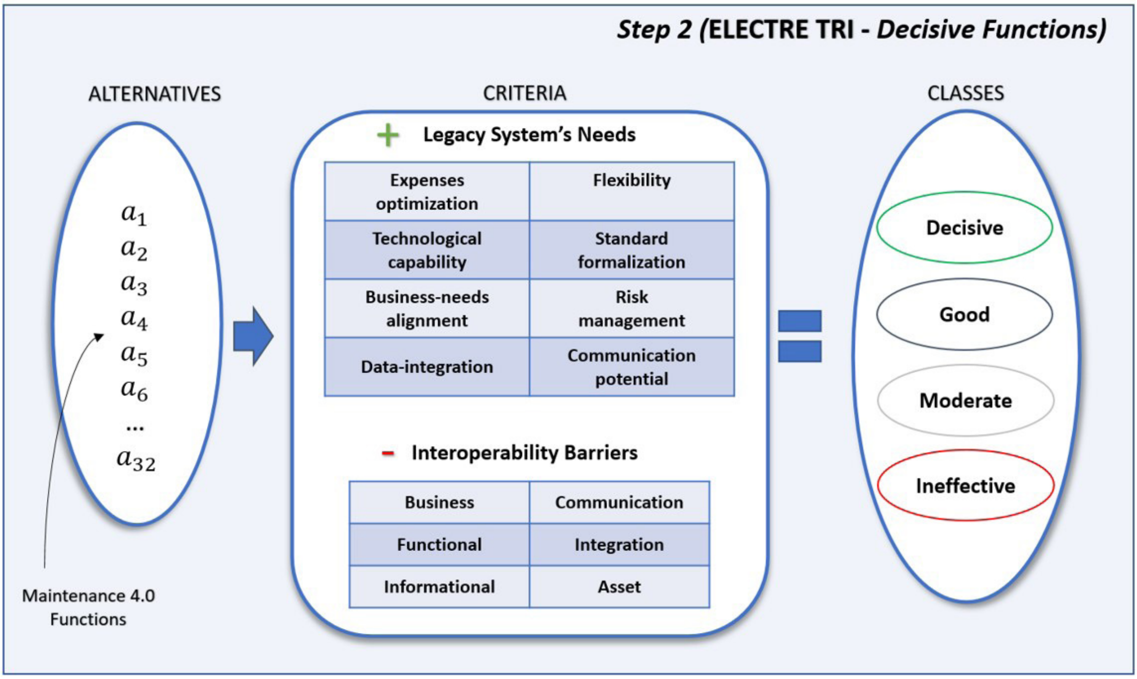

Figure 6. ELECTRE TRI model for the Step 2 Analysis.

maintenance affects both the performance of the production process and the quality of the finished product. An appropriate maintenance strategy not only reduces the likelihood of equipment failure but also improves the working condition of the assets, resulting in lower maintenance costs and/or higher product quality (Vaisnys et al., 2006).

Various concepts have been developed to increase maintenance effectiveness. One of the most commonly used concepts in organizations around the world is Total Productive Maintenance (TPM). The TPM emphasizes proactive and preventive maintenance to maximize the operational efficiency of the equipment.

Production losses, together with indirect and hidden costs, make up the bulk of the total production cost (Kodali et al., 2009; Vaisnys et al., 2006). Overall Equipment Effectiveness (OEE) is a metric that identifies the percentage of planned production time that is truly productive. It was developed to support TPM initiatives, accurately tracking progress towards achieving “perfect production” The use of OEE can be seen as an attempt to reveal hidden costs of production (Vaisnys et al., 2006). The OEE loss of availability, loss of performance, and loss of quality can be subdivided into what is commonly called Six Big Losses, the most common causes of lost productivity in manufacturing.

The product of this maintenance study under the I4.0 context was an architecture based on the six major losses, as shown in Figure 7. Thus, for the modeling architecture, a digital asset management platform was used. As a commercially validated source, such a platform is reliable for defining applications. With operations in more than 10 countries and more than 15 years of know-how in the maintenance area, today, it serves as a guide for defining maintenance applications in various organizations around the world. As the scientific literature may bring broad conceptualization to practical maintenance applications, considering that they vary widely from study to study, this platform was chosen as a tool to define the structure of the study.

It is possible that a fully Maintenance-4.0 system enhances the possibility of achieving zero waste in manufacturing operations, which can be accomplished by the functions addressed in this architecture. As the application of maintenance functions varies, depending on the strategy adopted by the organization, it is difficult to build an adequate generic model. One way out of this problem may be to customize this level of the model depending on the organization interested in the implementation.

The 32 functions presented below are divided into six courses of action, in the sense that they intend to overcome large TPM losses. Their application is based on Industry 4.0 technologies and concerns the means of being able to apply some maintenance techniques, depending on the company in question. Both courses of action and their functions are presented as follows:

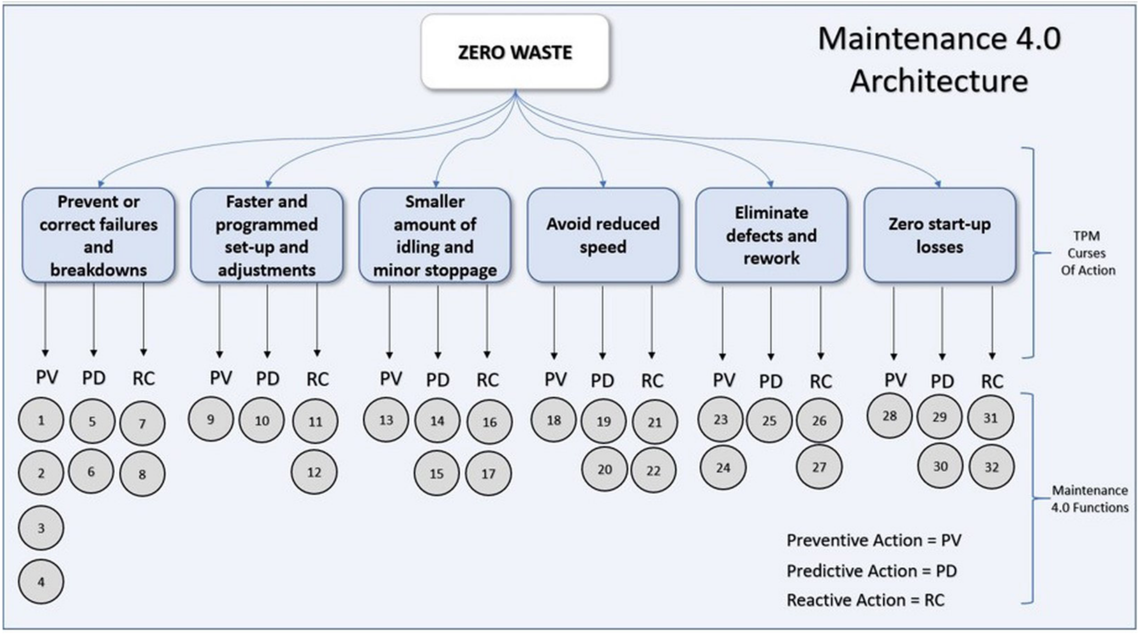

Figure 7. Maintenance 4.0 Architecture.

- Prevent or correct failures and breakdowns – (f1) Equipment upgrade to prevent failures; (f2) Improvement due to education and training; (f3) Preventive decision making to prevent failures and breakdowns; (f4) Inspection routine to prevent or correct failures; (f5) Predictive maintenance due to predictive plan; (f6) Predictive decision making to prevent failures and breakdowns; (f7) Corrective maintenance to correct failures due to service execution; (f8) Corrective decision making to correct failures due to analysis;
- Faster and programmed set-up and adjustments – (f9) Preventive decision making due to schedule; (f10) Predictive decision making due to setting time; (f11) Corrective adjustment due to a faster and programmed set-up; (f12) Corrective decision making to a faster set-up due to analysis;
- Smaller amounts of idling and minor stoppages – (f13) Preventive decision making for smaller amounts of idling; (f14) Machine-to-machine communication due to report management; (f15) Predictive decision making to a smaller amount of idling; (f16) Corrective maintenance to reduce stoppage service; (f17) Corrective decision making to a smaller amount of idling due to analysis;
- Avoid reduced speed – (f18) Preventive decision making to avoid speed reduction due to KPIs; (f19) Facility alignment to avoid speed reduction; (f20) Predictive decision making to avoid reduced speed; (f21) Corrective maintenance to avoid speed reduction due to service execution; (f22) Corrective decision making to avoid reduced speed due to analysis;
- Eliminate defects and rework – (f23) Cost optimization to eliminate defects and rework; (f24) Preventive decision making to eliminate rework; (f25) Predictive decision making due to quality monitoring to eliminate defects; (f26) Corrective maintenance to eliminate rework; (f27) Corrective decision making to eliminate defects due to analysis;
- Zero start-up losses – (f28) Preventive decision-making to reduce start-up losses due to system integration; (f29) Startup planning to zero losses due to validation test; (f30) Predictive decision making to zero start-up losses due to acquired data; (f31) Corrective maintenance to reduce start-up losses; (f32) Corrective decision making to zero start-up losses due to analysis.

3.3. Implementation analysis (step 3)

The next step proposes suitable technologies to implement the previously validated decisive functions. In conclusion, Step 3 works as a technology implementation strategy. To this end, the PROMETHEE II method was applied. Ultimately, the system upgraded with the suggested I4.0 technologies can be called an SLS. Figure 8 demonstrates this decision model.

This model uses the decisive functions from Step 2 as inputs (Figure 8). Now, the functions are criteria to be chosen between technologies that better suit the system analyzed. In this way, a partial-literature review of I4.0 technologies used in maintenance was conducted to identify the most suitable ones.

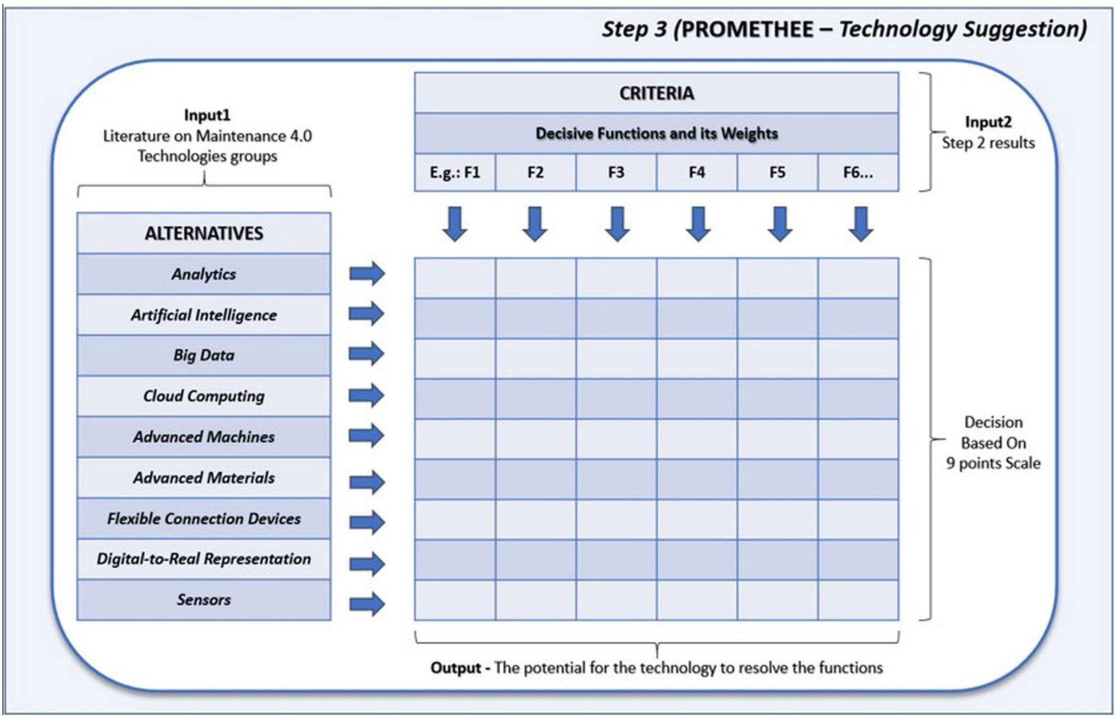

Figure 8. PROMETHEE II model for the Step 3 Analysis.

3.3.1. Maintenance 4.0 technologies

Such review was conducted under three research rounds:

i) The first round focused on professional technology consulting groups' white papers. The premise was that they were ahead of I.40 technology application research;

ii) A second-round review was executed, focusing on understanding which technologies were most commonly used in maintenance. This was done by crossing the first findings with the academic papers;

iii) Finally, the third round of research was conducted, considering papers dated from 2010 and before. This was done to better understand how some of the technologies were already being used in industrial maintenance before the concept of Industry 4.0 was born.

The Maintenance-4.0 technologies groups that will be suggested as alternatives for Step 3 are analytics, AI, big data, cloud computing, advanced machines, advanced materials, flexible connection devices, digital-to-Real representation, and sensors. Some of the main references are found in works such as (Biahmou et al., 2016; Colombo et al., 2017; Knoll et al., 2016; McKinsey & Company, 2015; Mourtzis et al., 2016; OMRON, 2018; Qin et al., 2016; Romero & Vernadat, 2016; Rosendahl et al., 2015; Vallhagen et al., 2017; Zaman et al., 2017).

4. Application cases

Two different legacy systems served to test the framework, each from a particular manufacturing company, proposed by engineers that utilize them in their daily routines (one from each case). These engineers acted as DMs to their respective cases. In this way, case study C1 describes a multinational automotive industry, specifically, a manufacturing complex in the southern region of Brazil. It is separated into three factories: motors, utility vehicles, and passenger vehicles; the last being the location of the case study, regarding its maintenance area responsible for welding robots. Their function is to assemble the sides and bottoms of cars. Case C2 refers to a multinational industry with operations spread across business sectors, such as mobility, consumer goods, industrial technology, energy, and building technology. The factory in question is located in the Hunan province, China. This case proposes a checkup maintenance process for workstation assembly and testing, required by the company's customers and also itself, as a client in its manufacturing operations.

The tools used to develop the three-step decision analysis were free MCDM modeling and analysis software: Superdecision for the AHP in Step 1, Lamsade for the ELECTRE TRI in Step 2, and Visual PROMETHEE for PROMETHEE II in Step 3. Microsoft Excel was used to create the model for Step 2, facilitating the DMs' interaction with the analysis. It was also used to build the Mudge decision diagram, a matrixial subprocess needed to weigh the Step 2 criteria (Schuster et al., 2014).

Regarding the assessments made, each case was analyzed in about three hours, where Step 1 and Step 2 took an average of one hour each, plus one hour for the assessment introduction. Step 1 was applied directly to the Superdecision software. For Step 2, the input for the ELECTRE TRI method was via the Excel model. Subsequently, in each case, extra time was used to transport the Step 2 data from the model to the software. Then, the results (most decisive function weights) were imputed in the Visual Promethee for Step 3. Contrary to Step 1 and Step 2, this final analysis was made by the authors (in the role of DMs), not the engineers. The motive is that Step 3 serves as a technology implementation strategy; therefore, the engineers did not have the knowledge based on I4.0 maintenance technologies. The analysis duration was approximately 4 h.

4.1. Cases overview

Automobile manufacturer (C1): This case describes welding robots. Robots are part of a process that assembles the side and bottom of the soldering points of cars. When the electrode is worn (200–300 operations), it performs preventive maintenance autonomously. The process is performed by milling the tip of an electrode, allowing the robot to continue pinching its points. This is done so that there is no wear of the tool, which causes damage to the car. There is no human interaction in the production line, except when it stops for corrective measures. This can occur when there is a problem with the automatic exchange of electrodes or when there is premature wear of the tool, which can cause damage to the car, and must be monitored by quality personnel. For this system, it is important to predict the failure, as the stoppage for corrective maintenance on the machines directly affects the line, which must also be stopped.

Multisector manufacturer (C2): A workstation assembly process and its testing system are proposed in this case. It consists of the following specific actions: building the assembly line composed of workstations and machines, and testing and fixing its errors. The engineer states that it is expected that at least one machine will not function properly in the first setup. What characterizes this as a maintenance system is the debugging and monitoring of the stations. Once assembled, even following the proper parameters, it is expected that the stations will present errors. Therefore, multifunctional specialists must be present, both for hardware (workstation) and software (testing system) correction of the delivered stations. The initial interest in this line is that the assembly is correct in its first debug or the closest to it.

4.2. Step1 - Feasibility to upgrade

Both cases C1 and C2 were validated by their engineers, as in the 3rd quadrant for the AHP Step 1 analysis, represented as a necessary condition to proceed with the next steps. It also presents the understanding that these systems are key strategically; however, they cannot suffer drastic changes at once, that is, high both in business value and technical importance. In addition, because both case studies were pointed for a simplified adaptation, it becomes evident that world-class organizations, which already have a strong defined culture and consolidated process standards, encounter various barriers to changing their legacy systems drastically.

In C1, it was perceived as an unsustainable deterioration problem because the organization keeps its robots; in the meantime, it also reworks its system's code. This externalizes a legacy characteristic, which expresses the aging of a system as a result of continuous changes. This aging of code brings some incompatibilities to implementing new technologies, while also consuming its hardware memory. In addition, the robots' error reports are transmitted to the external computer for checking. The system behind this process is characterized as a legacy, as it lacks output for monitoring the robot's health. A priori analysis indicated that improving it could minimize human time to corrective measures.

The analysis in C2 suggested that, although the parameterization of workstations and their arrangements may differ, the process always uses new hardware. Therefore, the legacy characteristic is in its software system and the way the processes around it are being executed. While the analysis proceeded, it was stated by the DM that the maintainers neglected some peculiarities necessary to install the machines in characteristic scenarios. Although the parts used to assemble the stations and their machines are new, the maintenance software system is considered legacy because of its obsolete test processes. Historically, it has failed to treat different sets of errors, drastically affecting the speed at which the stations are delivered. In the first conclusion, displaying the errors with history feedback and digitally assisting operations could benefit the assembly process.

4.3. Step2 – Classification of decisive functions

Before applying the ELECTRE TRI method, in both cases, a weighting procedure was carried out (Mudge diagram) to highlight the DM preferences between criteria in Step 2. While the set of criteria 1, the system's needs, focuses on peculiarities of the maintenance system analyzed, criteria set 2 intends to limit what can be done due to interoperability perspectives. In synthesis, the output of this step corresponds to analyzing 14 criteria (eight legacy system needs and six interoperability barriers) with 32 Maintenance-4.0 ideal functions from the referential architecture.

From C1, during the DM's comparisons, it was noticed that the criterion "Expenses optimization" was shown to be inverse to the criterion "Business interoperability barrier." In other words, when a company decides to optimize its expenses by accepting and encouraging simpler and cheaper solutions, many interoperability barriers are not encountered by the organization's management layer. In addition, criteria that are preoccupied with start-up losses from the machine setup do not need to be considered in the opinion of the engineer. This is because, by default, the system should already be set up at the beginning of a new shift. The maintenance 4.0 functions which were considered decisive for implementation were: (f3), (f5), (f6), (f12), (f14), (f16), (f17), and (f21).

The evaluation of C2 showed that the DM considering high scores for some of the functions regarding the legacy system's needs also scored high on its barriers, canceling out those functions that were thought interesting to have. Interoperability barriers at the communication layer were highly scored, highlighting the lack of the following communication protocols by the assembly operators. In the DM's view, maintainers neglect to perform tasks regarding the new machinery, committing mistakes due to electrical, mechanical, and testing planning. Some of these machines have specific standards, but many maintainers assemble all those machines following the legacy protocol, without considering the new hardware scenario. The functions chosen to be implemented are (f21), (f23), (f24), (f25), (f26), (f27), (f28), (f30), (f31), and (f32).

4.4. Step3 – Technologies implementation proposal

Since a specialist view is required for this suggestion, the authors played the role of DMs due to the literature review on the application of I4.0 technologies in maintenance. This is not detrimental to the analysis, in the sense that if engineers had the knowledge bases of the maintenance technologies review, they could also be part of the analysis. Furthermore, the engineers validated the final analysis, as described in Section 5. Step 3 highly depends on the previous, as the preferred functions are input as criteria. Now, the PROMETHEE II analysis will evaluate technologies based on intensity, how much a technology group impacts the decisive functions and quantity, or how many functions a technology can impact.

An analysis from C1 shows that the presented legacy system could be upgraded first, aiming for better analytics technologies. Dedicated displays on the factory floor and tablets (part of the analysts' tools) using the maintenance system database linked with business intelligence tools, already in the company budget, could be implemented without many interoperability barriers. To retrieve the necessary data, sensors can also be implemented (e.g., directly to the robots). Further, if this analysis and real-time data could be delivered to the maintainers, corrective actions would be performed faster and even guided. To sustain the connection of these technologies, a reevaluation of the factory's wireless on the shop floor is recommended.

Regarding C2, because the system uses new parts to assemble its workstations, it does not require advanced machine technologies. Advanced materials are not used for workstation assembling/testing. Using the engineer's insights from the previous step, solutions based on technologies that could provide guidelines for the new hardware setup could be an efficient measure. For this purpose, the setup could be delivered online to the assembly staff. In addition, data from different assembly scenarios could be sorted and analyzed, providing machinery setup insights, without having to rely solely on the maintainer's decisions. Not as a priority but Analytic, A.I. and guided devices could support decisions further, helping maintainers that tend to assemble the workstations modules without considering specificities.

Table 1 shows the result rank and a comparison of Maintenance-4.0 technologies that better support both legacy systems to achieve smart capabilities, adhering to I4.0.

Section 5 presents the results commented by engineers from both companies, as well as feedback, one year apart from the proposed solutions. Although the engineer did not have the authority to formalize the suggested strategies, optimizations made in C1 were very similar to the framework proposal. The C2 engineer discussed more scenarios in which the proposed framework analysis could also be relevant.

Table 1. Maintenance-4.0 technologies suggestion.

Case 1	Rank	Case 2
Analytics	1	Big Data
Sensors	2	Cloud Computing
Flexible Connection Devices	3	Analytics
Big Data	4	A.I.
Cloud Computing	5	Digital-to-Real Representation
Digital-to-Real Representation	6	Flexible Connection Devices
A.I.	7	Sensors
Advanced Machines	8	Advanced Machines
Advanced Materials	9	Advanced Materials

5. Discussions and limitations

This research is an adaptation of our previous work (Venâncio et al., 2022). It was a new proposed methodology which combined the evaluation of system maturity and giving decision guidelines to implement technology. The present research brings an element of characterizing if the system is ready or not to be digitally transformed, instead of measuring its maturity. The premise is that it is more feasible to understand if the system is prone to receive digital transformation, in Step 1, letting the next steps present the level of implementation to be received.

Both cases have a considerable part of their systems and processes, depending on human interaction. Their outputs are not digitalized enough to provide reactivity, in C1 to monitor the health of the robots and their tools, and in C2 to set up the assembly line. The solutions suggested should highlight the idea that DT primarily depends on the workforce. In addition, although it would be ideal to fully digitalize the systems, this could not be done without the high cost and technical complexity. Thus, following the premise of the adequacy of legacy systems to become an SLS, the solutions need to be implemented gradually. The framework conducted both systems to a more autonomous execution of their tasks, minimally affecting their processes while optimizing their users' work. Further, if any of the technologies proposed could not beneficiate the workforce by any means, there would be no success regarding the framework's suggestion.

The technologies pointed out by the output in Step 3 were validated by each respective engineer. In relation to the analysis in C1, the engineer stated that there was no specification in the robot alarms regarding the type of failure. Once the framework's suggestion of analytics technologies could be implemented, aiming for better recognition of errors, the reactivity to corrective failures could be faster. Sensors were also validated, as many aspects of the machines are not directly connected to the maintenance system, so they could provide new data to monitor the robots' health. This concept is closely related to the idea of digital twin and cyber-physical systems, where all aspects of the machine can be perceived in real-time.

In relation to C2, the engineer stated that the solution was viable. The workers in charge of assembling the machines in the line already had notebooks to access. In this way, big data and analytics (Table 1, suggestions 1 and 3) were welcome if implemented to generate insightful information about past assembling mistakes and good practices. For the software development of the stations, the Cloud Computing solution is feasible since the program for each may vary, and remote assistance could be an advantage. At the end of the suggestion, the C1 engineer contacted its manufacturing managers to understand the possibility of the suggested technologies. The C2 engineer validated these necessities with the manufacturing teams.

A year after the feedback, the engineers were reinterviewed. In C1, the engineer explained how the adaptations asserted by the manufacturing project teams were very similar to the ones presented by the framework.

The engineer stated that every robot received a screen accessible in a safe location. These are used to display the numbers of different variants, which were imputed by sensors in the robots and the line. Due to this, several noise alarms can be perceived, and the most relevant ones are known by maintainers. The maintenance legacy software was updated to adhere to the new capabilities retrieved by the sensors. Smart devices can also receive status from a line close to real-time.

The C2 engineer was working in assembling lines along with factories in other countries. Regarding the cloud computing solution, it could be easily replicated in other region operations. Some teams do not have programmers with the expertise to set up the stations. In this case, the application of cloud computing can resolve the necessity of a remote setup as well. The engineer also described two main replicable issues with the assembling process: the setup of the control station electric connection and software debugging. The suggestions proposed in the framework can be replicated to a point in which they could impact quality. A technology to analyze historic data and guide maintainers would help them to do right at the first time, and "even with all training, errors due to quality are still the most committed. This is the most important part because it is easy to correct a wrongly connected cable; however, the quality of the installation is the most detrimental (in the audit)," stated the engineer.

There are some works that, similarly, address investment to improve performance in maintenance activities. Those works offer simulations to test different parameters and scenarios to improve the performance of manufacturing systems, providing better decision-making strategies (Renna, 2017; Renna & Ambrico, 2019). One of them, provides the "worst-case strategy" (regarding setup-time and time between failures), suggesting that the goal is to remove extreme events and implement solutions with ease while avoiding high costs (Utiyama et al., 2021).

Regarding the step-by-step strategy used, some limitations can be discussed. Even though the method was built for a macro decision approach, some specific applications of technologies could be presented as guidelines for a better understanding in step 3. A second point to consider is that each step could be evaluated by different types of professionals, with top organizational management in step 1, and more spatialized in the operational part for step 2. This approach could provide the idea of cooperation between well-defined domains (i.e., organizational, and operational), highlighting the specific know-how at each stage. In decision-making theory, the ideal is that the individual will contribute with better judgment if allocated to a domain that is more familiar to him.

6. Conclusions

A strategic framework for the adequacy of legacy systems, with a bias in interoperability aspects, was the scope of this study. To remain competitive, businesses must continually change their process, sometimes radically, though more often incrementally, coping with their changing environment. Legacy systems have become inadequate in reflecting business needs, either operationally or economically. In this way, DT projects have become necessary. They are related first to strategy, leadership, and organizational culture. Only then, with the adoption and use of digital technology. With this in mind, interoperability was highlighted due to the idea that DT needs to consider not only technical aspects but also all enterprise layers.

This work addresses the fact that a legacy system cannot be drastically changed. Considerable interoperability must be analyzed. In this case, embedded digital capabilities in a legacy system, making it perform along with cyber-physical systems in smart manufacturing, is a process that will get it to the degree of an SLS. To guide legacy systems towards this DT process, a series of three MCDM models are proposed to analyze the critical decision points. Thus, references related to legacy system optimization strategies, interoperability referential models, and I4.0 architecture were explored.

In the end, two cases explored the 4.0DTFCI framework in the industrial maintenance domain. Conclusively, this work contributes to the adequacy of legacy systems by highlighting interoperability aspects in an Industry 4.0 scenario. In addition, maintenance systems can be perceived through the lens of smart manufacturing as well, contributing to data for future work.

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