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Proposal of a Model for Evaluating the Maturity of Industry 4.0 Implementation in the Steel Industry

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Abstract

Industry 4.0 has been progressively adopted by industrial sectors as a strategic response to competitiveness, efficiency, and digital integration challenges. In capital-intensive and continuous-process industries such as steelmaking, the implementation of Industry 4.0 follows a gradual and selective path, primarily focused on operational efficiency and process optimization. Although several Industry 4.0 maturity models have been proposed in the literature, most are generic and do not adequately address the specific characteristics of the steel industry. This paper proposes and applies a sector-oriented Industry 4.0 maturity assessment model tailored to the steel industry, structured around five dimensions: Strategy and Organization, Production, Smart Operations, Product, and Human Resources. Data were collected through a structured survey applied to professionals from steel companies. The results indicate that the overall maturity level of the analyzed companies is low to intermediate, with higher development in production-related aspects and lower maturity in product digitalization and human resources. The findings highlight key gaps and provide managerial insights to support strategic decision-making and prioritization of Industry 4.0 initiatives in the steel sector.

Keywords
Industry 4.0, Maturity Assessment Model, Steel Industry

1. Introduction
Industry 4.0 represents a paradigm shift in industrial production systems, driven by the integration of advanced digital technologies such as cyber-physical systems, Internet of Things (IoT), Big Data analytics,

cloud computing, and intelligent automation. These technologies enable higher levels of integration, flexibility, and data-driven decision-making across industrial value chains.

In the steel industry, which is characterized by continuous processes, high capital intensity, and strong operational interdependencies, the adoption of Industry 4.0 technologies has been primarily oriented toward process optimization, cost reduction, and operational reliability. Unlike discrete manufacturing industries, steelmaking presents specific technological and organizational constraints that influence the pace and scope of digital transformation.

Despite the growing interest in Industry 4.0, existing maturity models are mostly generic and do not fully capture the specificities of continuous-process industries such as steel. Consequently, there is a need for sector-specific maturity assessment approaches that support strategic planning and investment decisions.
This study addresses this gap by proposing and applying an Industry 4.0 maturity model tailored to the steel industry, aiming to assess the current level of implementation and identify critical development opportunities.

1.1.Objectives

This study addresses this gap by proposing and applying an Industry 4.0 maturity model tailored to the steel industry, aiming to assess the current level of implementation and identify critical development opportunities.

2. Literature Review

Several Industry 4.0 maturity models have been proposed in the literature to assess organizational readiness and implementation progress.

Storolli et al. (2018) constructed a maturity assessment model where the evaluated maturity items were some of the main technologies of Industry 4.0, which are IoT (Internet of Things), IoS (Internet of Services), Big Data and Big Data Analytics, Cyber Security, CPS (Cyber-Physical System), Smart Factory, Intelligent Sensing, Traceability, Predictive Maintenance, AGV (Automatic Guided Vehicle), and AR (Augmented Reality). The maturity levels were defined based on the number of technologies applied, where the Initial level uses none or less than 25% of the tools linked to the Industry 4.0 concept; In implementation when 25% to less than 50% of the tools linked to the Industry 4.0 concept are used; Intermediate when 50% to less than 75% of the tools linked to the Industry 4.0 concept are used; Final implementation phase when 75% to less than 100% of the tools linked to the Industry 4.0 concept are used; and Implemented when 100% of the tools linked to the Industry 4.0 concept are used.

Trotta, D. and Garengo, P (2019) proposed a model where the defined dimensions were Strategy, Technology, Production, Products, and People. Maturity levels were measured through the application of the Likert scale across all dimensions, where a value of 1 is "not implemented/not present" and 5 is "fully implemented/present".

Schumacher et al. (2016), based on experiences in workshops, expert recommendations, scientific articles, studies, and reports, developed their model entitled Industry 4.0 Maturity Model. This model uses nine dimensions and sixty-two maturity items to determine the Industry 4.0 maturity of companies, with five possible levels, where companies evaluated as level 1 do not possess the necessary attributes for Industry 4.0 concepts, and those evaluated as level 5 meet the necessary requirements of Industry 4.0, as briefly shown in Table 1.

Table 1. Dimensions and maturity items used in the Maturity Model for Industry 4.0. Source: Schumacher et al. 2016. Adapted.

Dimension	Example of a maturity item:
Strategy	Roadmap for Industry 4.0, Available resources
Leadership	Leadership commitment, Top management competencies
Customers	Use of customer data, Digitalization of sales/services
Products	Single-unit batches, Digitalization of products
Operations	Decentralization of processes, Modeling and simulation
Culture	Knowledge sharing, Collaboration between departments
People	Employee competencies, Employee autonomy
Governance	Legal requirements for Industry 4.0, Intellectual property protection
Technology	Existence of modern ICT, Use of M2M communication

The evaluation is carried out through questionnaires using the Likert scale, with scores from 1 to 5, where each question has a specific weight, and then the company's maturity level is calculated using a specific equation for this purpose (Schumacher et al., 2016).

The steel industry is called a continuous process industry (CNI, 2016), that is, industries with continuous processes and minimal interruptions. For this segment, the impacts of implementing Industry 4.0 technologies should focus on improvements in the production process and the digital integration of the supply chain, between customers and suppliers.

Unlike discrete process industries, these will need to pursue a dual strategy, investing in more technological products and incorporating enabling technologies into production.
Based on the CNI study (2016) for the steel industry segment, where Industry 4.0 is expected to focus on process improvements, the application of maturity assessment models is expected to be valid. Models that primarily assess the implementation of enabling technologies and everything involved in this implementation are the ones most likely to be applied in this segment.
In this industry, given its size, as shown by Fir e. V. (2020), some organizations use Industry 4.0 only in selected areas of the organization, as independent islands.
After analyzing and comparing different maturity assessment models for Industry 4.0 implementation (Sampaio, 2023), it was observed that the Industry 4.0 implementation maturity assessment model is composed of dimensions, elements, and maturity levels.
Antoni, J. et al (2021) evaluate the criticality of the dimensions in manufacturing, service, small and medium-sized companies, comparing various models found in the literature.

For manufacturing companies, the authors define the main dimensions as:
- Technological readiness
- Industry strategy readiness
- Organizational culture
- Leadership and support from senior management for the industry
- Digitalization of supply chains
- Innovative industry business model
- Employee adaptability to the industry
- Extent of the organization's digital transformation
- Employee rewards and recognition
- Smart products and services

Trotta, D. and Garengo, P. (2019) defined the following dimensions in their model for a manufacturing company:
• Strategy
• Technology
• Production
• Products
• People

In the steel industry, digital transformation initiatives tend to prioritize simulation, process monitoring, Big Data analytics, and cloud-based integration, while product digitalization and smart services remain limited (Peters et al., 2016; Gajdzik et al., 2022). These findings reinforce the need for maturity models that reflect sector-specific characteristics.

3. Maturity Model

The proposed maturity model was developed based on a synthesis of existing Industry 4.0 maturity frameworks and the specific characteristics of the steel industry. The model is structured in five dimensions, which were based on the set of dimensions defined by Antoni, J. et al (2021) and Trotta, D. and Garengo, P. (2019):
(i) Strategy and Organization;
(ii) Production;
(iii) Smart Operations;
(iv) Product;
(v) Human Resources.

Each dimension is composed of evaluation elements assessed using a five-level Likert scale, ranging from initial to advanced maturity. Table 2 shows the dimensions with their respective elements of the Industry 4.0 maturity assessment model. The model aims to capture both technological and organizational aspects of Industry 4.0 implementation.

Table 2. Dimensions and elements of the Industry 4.0 maturity assessment model

Dimension	**Elements**
Strategy and Organization	Strategy implementation level
	Indicators for monitoring the implementation status
	Technology used in the company
	Areas of the company with investments in Industry 4.0 in the last 2 years.
Production	Technology used in production
Smart Operation	Technology used in the inventory control of supplies.
	Tecnologia utilizada no controle de produtos acabados
	Technology used in the control of finished products.
	External information shared between customers and suppliers integrated into the central system.
Product	I4.0 technology in the product
Human Resources	Position held by the respondent
	Área onde o desenvolvimento ocorreu ou está previsto
	People hired with training in Industry 4.0 technologies.
	The company provided training in which technological areas of Industry 4.0

For each element that makes up the different dimensions, a maturity level was defined so that it could be measured. Table 3 shows the elements and their respective maturity levels, ranging from a situation where there is no technology or investment to the maximum level where many technologies are already employed, as well as very well-defined strategic models.

Table 3. Elements and assessment levels of Industry 4.0 maturity

<table>
<tr><th>Elements</th><th>Maturity Levels</th></tr>
<tr><td>Strategy implementation level</td><td>No Strategy Exists – Level 0
Some pilot initiatives have been launched – Level 1
The strategy is under development – Level 2
The strategy is formulated – Level 3
The strategy is being implemented – Level 4
The strategy is implemented – Level 5</td></tr>
<tr><td>Indicators to monitor the implementation status</td><td>No indicators exist – Level 0
Increased efficiency of the management system – Level 1
Indicator system that provides some guidance – Level 3
Indicator system considered adequate – Level 5</td></tr>
<tr><td>Technology used in the company</td><td>No technology – Level 0
≤ 2 technologies – Level 1
>2 and ≤4 technologies – Level 2
>4 and ≤6 technologies – Level 3
>6 and ≤8 technologies – Level 4
>8 technologies – Level 5</td></tr>
<tr><td>Company areas with investments in Industry 4.0 in the last 2 years</td><td>No Investment
Small Investment
Medium Investment
Large Investment</td></tr>
<tr><td>Technology used in production</td><td rowspan="3">No technology – Level 0
≤ 2 technologies – Level 1
>2 and ≤4 technologies – Level 2
>4 and ≤6 technologies – Level 3
>6 and ≤8 technologies – Level 4
>8 technologies – Level 5</td></tr>
<tr><td>Technology used in the control of raw material inventory</td></tr>
<tr><td>Technology used in the control of finished products</td></tr>
<tr><td>Internal information shared and integrated into the central system</td><td rowspan="2">No areas – Level 0
≤ 2 areas – Level 1
>2 and ≤4 areas – Level 2
>4 and ≤6 areas – Level 3
>6 and ≤8 areas – Level 4
>8 areas – Level 5</td></tr>
<tr><td>External information shared between customers and suppliers, integrated into the central system</td></tr>
<tr><td>Industry 4.0 technology in the product</td><td>No technology – Level 0
≤ 2 technologies – Level 1
>2 and ≤4 technologies – Level 2
>4 and ≤6 technologies – Level 3
>6 and ≤8 technologies – Level 4
>8 technologies – Level 5</td></tr>
<tr><td>Area where development occurred or is planned</td><td>No areas – Level 0
≤ 2 areas – Level 1
>2 and ≤4 areas – Level 2
>4 and ≤6 areas – Level 3
>6 and ≤8 areas – Level 4
>8 areas – Level 5</td></tr>
<tr><td>People hired with training in Industry 4.0 technologies</td><td>No technology – Level 0
≤ 2 technologies – Level 1</td></tr>
</table>

The company provided training in which technological areas of Industry 4.0	>2 and ≤4 technologies – Level 2 >4 and ≤6 technologies – Level 3 >6 and ≤8 technologies – Level 4 >8 technologies – Level 5

For the Strategy and Organization dimension, the elements Strategy Implementation Level and Implementation Indicators were defined with the aim of measuring the company's governance and long-term vision regarding the implementation of the Industry 4.0 concept. According to Dwivedy, M. et al., a comprehensive implementation strategy is necessary for companies to successfully restructure and improve their processes in accordance with Industry 4.0 criteria.

The elements Technology Used and Areas with Investment in Industry 4.0 in the last 2 years help to indirectly map technological maturity, as they allow for the evaluation of the alignment between the corporate strategy and operational areas and measure the integration between strategic vision and investment mapping.

For the Production dimension, the Technology used in production is an essential element that indicates the degree of automation and digitalization of the production lines.

Technology for controlling raw material inventory, technology for controlling finished products, and internal and external information integration, in the Intelligent Operation dimension, were defined because they align with the concept of "smart operations," which evaluates horizontal and vertical integration (internal + external), and the importance of the digital supply chain in the steel industry.

In the Product dimension, the I4.0 technology in the product is important, but steel companies typically produce intermediate goods, not "smart products" in the traditional sense. However, this element allows for the evaluation of initiatives such as digital traceability, automatic quality certification, RFID labeling, and batch tracing.

4. Data Collection

Data were collected through an online survey distributed to professionals working in steel companies. The respondents included executives, managers, engineers, and technical specialists involved in digital transformation initiatives.

A total of 15 valid responses were obtained. Although the sample size is limited, the respondents occupy strategic and technical positions, ensuring informed perspectives on Industry 4.0 implementation within their organizations.

5. Results and Discussion

The results indicate that the Production dimension presents the highest average maturity level among the evaluated dimensions. This confirms that Industry 4.0 initiatives in the steel industry are primarily focused on operational efficiency, process monitoring, and optimization.

Technologies such as simulation, Big Data analytics, and cloud computing are widely adopted to support production planning, quality control, and decision-making. These findings are consistent with previous studies that highlight the process-oriented nature of digital transformation in the steel sector (Gajdzik et al., 2020; Martins et al., 2021).

The Strategy and Organization dimension shows an intermediate maturity level, indicating that while companies recognize the importance of Industry 4.0, strategic governance mechanisms and performance indicators are still underdeveloped.

The Smart Operations dimension reveals a strong integration of internal information systems, typically based on ERP and MES architectures. However, the adoption of advanced technologies for intelligent inventory management and external integration with suppliers and customers remains limited.

Cloud computing and Big Data stand out as key enablers, while technologies such as artificial intelligence and IoT are still applied selectively. These results suggest that companies are in a transitional phase, with consolidated internal integration but limited horizontal integration across the supply chain. The Product dimension presents the lowest maturity level. Most companies do not incorporate Industry 4.0 technologies directly into their products, focusing instead on process digitalization.

This result reflects the nature of steel products as intermediate goods and the complexity of embedding digital intelligence into such products. The literature indicates that product digitalization is typically associated with advanced maturity stages and new business models, which are still emerging in the steel industry (Porter and Heppelmann, 2014).

The Human Resources dimension shows low to intermediate maturity. Although companies have hired professionals with skills in Big Data, cloud computing, and artificial intelligence, training programs remain fragmented and limited in scope.

This finding confirms that human capital development is one of the main bottlenecks of Industry 4.0 implementation, as also reported in previous studies (Sony and Naik, 2020).

Figure 1 presents the comparative analysis of the dimensions, showing the average implementation levels of the dimensions evaluated in the proposed maturity model, allowing the identification of which areas are relatively more organized among the companies whose interviewees participated in the research. The average values were: Production (2.0), Strategy and Organization (1.9), Intelligent Operation (1.9), Human Resources (1.9), and Product (1.0), on a maturity scale of zero to five levels.

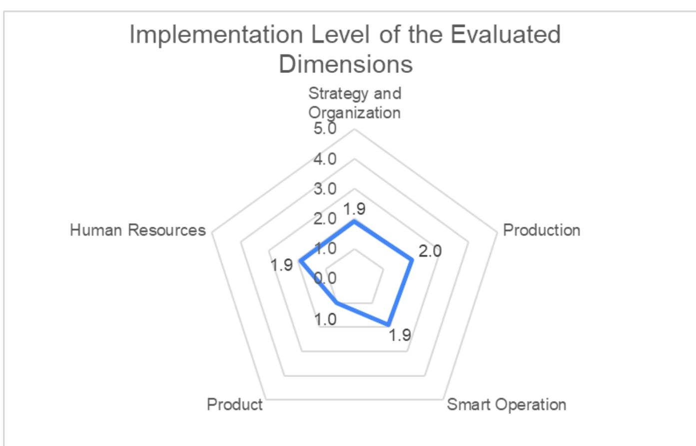

Figure 1. Implementation Level of the Dimensions Evaluated in the Maturity Model

This comparative analysis of the dimensions reveals a hierarchical maturity pattern:

Production is the most developed dimension, followed by Strategy and Organization, Smart Operations, and Human Resources, while Product remains the least developed.

This pattern aligns with maturity models that describe Industry 4.0 implementation as an incremental process, starting with internal efficiency and gradually expanding toward integration, human capabilities, and product innovation.

The results reveal an overall maturity profile that is predominantly low to intermediate, with none of the dimensions reaching higher levels on the scale. This pattern is consistent with empirical studies and systematic reviews that indicate that most industrial companies are still in the early or intermediate stages of implementing Industry 4.0 technologies (Schumacher; Erol; Sihn, 2016; Dikhanbayeva et al., 2020; Nayerniya et al., 2022).

The Production dimension shows the highest average level of implementation, with a value of 2.0, indicating that the efforts to apply Industry 4.0 technologies are primarily concentrated in the operational core of the companies. This result confirms the pattern widely described in the literature, according to which industrial digitalization tends to begin on the factory floor, through advanced automation, process monitoring, digital quality control, and integration between production systems (Frank; Dalenogare; Ayala, 2019; Gajdzik; Grabowska; Saniuk, 2020), which has already been shown above as the main initial driver for generating efficiency gains.

The Strategy and Organization, Intelligent Operations, and Human Resources dimensions show similar average levels, all around 1.9, indicating a similar stage of maturity in these areas. This result suggests that, although there are strategic initiatives, operational integration efforts, and training actions, these dimensions are still at an initial to intermediate level of development, with low institutionalization and limited integration between strategy, technology, and people management.

In the case of the Strategy and Organization dimension, the observed level indicates that companies already recognize the importance of digital transformation and have strategic initiatives underway, but still lack robust governance mechanisms, structured indicators, and long-term alignment.
Schuh et al., 2017; Hajoary, 2020 point out that strategic formulation in Industry 4.0 often precedes the consolidation of formal systems for monitoring and managing digital performance.

The Intelligent Operations dimension, also with an average level of 1.9, reflects the existence of a relatively consolidated internal integration base, but with still limited use of advanced technologies for inventory automation, external integration, and intelligent decision-making. This profile is typical of intermediate stages of maturity, in which vertical integration is more developed than horizontal integration and data-driven automation (Huber; Roglinger; Scharlau, 2022; Rar et al., 2022). Similarly, the Human Resources dimension presents an average level of 1.9, indicating that the management of digital skills is still in an incipient stage. Although there are occasional hirings and specific training programs, there is still no structured corporate policy for human capital development focused on Industry 4.0.

On the other hand, the Product dimension presents the lowest average level of implementation, with a value of only 1.0, indicating a significantly lower level of maturity compared to the other dimensions. This result shows that the incorporation of Industry 4.0 technologies directly into products is still extremely limited in the companies analyzed, since it is raw material for subsequent processes.

Taken together, the results indicate that the observed maturity pattern follows a typical hierarchy of industrial digital transformation, in which:

1. Production constitutes the main initial axis of development;
2. Strategy, operations, and human resources evolve gradually and relatively synchronously;
3. The product remains the least developed dimension.

This profile is consistent with maturity models described in the literature, in which the initial and intermediate stages are characterized by a focus on operational efficiency and internal integration, while the more advanced stages involve interorganizational integration, intelligent automation, and value creation through digital products and services (Schumacher; Erol; Sihn, 2016; Schuh et al., 2017; Dikhanbayeva et al., 2020).

6. Conclusions

This study aimed to develop and apply a maturity assessment model for the implementation of Industry 4.0 specifically tailored to the steel industry sector, considering its structural, technological, and organizational characteristics as a continuous process and capital-intensive industry. Unlike the generic models widely found in the literature, the proposed model incorporates dimensions, elements, and maturity levels aligned with the operational, strategic, and technological particularities of the sector.

The empirical results obtained from the application of the model show that the surveyed companies are, in general, at an initial to intermediate overall maturity stage, with a heterogeneous distribution across the evaluated dimensions. The Production dimension presented the highest average level of implementation, confirming that digital transformation efforts in the steel industry are primarily concentrated in the operational core, with an emphasis on computational simulation, Big Data, and cloud computing. This pattern reinforces the incremental nature of digital transformation in the sector, initially oriented towards operational efficiency and the reduction of production risks.

The Strategy and Organization, Intelligent Operations, and Human Resources dimensions showed similar and moderate average levels, indicating that, although strategic initiatives, consolidated internal integration, and training actions exist, fragmented approaches still prevail, with limited institutionalization of formal governance mechanisms, performance indicators, and structured policies for developing digital skills. In particular, the low maturity observed in strategic monitoring indicators and external integration shows that the governance of digital transformation still represents one of the main bottlenecks for the sustainable evolution of Industry 4.0 in the sector.

The Product dimension showed the lowest level of maturity, confirming that the direct incorporation of Industry 4.0 technologies into steel products is still in its early stages. This result reflects both the nature of steel products as intermediate goods and the historical prioritization of process digitalization over the creation of intelligent products. This finding indicates that value creation through digital products and advanced services remains a strategic frontier that is still largely unexplored by companies in the sector.

In an integrated manner, the results reveal a hierarchical pattern of maturity evolution, in which digital transformation begins with production, progressively consolidates in internal integration and data infrastructure, and shows slower progress in external integration, people management, and product digitalization. This pattern is consistent with the main maturity models described in the literature and confirms the suitability of the proposed model for capturing the specific dynamics of the steel industry.

As a main scientific contribution, this study offers a sector-oriented maturity assessment model capable of supporting both researchers and managers in understanding the current stage of digital transformation, identifying critical gaps, and defining strategic priorities for the evolution of Industry 4.0 in the steel sector. From a managerial perspective, the model provides a practical tool for diagnosis, benchmarking, and planning of technological and organizational investments. The findings provide practical insights by identifying priority areas for investment, particularly in governance mechanisms, human resource development, and product digitalization.

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Biographies

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