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ARTICLE

Philosophical currents and decision-making in intelligent industrial automation systems: a capability framework for Industry 4.0

Corrientes filosóficas y toma de decisiones en sistemas inteligentes de automatización industrial: un marco de capacidades para la Industria 4.0

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Abstract

The incorporation of intelligent systems into industrial automation is transforming supervision and decision-making, requiring professionals capable of combining technical expertise, causal understanding, contextual interpretation, and responsibility for the consequences of their decisions. In this context, the objective was to analyze the contribution of positivism, critical realism, and hermeneutics to capability development and decision-making in order to propose an integrated framework for Industry 4.0. A transdisciplinary approach and a documentary philosophical-analytical methodology were adopted, supported by a scoping review conducted in Scopus, Web of Science, and Google Scholar covering the period 2020–2026. After applying the selection criteria, a corpus of 22 sources was established and analyzed through thematic coding. The results show that positivism supports measurement and control, critical realism extends diagnosis through the identification of causal mechanisms, and hermeneutics incorporates the interpretation of the human–technology context. This articulation enabled the development of a capability framework organized into operational, tactical, and strategic levels, with environmental philosophy as a cross-cutting dimension and human oversight of decisions mediated by artificial intelligence. It is concluded that this integration could strengthen professional judgment in increasingly automated industrial systems, although further validation is required.

Keywords: Industrial automation, intelligent systems, decision-making, positivism, critical realism, hermeneutics

Resumen

La incorporación de sistemas inteligentes en la automatización industrial transforma la supervisión y la toma de decisiones, exigiendo profesionales capaces de combinar dominio técnico, comprensión causal, interpretación contextual y responsabilidad ante sus consecuencias. En este contexto, el objetivo fue analizar la contribución del positivismo, el realismo crítico y la hermenéutica a la formación de capacidades y la toma de decisiones, para proponer un marco integrado orientado a la Industria 4.0. Se adoptó un enfoque transdisciplinario y una metodología filosófico-analítica documental, sustentada en una revisión de alcance realizada en Scopus, Web of Science y Google Scholar durante 2020–2026. Tras aplicar los criterios de selección, se conformó un corpus de 22 fuentes, analizado mediante codificación temática. Los resultados muestran que el positivismo sustenta la medición y el control, el realismo crítico amplía el diagnóstico mediante mecanismos causales y la hermenéutica incorpora la interpretación del contexto humano–tecnología. Esta articulación permitió construir un marco de capacidades organizado en niveles operativo, táctico y estratégico, con la filosofía ambiental como dimensión transversal y la supervisión humana ante decisiones mediadas por inteligencia artificial. Se concluye que esta integración podría fortalecer el juicio profesional frente a sistemas industriales progresivamente automatizados, aunque requiere validación posterior.

Palabras clave: Automatización industrial, sistemas inteligentes, toma de decisiones, positivismo, realismo crítico, hermenéutica

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1. Introduction

The so-called Fourth Industrial Revolution, or Industry 4.0, has driven an unprecedented transformation in production environments, characterized by hyperconnectivity, cyber-physical systems, and large-scale data analytics, within a scenario in which industrial automation is no longer limited to replacing human intervention in repetitive tasks through rigid programmable logic control schemes, but is evolving toward socio-technical ecosystems in which devices, data, algorithms, and people converge. This evolution can be observed in contemporary automation architectures, which incorporate distributed processing, communication, and decision-making capabilities at different levels of industrial systems [1], broadening the demands associated with their operation and supervision and progressively shifting attention toward the capabilities required to understand the relationships established between technological and human components.

In line with this expansion of the required capabilities, professional training faces issues that go beyond the strictly technical domain and extend to the way engineers observe, explain, and interpret the behavior of systems, especially considering that engineering education has traditionally remained tied to a technical-instrumental view, while contemporary technological systems incorporate ontological, epistemological, and ethical dimensions that intervene both in their design and in their use [2]. This relationship becomes more complex when decision-making processes incorporate intelligent systems whose internal operations can hinder effective interpretation and human oversight [3, 4], giving rise to scenarios in which instrumental knowledge begins to relate to forms of reasoning oriented toward explaining causalities, interpreting contexts, and assessing the implications derived from technological decisions.

Building on this coexistence between instrumental knowledge and diverse forms of reasoning, different philosophical perspectives make it possible to approach complementary dimensions of technological reality. Among them is logical positivism, linked to empirical observation and quantification, although its ideal of value neutrality has been questioned in recent engineering education [5], and critical realism, which incorporates causal retroduction to explore underlying mechanisms that are not always directly observable [6], through procedures that make it possible to structure this type of reasoning [7]. To these approaches is added hermeneutics, from which contextual interpretation and the relationships between technology and human experience acquire relevance [8, 9, 10], together with environmental philosophy, which incorporates the ethical and ecosystemic dimensions associated with technological development [11] – perspectives whose respective emphases on measurement, causality, interpretation, and responsibility open up the possibility of examining how these forms of reasoning project onto the professional capabilities required in industrial systems.

From this projection toward professional capabilities, the competencies prioritized in educational and business programs acquire particular relevance, given that training related to automation tends to concentrate on capabilities related to the operation, integration, and optimization of technologies, while the assumptions from which a problem is interpreted and the form of reasoning used to address it remain less explicit. An anomaly recorded by a sensor may require quantitative verification and, at the same time, lead to the exploration of non-evident causal mechanisms, to consideration of the particular conditions of the operating environment, or to an assessment of the implications associated with a given response, relationships that take on new configurations as artificial intelligence systems participate more frequently in supervision, prediction, and decision-support activities.

Given this growing participation of intelligent systems in decision-making processes, the possibilities for processing and analyzing information expand together with conditions related to the opacity of certain models, the dependence on the data employed, and the particularities of the operating context, aspects that come into play when a quantitatively consistent algorithmic response needs to be interpreted before being translated into an industrial decision. Under these conditions, empirical verification can be related to causal exploration, while contextual interpretation and ethical consideration provide other levels of reading on the same situation, giving rise to an interaction between forms of reasoning whose correspondence with professional capabilities raises the need to examine how philosophical foundations can be integrated into training related to industrial automation.

In response to this need to articulate philosophical foundations with professional capabilities, the objective of the research is to analyze how logical positivism, critical realism, hermeneutics, and environmental philosophy interact in professional training, and to propose an integrated capability plan for future technological architects of industrial automation, considering the correspondence between philosophical perspectives, the forms of reasoning they promote, and the capabilities associated with different levels of decision-making. The proposal is developed from these relationships and seeks to represent their articulation within a structure that links philosophical foundations with professional capabilities and the situations characteristic of contemporary industrial systems, while maintaining as a reference the documentary and conceptual character from which the study is approached.

In line with this purpose, the remainder of the article is organized as follows. Section 2 examines the work related to the four lines of literature considered and the research gaps identified, while Section 3 describes the methods used and specifies the exclusively documentary character of the study's empirical basis, without the application of instruments to human subjects. Section 4 presents the results of the documentary analysis, the mapping of the pyramid, and the proposed integrated model with its associated algorithm. Subsequently, Section 5 contrasts the findings with the current literature and examines the limitations related to the conceptual scope of the study, while Section 6 presents the conclusions and the possibilities for empirical validation of the proposal in real industrial settings.

2. Related work

This section examines work related to the influence of the philosophy of science on engineering and industrial automation, considering contributions related to philosophical training in engineering, critical realism and causal retroduction, human-centered design in Industry 4.0 and 5.0, and human oversight of intelligent systems. The review is organized around these perspectives due to their connection with the philosophical currents considered in the study and with different levels of analysis spanning professional training, the explanation of causal mechanisms, human-technology interaction, and the oversight of algorithmic systems. Based on this organization, the background literature is examined attending both to its contributions and to the relationships that can be established among them regarding training and decision-making in industrial automation.

From the field of engineering education, Lysak [2] developed a theoretical analysis of the philosophical dimensions present in engineers' education and related the absence of explicit philosophical training to difficulties in ontological classification and to ethical blind spots during the design of technical systems, providing a basis for recognizing that professional decisions do not depend exclusively on instrumental knowledge. Although this perspective makes it possible to incorporate philosophical reflection into engineering education, its development remains mainly at the general curricular level and does not establish a correspondence between philosophical currents, professional capabilities, and specific levels of decision-making within industrial automation systems. In response to this gap, the present study shifts the discussion toward the context of automation by linking philosophical foundations with differentiated capabilities sustained through an automation pyramid, further incorporating a prioritization mechanism that seeks to turn these foundations into criteria applicable to decision-making situations.

This need to translate philosophical foundations into applicable forms of reasoning finds a relevant precedent in critical realism, particularly in work oriented toward operationalizing causal explanation. For example, Rieder et al. [7] proposed four steps for coding causal retroduction in agent-based models, turning a philosophical principle into a reproducible procedure applied to the computational simulation of social phenomena, while Mukumbang [6] showed how retroduction can integrate qualitative and quantitative methods through the distinction between observable events and underlying generative mechanisms. These contributions advance the translation of philosophical reasoning into analytical procedures, although their applications are not specifically oriented toward decision-making in industrial automation systems, nor do they establish their relationship with differentiated professional capabilities. Addressing this gap, the present study adapts retroductive logic to the analysis of anomalies within automated processes and incorporates it as part of the proposed diagnostic mechanism, relating the identification of observable events to the exploration of possible generative mechanisms and to the selection of capabilities required for their interpretation.

Therefore, the interpretation of these situations does not depend solely on the identification of causal mechanisms, but also on the conditions under which people and technological systems interact, an aspect that has gained greater presence in studies on Industry 4.0 and 5.0. Nguyen et al. [9] reviewed cases of human-centered design in Industry 4.0 and identified a limited articulation between these approaches and competency-development frameworks, while Yaqot et al. [10] analyzed the relationship between industry and human participation in Industry 5.0, considering the tensions associated with the progressive substitution of human effort by autonomous systems. Both contributions broaden the understanding of automation by situating human experience and participation within the production system, although the relationship between these dimensions and the hermeneutic foundations that can guide professional interpretation capabilities remains less developed. Accordingly, the present work addresses this gap by incorporating the hermeneutic perspective into the capability plan, linking it to situations in which the professional must interpret the operating context, human-technology interactions, and the implications associated with decisions that go beyond exclusively quantitative analysis.

Added to this is the growing human participation in interpretive tasks, which takes on another dimension when intelligent systems assume prediction, recommendation, or decision-making functions and the professional shifts from directly intervening in the process to overseeing its outcomes. In this context, Laux [3] analyzed the human-oversight requirements associated with the European Union's Artificial Intelligence Act, while Sterz et al. [12] and Langer et al. [4] developed interdisciplinary frameworks to examine the conditions that determine the effectiveness of such oversight in the face of systems characterized by different degrees of opacity, to which Vallor and Vierkant [13] added an analysis of the relational vulnerability and responsibility gaps that can arise between people and socio-technical systems. Indeed, this body of work shifts attention from the mere presence of an operator toward the conditions necessary to exercise meaningful oversight, although it pays less attention to how a professional's philosophical training can contribute to interpreting, questioning, and assessing the responses generated by intelligent systems. In response to this gap, the manuscript incorporates human oversight within the proposed model's escalation mechanism and relates it to reasoning capabilities that combine verification, causal explanation, contextual interpretation, and assessment of the implications associated with the decision.

In this way, the convergence of this prior work makes it possible to observe that the literature has developed relevant contributions to understanding, in a differentiated manner, philosophical training in engineering [2], the operationalization of causal reasoning [7, 6], human participation in industrial systems [9, 10], and the conditions associated with oversight and responsibility regarding intelligent systems [3, 12, 4, 13]. However, these developments remain distributed among different conceptual frameworks and fields of application, leaving less explored their articulation within a structure that relates philosophical currents, forms of reasoning, professional capabilities, and levels of decision-making specific to industrial automation. The study therefore addresses this gap through an integrated capability proposal that articulates philosophical perspectives with the forms of reasoning required in industrial automation, establishing their correspondence with different levels of decision-making and translating this articulation into a structure that incorporates prioritization and diagnostic mechanisms. In this way, the proposal seeks to overcome the fragmented treatment of these dimensions through a framework that relates philosophical foundations, professional capabilities, and decision-making situations within contemporary industrial systems.

3. Methodology

This section describes the procedure followed to identify, select, analyze, and integrate the literature underlying the construction of the proposed capability framework for decision-making in intelligent industrial automation systems. Since the aim of the study is not merely to characterize philosophical currents, but to establish well-founded correspondences between their principles, professional capabilities, and the different levels of decision-making present in Industry 4.0, a methodological strategy was defined to allow a traceable progression from the documentary evidence to the formulation of the conceptual framework. To this end, the research was developed from a transdisciplinary epistemological approach and through a documentary philosophical-analytical methodology, in which the units of analysis consisted exclusively of academic publications and specialized documents.

On this basis, a scoping literature review design was adopted [14], suitable for examining contributions from different fields of knowledge, establishing relationships among their foundations, and synthesizing them within an integrating conceptual structure. The methodological procedure was structured through five articulated components: literature search and corpus construction, directed document analysis and thematic coding, construction of the analogical model, application of the framework to decision-making in industrial automation, and incorporation of environmental philosophy. Figure 1 represents the articulation of the methodological procedure. The path begins with the identification and formation of the corpus, continues with its coding and conceptual analysis, and subsequently translates the categories obtained into the automation structure and the levels of decision-making. Environmental philosophy is incorporated to broaden the analysis of capabilities beyond technical efficiency and to consider the environmental implications of industrial decisions. Although the procedure establishes an analytical sequence to ensure its traceability, the conceptual construction retains an iterative character, such that the correspondences identified during the integration of the model make it possible to review and refine the categories obtained during the documentary analysis.

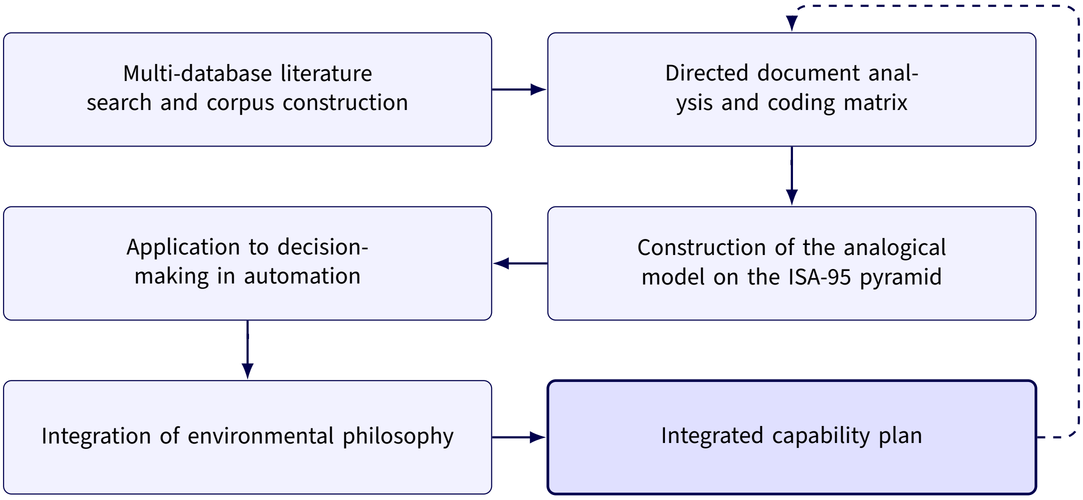

Figura 1. Methodological procedure followed for the construction of the integrated capability framework

3.1 Literature search and corpus construction

The first part of the procedure was aimed at building a documentary corpus that would provide the conceptual support needed to relate the philosophical currents studied to the capabilities required for decision-making within intelligent industrial automation systems. To this end, a structured search was carried out in Scopus, Web of Science, and Google Scholar, combining terms related to positivism, critical realism, hermeneutics, environmental philosophy, industrial automation, and Industry 4.0. Querying different sources made it possible to broaden the thematic coverage and retrieve contributions from both the philosophical field and engineering and automation. The strategy followed the principles of multi-database searching used in scoping reviews [14], together with recommendations aimed at maintaining transparency in the identification and documentation of sources [15].

The search was limited to the 2020–2026 period in order to consider recent developments related to the transformation of industrial systems. The inclusion criteria established were correspondence with the defined period, availability of the full text, and substantive connection with at least one of the study's conceptual axes: philosophical currents, professional capabilities, industrial automation, intelligent systems, or decision-making. The retrieved documents were subsequently subjected to a screening and relevance-review process, through which duplicate records, publications unrelated to the research problem, and works that did not provide conceptual or methodological grounding for the construction of the framework were excluded. In the final selection, priority was given to studies that, in addition to addressing the defined axes, allowed conceptual relationships to be established between philosophical perspectives and their application to the context of industrial automation.

In this way, the construction of the corpus followed a sequence of identification, screening, relevance assessment, and selection, as represented in Figure 2. Applying these criteria led to a final corpus of 22 publications, which constituted the documentary units used in the directed analysis and thematic coding. This delimitation made it possible to establish a traceable documentary basis for identifying the contributions of each philosophical current, contrasting them with the requirements of automation systems, and subsequently substantiating the correspondences incorporated into the capability framework.

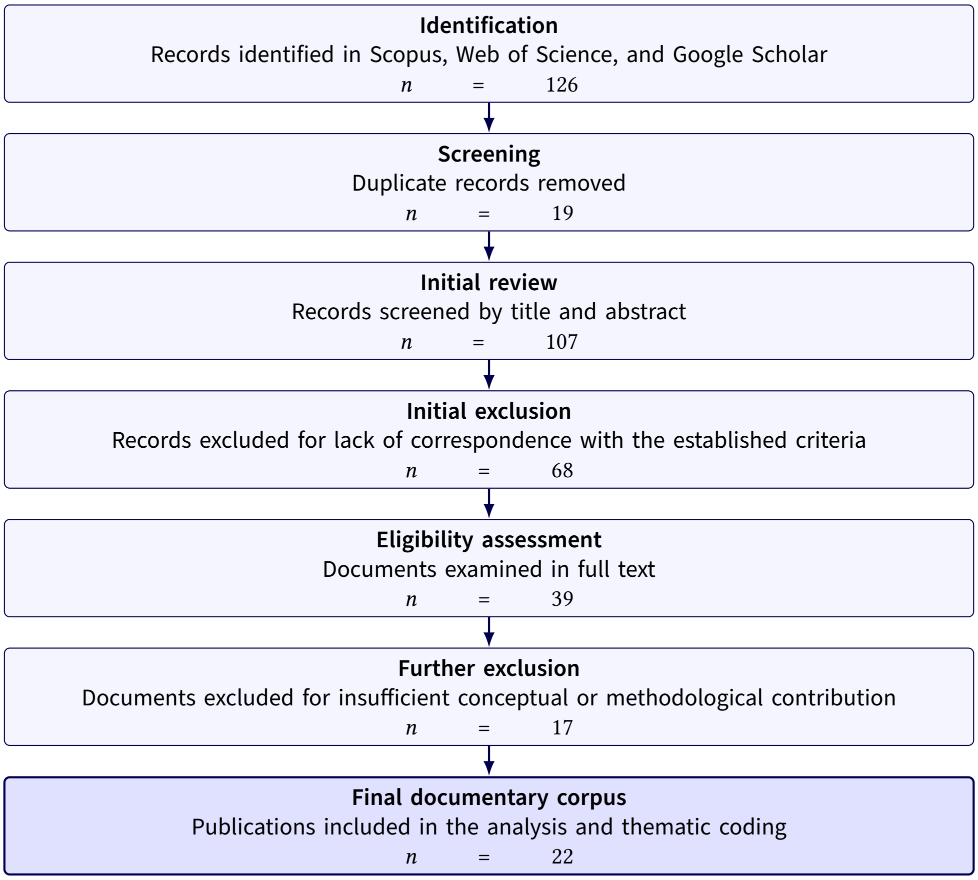

Figura 2. Process of identification, screening, assessment, and selection of the documentary corpus.

3.2 Directed document analysis and coding matrix

Once the corpus had been established, a directed document analysis was carried out with the purpose of transforming the information contained in the sources into comparable categories suitable for integration. Each document was examined according to its conceptual contribution and classified according to the predominant philosophical current underlying its argumentation: positivism, critical realism, hermeneutics, or environmental philosophy. In a complementary manner, publications whose main contribution corresponded to the technological or methodological domain were coded according to their supporting function, particularly in relation to dynamic capabilities, automation architecture, and oversight of artificial intelligence systems.

This procedure made it possible to establish a common structure for comparing documents from different disciplinary fields and to recognize convergences between philosophical foundations, capabilities, and decision-making needs. The strategy is consistent with recent approaches that combine directed qualitative analysis with systematic procedures of documentary synthesis [16]. As a result, the thematic coding matrix presented in Table 2 was constructed, subsequently used as a traceability mechanism to link the sources of the corpus with the categories underlying the construction of the model.

3.3 Construction of the analogical model

Based on the categories obtained during the document analysis, the next methodological component consisted of establishing correspondences between the epistemological foundations identified and the capabilities required in contemporary industrial automation systems. This operation made it possible to translate concepts initially formulated at the philosophical level into concrete situations of interpretation, diagnosis, and technological decision-making, without assuming a direct equivalence between both domains, but rather conceptual relationships grounded in the functions that each perspective contributes to the decision-making process. To organize these correspondences, the ISA-95 automation pyramid was used as a reference structure, given that it makes it possible to differentiate levels of operation, supervision, management, and decision-making within industrial systems. Its relevance has been examined in recent reference architectures for Industry 4.0 [1] and in applications related to the construction of digital twins in educational manufacturing systems [17]. On this structure, the relationships between levels of automation, interpretation needs, and capabilities associated with the different philosophical currents were mapped, whose representation is presented in Figure 3.

In addition, the conceptual consistency of this articulation was subsequently contrasted with the dynamic-capabilities theory reviewed by Cristofaro et al. [18], particularly with its proposition regarding the need to integrate, build, and reconfigure internal and external competencies in the face of changing environments. Indeed, this perspective provides an organizational foundation for interpreting the proposed capabilities not as static knowledge, but as resources susceptible to adaptation in the face of the technological evolution characteristic of Industry 4.0.

3.4 Application to decision-making in industrial automation

Once the conceptual correspondences had been established, their applicability was examined in decision-making situations typical of the different levels of industrial automation. To this end, decisions were differentiated according to their purpose and context of action, distinguishing those of a reactive nature, linked to the response to events, failures, or process deviations, from those of a progressive nature, associated with continuous improvement, adaptation, and innovation. This distinction is consistent with recent developments on automation and supervision systems for Industry 4.0 [19].

In this way, the analysis made it possible to relate each level of the pyramid to the predominant type of decision and to the philosophical perspectives offering greater explanatory or interpretive capacity for each situation. These relationships were systematized in Table 3 and subsequently served as the basis for constructing the philosophical-causal diagnostic algorithm presented in Section 4.5.1. Its logic establishes a progressive path that begins with the quantitative explanation of observed behavior, continues with the identification of causal mechanisms and contextual interpretation, and, when the nature or consequences of the decision so require, incorporates human oversight. Likewise, Figure 5 synthesizes this procedure and shows how the philosophical perspectives are articulated as complementary resources to broaden the diagnostic and decision-making capacity.

3.5 Environmental philosophy in industrial automation

The final methodological component incorporated environmental philosophy as a criterion for analyzing the implications of technological decisions within industrial automation systems. To this end, the categories obtained from the document analysis were examined considering not only their contribution to technical and operational performance, but also their relationship with the responsible use of resources, energy efficiency, process sustainability, and the environmental consequences derived from industrial decisions. This procedure made it possible to broaden the conception of the capabilities required in Industry 4.0, recognizing that the selection, configuration, and operation of intelligent technologies entail responsibilities that go beyond immediate outcomes and reach their future ecological effects, in line with approaches to environmental ethics applied to engineering [11]. Based on this integration, environmental responsibility was established as a fourth pillar of the proposed framework, complementing the quantitative explanation, causal understanding, and contextual interpretation developed in the preceding components.

4. Results

This section presents the results derived from the document analysis and the conceptual integration developed in the study. The presentation follows a sequence that moves from the identification of the capabilities associated with each philosophical current to their application at the different levels of industrial automation. First, the contributions of positivism, critical realism, and hermeneutics are examined; subsequently, these relationships are synthesized through correspondence matrices and thematic coding. On this basis, the philosophical mapping of the ISA-95 automation pyramid is constructed and the integrated capability plan is formulated. Finally, the philosophical-causal diagnostic algorithm is presented, together with the incorporation of environmental philosophy and human oversight as complementary dimensions for decision-making in intelligent systems.

4.1 Influence of logical positivism on operational competencies

The analysis of the corpus made it possible to identify that a significant part of the operational capabilities described in the automation literature is grounded in principles related to observation, measurement, and quantitative verification. Indicators such as overall equipment effectiveness, defect rates, or return on investment represent this orientation, as they provide objective criteria for evaluating process behavior and establishing corrective actions. From this perspective, positivism provides a necessary basis for ensuring control, predictability, and consistency at the operational levels of automation. However, its isolated application can prove insufficient when explaining an anomaly requires understanding causal structures that are not directly observable. This limitation is therefore consistent with what was noted by Lysak [2], who warns that the absence of explicit philosophical foundations in engineering education can lead to insufficient ontological interpretations of a system's real capabilities, particularly when machine-learning components are involved whose internal logic cannot be explained solely through quantifiable results. Positivism therefore constitutes a fundamental basis for operational competencies, but needs to be complemented with forms of reasoning capable of addressing structural causes, contexts of use, and the implications of technological decisions.

Likewise, this need for complementarity is also related to what was proposed by Ferdman and Ratti [5], who show that the ideal of value neutrality inherited from positivism can make it difficult for professionals to recognize the ethical and social dimensions embedded in technological designs themselves. Accordingly, the proposed capability plan retains quantitative and technical competencies as the basis of industrial performance, but avoids treating them as sufficient to respond to situations that demand causal explanations, contextual interpretation, or an assessment of consequences.

4.2 Contribution of critical realism to structural resilience

This section analyzes the contribution of critical realism to the understanding of problems that cannot be solved by observing only the visible data of an industrial system. While positivism makes it possible to measure a deviation, identify an alarm, or verify that a variable exceeded a given threshold, critical realism directs the analysis toward an additional question: what mechanisms or conditions caused that event to occur? This perspective is especially relevant in interconnected automation systems, where the same failure can originate from different combinations of factors. To address this complexity, causal retroduction is used, understood as a form of reasoning that starts from the observed event and seeks to identify the mechanisms capable of explaining it [6]. Thus, faced with a recurring machine stoppage, the professional not only records its frequency, but also examines possible relationships among sensors, programming, maintenance, and operating conditions.

This way of analyzing problems contributes to structural resilience because it makes it possible to move from correcting the immediate effects of an anomaly to understanding and addressing the causes that favor its occurrence. Rieder et al. [7] show that the identification of these generative mechanisms can be organized through explicit procedures, making it possible to translate this philosophical foundation into systematic diagnostic processes. In this way, in the proposed framework, critical realism does not replace positivism, but rather extends its explanatory capacity when quantitative indicators leave questions unresolved, making it possible to formulate possible causes, contrast them with the available evidence, and guide actions on the structure that gives rise to the problem. This complementarity constitutes one of the foundations of Algorithm 1, developed later in Section 4.5.1, where this reasoning is incorporated as part of the diagnostic and decision-making process.

4.3 Impact of hermeneutics on human-centered design

After broadening the analysis from the measurement of events to the understanding of the mechanisms that produce them, hermeneutics incorporates a third perspective that makes it possible to consider the human and contextual conditions present in the functioning of automated systems. From this viewpoint, a decision does not depend solely on the available data or on the identification of its possible causes, but also on the way operators interpret information, understand a situation, and act in response to it; this capability therefore takes on special relevance when intelligent systems participate in supervision, recommendation, and decision-support tasks, where the interaction between people and technology becomes part of the decision-making process itself. This orientation is consistent with recent studies on human-centered design in Industry 4.0 and 5.0 scenarios, which highlight the need to move beyond an exclusively instrumental conception of automation [9, 10].

In this sense, hermeneutics contributes concepts such as pre-understanding and the interpretation of context, through which a failure or an unexpected response ceases to be understood exclusively as a technical occurrence and begins to be analyzed also from the experience of those who interact with the system. Grunwald et al. [8] argue that breakdown situations make it possible to reconsider the relationship among people, systems, and the circumstances in which both interact; applied to industrial automation, this means that a misunderstood alarm, a rarely used interface, or an operator's resistance to an algorithmic recommendation can reveal difficulties that do not necessarily originate in the technical configuration. In this way, hermeneutics completes the path begun with positivist measurement and extended through the causal explanation of critical realism, incorporating the understanding of context as a capability necessary for interpreting situations of greater complexity.

This articulation makes it possible to understand the three currents as complementary perspectives within the same decision-making process, since while positivism provides criteria for observing, measuring, and verifying the behavior of the system, critical realism makes it possible to delve into the mechanisms that can explain that behavior, and hermeneutics incorporates the human and contextual conditions that intervene in its interpretation. In order to make this complementarity explicit, Table 1 organizes the main correspondences identified between each philosophical current, its approach to analysis, the competency it prioritizes, and its impact on decisions in industrial automation.

Tabla 1. Matrix of philosophical currents and their impact on automation capabilities

Philosophical current	Main approach	Prioritized competency	Impact on decision-making	Ref.
Positivism	Empiricism, quantification, logical laws	Hard technical skills, programming, precise control	Linear optimization and operational efficiency	[5]
Critical realism	Stratified ontology, causal retroduction	Failure analysis, systemic resilience	Deep structural diagnosis in the face of anomalies	[6, 7]
Hermeneutics	Interpretation of meaning and contexts	Human-centered design, innovation	Socio-technical integration and cultural adaptability	[8, 9, 10]

As shown in Table 1, the difference between the currents does not lie in one replacing the others, but in the type of problem each one makes it possible to address in greater depth. Thus, the measurement and control provided by positivism constitute a basis for recognizing the observable behavior of the system, on which critical realism extends the explanation toward causal mechanisms, while hermeneutics incorporates the interpretation of human and contextual conditions. Consequently, an increase in the complexity of a decision requires progressively broadening the capabilities mobilized, making it possible to move from a predominantly technical response toward an understanding that articulates data, causes, and context.

Establishing this conceptual correspondence also requires showing how it was supported by the documentary corpus, since the construction of the framework did not rely exclusively on publications directly linked to positivism, critical realism, and hermeneutics. On the contrary, during coding, complementary contributions related to dynamic capabilities, automation architecture, human oversight, environmental philosophy, and methodological foundations were identified, which made it possible to connect the philosophical currents with problems specific to intelligent industrial systems. This organization is presented in Table 2, which shows the thematic distribution of the 22 sources that made up the documentary corpus.

Tabla 2. Thematic coding matrix of the documentary corpus

Thematic category	No. of sources	References
Positivism and technical training	1	[5]
Critical realism and retroduction	2	[6, 7]
Hermeneutics and human-centered design	3	[8, 9, 10]
Environmental philosophy and engineering ethics	1	[11]
Organizational dynamic capabilities	2	[18, 20]
Human oversight and AI system agency	6	[3, 12, 4, 13, 21, 22]
Industrial automation architecture	3	[1, 17, 19]
Philosophy and engineering education	1	[2]
Literature review method	3	[16, 15, 14]

Based on the distribution presented in Table 2, it can be observed that the documentary support for the framework extends beyond the three philosophical currents directly analyzed, since their application to the industrial context requires establishing links with other fields that explain how these forms of reasoning can be translated into concrete capabilities. In particular, the greater presence of studies related to human oversight and AI system agency evidences the importance that professional judgment acquires as intelligent systems increase their participation in decision-making; at the same time, sources on automation architecture provide the technological structure needed to situate these capabilities at concrete levels of operation, supervision, planning, and management. This connection makes it possible to move forward toward the philosophical mapping of the automation pyramid developed in the following subsection.

4.4 Philosophical mapping of the automation pyramid

Once the particular contributions of each current had been identified, the next result consisted of determining how these forms of reasoning can be related to the different levels of industrial automation. To this end, the hierarchical organization of ISA-95 [1, 17] was used as a reference, establishing a correspondence between technological level, the predominant nature of the decision, and the required philosophical perspective. Table 3 presents this mapping and makes it possible to observe how the need to integrate different forms of reasoning increases as decisions go beyond the immediate operational response.

Tabla 3. Levels of the automation pyramid, type of decision, and dominant philosophical current

Level	Type of decision	Dominant current	Ref.
Field (sensors and actuators)	Reactive	Positivism	[1, 17]
Control (PLC/DCS)	Programmed	Positivism with causal anticipation	[1, 17]
Supervision (SCADA/HMI)	Tactical	Critical realism + hermeneutics	[19, 8]
Planning (MES/MOM)	Strategic	Critical realism + hermeneutics	[19, 10]
Management (ERP)	Corporate	Integration of the three currents + environmental philosophy	[1, 11]

Table 3 shows a progression in the complexity of the reasoning required. At the field and control levels, decisions based on measurements, rules, and previously established conditions predominate, while at the supervision and planning levels the need to explain causal mechanisms and interpret the context of interaction with operators increases. At the management level, where decisions affect the organization as a whole and can produce consequences of greater scope, the proposal converges toward an integration of the three currents together with environmental considerations. This progression is spatially represented in Figure 3, where the ISA-95 structure makes it possible to visualize the transition from a predominantly positivist base toward levels in which a progressive combination of philosophical perspectives is required.

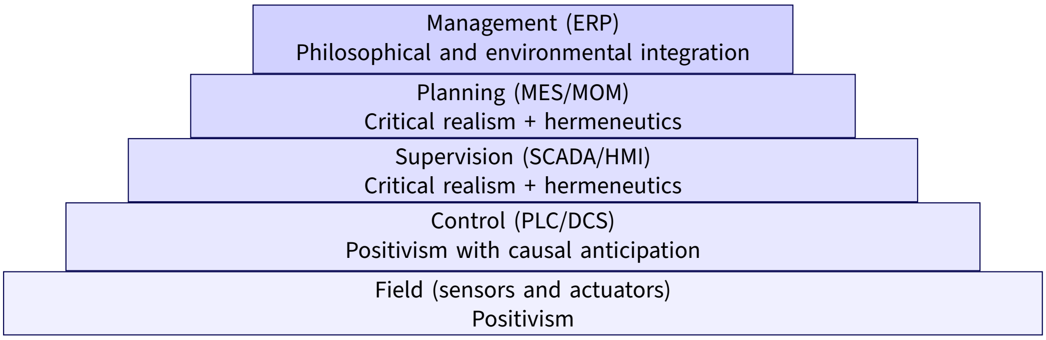

Figura 3. ISA-95 automation pyramid mapped according to the dominant philosophical current at each decision level [1]

Indeed, Figure 3 makes it possible to observe that the philosophical currents are not assigned as independent compartments. On the contrary, their participation broadens as the scope of the decision increases. Positivism retains its function at all levels because quantitative information continues to be necessary; however, at higher levels it proves insufficient without a causal and interpretive understanding capable of incorporating organizational and human conditions. In this direction, and with the purpose of making this overlap visible, Figure 4 conceptually represents the degree of convergence between quantitative and contextual reasoning across the levels of automation. Blue identifies the predominance of empirical and quantitative verification, while red represents the growing need for contextual interpretation. The intersection zone shows the space in which both approaches need to be articulated through causal reasoning.

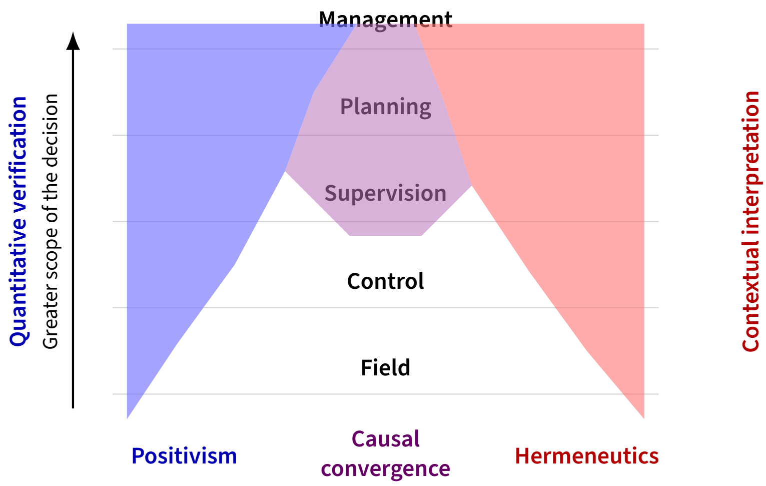

Figura 4. Conceptual convergence of philosophical perspectives according to the level of industrial automation

In this way, Figure 4 reinforces a central idea of the proposed framework: moving up within the automation structure does not mean abandoning the quantitative capabilities developed at the lower levels, but rather progressively incorporating other forms of reasoning. In this sense, the convergence zone symbolizes the articulating function of critical realism, which makes it possible to move from empirical observation toward the explanation of mechanisms and, subsequently, toward the contextual interpretation required by decisions of greater scope.

4.5 Proposal for the integrated capability plan

Once the relationship between the philosophical currents and the different levels of the automation pyramid had been established, the next step consisted of translating these correspondences into concrete capabilities that could guide professional training and performance. Under this logic, the proposed plan does not treat competencies as isolated technical knowledge, but as capabilities that complement one another as the complexity of the problem to be solved increases. Thus, an operational situation may initially require measurement and control, while a recurring failure calls for delving into its possible causes, and a decision involving people additionally demands understanding the context in which it occurs. Environmental responsibility is added to these capabilities as a cross-cutting criterion, given that technological decisions can also generate consequences for resources and the environment. This organization is synthesized in Table 4, where each layer is related to a philosophical current, a set of competencies, and an example of industrial application.

Tabla 4. Integrated capability plan by layer, philosophical current, and application example

Layer	Current	Key competencies	Application example	Ref.
Operational	Positivism	PLC/SCADA programming, sensor calibration, statistical process control	Parameter adjustment in response to an OEE deviation	[5]
Tactical	Critical realism	Causal retroduction, failure mode and effects analysis (FMEA)	Diagnosis of a generative mechanism following recurring failures	[7]
Strategic	Hermeneutics	Contextual interpretation, human-centered interface design	Redesign of SCADA alerts following operator resistance	[9, 10]
Cross-cutting (ethical)	Environmental philosophy	Ecological footprint assessment, intergenerational justice	Prioritization of investments according to environmental impact	[11]

As shown in Table 4, the plan follows a progression in which each layer broadens the capabilities of the previous one rather than replacing them. Thus, the operational layer provides the tools to program, measure, and control the process, while the tactical layer incorporates causal retroduction to investigate which mechanisms may lie behind a recurring failure [7]; when the decision reaches situations involving operators, interfaces, and particular conditions of use, the strategic layer adds contextual interpretation and human-centered design [9, 10]. In turn, environmental philosophy runs across the three layers to incorporate an additional question into the decision: beyond determining whether a solution works and responds to the problem identified, it is necessary to consider what consequences it may produce for resources, the environment, and future generations [11].

This integration therefore implies that the required capabilities do not remain fixed, since industrial problems, available technologies, and operating conditions change over time; for this reason, the proposed structure is related to dynamic-capabilities theory [18], according to which competencies must be able to be combined, adapted, and reconfigured in the face of new circumstances. In the same direction, Teece [20] links technological innovation to organizations' capacity to transform and articulate their resources and competencies, making it possible to understand the plan not as a rigid sequence of knowledge, but as an adaptable structure. On this basis, the next step consists of turning this conceptual integration into a procedure that guides which type of reasoning should be used when facing a specific anomaly, a purpose that gives rise to the philosophical-causal diagnostic algorithm presented below.

4.5.1 Philosophical-causal diagnostic algorithm

To translate the capability plan from its conceptual formulation into an applicable reasoning sequence for industrial anomalies, Algorithm 1 was developed. Its purpose is to determine which type of analysis should be prioritized as the difficulty of explaining an event through the usual control mechanisms increases. The procedure begins with quantitative verification, continues with the identification of causal mechanisms when that verification proves insufficient, incorporates the interpretation of the human–machine context when applicable, and finally establishes an instance of human oversight for decisions mediated by artificial intelligence systems whose behavior is not sufficiently transparent.

Algorithm 1 Philosophical-causal diagnosis for decision-making in response to an anomaly in industrial automation

```
Require: Empirical event e detected at level L of the automation pyramid
Ensure: Decision d and the philosophical current supporting it
Positivist verification: assess whether e is explained by established quantitative thresholds (OEE, defect rates, control limits)
if e is explained by quantitative thresholds then
    return d ← standard corrective action (positivism)
else
    Causal retroduction: decompose e into agents, events, and conditions [7]
    Conjecture candidate generative mechanisms and rule out those that are not plausible by contrasting them with the process's historical evidence
    if a single, plausible generative mechanism is identified then
        return d ← structural action targeting the mechanism (critical realism)
    else
        Hermeneutic interpretation:
        if e involves human–machine interaction (HMI/SCADA) then
            Interpret the operating context, the operator's cognitive load, and the meaning of the alert [8]
            return d ← interface or procedure redesign (hermeneutics)
        end if
    end if
end if
if e involves an opaque decision-making AI component then
    Human-oversight escalation: suspend autonomous execution and transfer the decision to an operator with integrated philosophical training [3, 4, 12]
end if
return d, the philosophical current(s) underlying it, and a traceable record of the decision
```

The sequence defined in Algorithm 1 follows a logic of progressive escalation. If the event can be understood through established indicators and thresholds, the decision remains at the operational level; when these elements prove insufficient, the search for causal mechanisms is activated, and if the situation involves human–machine interaction factors, the diagnosis is broadened toward contextual interpretation. Human oversight constitutes the safeguard level when intelligent systems are involved whose recommendation cannot be sufficiently clearly justified. This principle draws on the work on effective human oversight by Langer et al. [4] and Sterz et al. [12], as well as on the algorithmic-governance criteria proposed by Laux [3].

To facilitate the interpretation of this sequence, Figure 5 translates the logic of Algorithm 1 into a visual representation showing the path from the detection of the event to the recording of the decision and its philosophical foundation.

As shown in Figure 5, the procedure does not require applying all philosophical perspectives simultaneously, but rather incorporating additional levels of reasoning when the nature of the problem exceeds the explanatory capacity of the previous level. In practical terms, this organization responds to the question of what an automation team should attend to first when facing an anomaly and when the diagnosis should be broadened. In this way, the proposal avoids both reducing every problem to quantitative indicators and automatically shifting responsibility to an intelligent system. Algorithm 1 thus constitutes a conceptual proposal derived from the theoretical integration carried out in the study and, therefore, does not aim to replace the specific safety, maintenance, or control protocols existing in an industrial facility. Its contribution consists of providing an explicit and traceable sequence for identifying the type of reasoning required and documenting the basis of the decision adopted. The empirical evaluation of its behavior in real plant scenarios is proposed as a subsequent line of research.

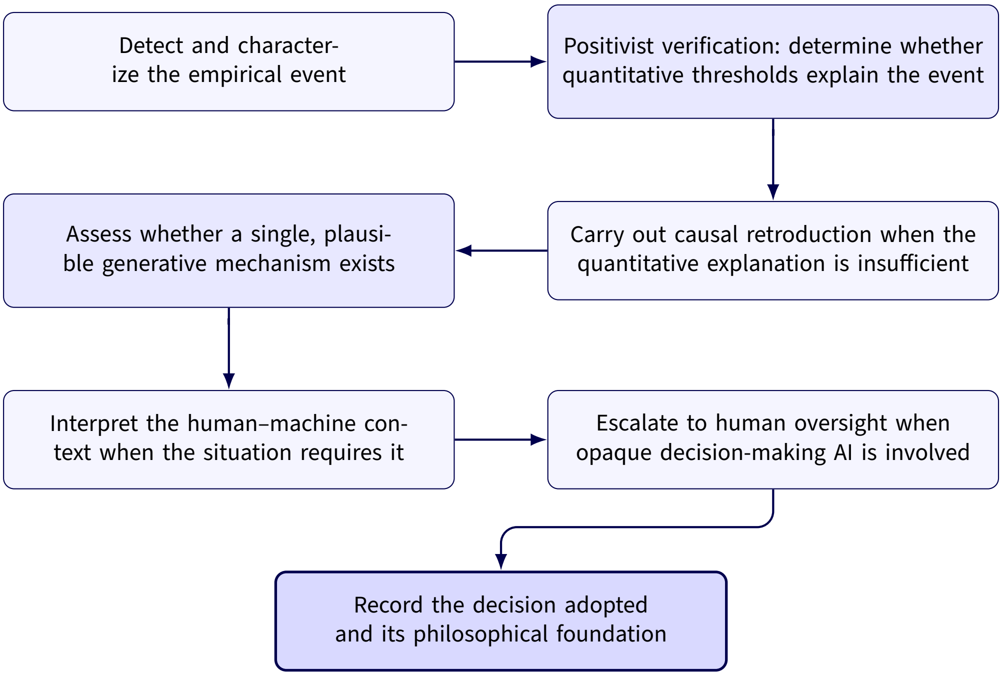

Figura 5. Representation of the philosophical-causal diagnostic procedure defined in Algorithm 1

4.6 Environmental philosophy, ethics, and values in industrial automation

Once the capabilities for measuring events, understanding their causes, and interpreting the context in which they occur have been integrated, it becomes necessary to broaden the analysis toward the consequences that a technological decision can produce beyond the immediate functioning of the system. From this perspective, an automation solution should not be evaluated solely for its ability to increase productivity, reduce errors, or improve control, but also for the way it uses resources and for the effects it may generate on the environment. At this point, environmental ethics applied to engineering [11] provides criteria for considering energy consumption, efficiency in the use of materials, ecological impact, and responsibility toward future generations; environmental philosophy is therefore incorporated into the framework as a cross-cutting dimension that accompanies the evaluation of decisions adopted at the different levels of automation.

This incorporation, in turn, makes it possible to connect environmental responsibility with the three forms of reasoning developed previously, so that each contributes from a different but complementary function. Thus, positivism provides indicators for measuring energy consumption, emissions, or resource efficiency; critical realism makes it possible to investigate the design, production, and operating conditions that may be generating certain impacts, while hermeneutics broadens the analysis by considering who may be affected, what values come into play in the decision, and what consequences may project into the future. This articulation explains its incorporation as a cross-cutting dimension in Table 4, since an industrial decision should not respond solely to the question of whether a solution works, but also to whether its results are environmentally responsible and justifiable over time [11].

4.7 Human–AI interaction and philosophically informed oversight

The incorporation of this responsibility broadens the criterion by which technological decisions are evaluated and leads to an equally important question: determining who should retain the capacity to judge and assume responsibility when an intelligent system actively participates in a decision. This question becomes relevant when artificial intelligence ceases to be limited to information processing and begins to generate recommendations or intervene in industrial processes, because the decision comes to be constructed through the interaction between professional knowledge and the system's capabilities. Vallor and Vierkant [13] explain this relationship through a conception of agency distributed between human and technological components; however, this interaction does not imply fully transferring judgment to the algorithm, since a recommendation based on large volumes of data may also need to be questioned when its results are not sufficiently explainable or do not adequately respond to the context [3, 12, 4].

For this reason, the proposed human oversight does not consist solely of observing what the system does, but of having the capabilities needed to accept, question, or halt a recommendation when circumstances justify it. In this process, critical realism makes it possible to examine the causes and structures that can explain an algorithmic response [6, 7], while hermeneutics helps interpret its meaning within the human and organizational context [8]. In this way, human–AI collaboration combines the system's analytical capabilities with professional knowledge and judgment [21], while also making it possible to maintain traceability regarding responsibility for the decision [22]. Therefore, Table 4, Algorithm 1, and Figure 5 converge on a framework in which quantification, causal explanation, contextual interpretation, environmental responsibility, and human oversight act in a complementary manner.

5. Discussion

Based on the results obtained, the main contribution of the study lies in showing that training for Industry 4.0 requires broadening the technical domain toward capabilities that make it possible to explain, interpret, and evaluate the decisions made in intelligent automation systems. In this sense, the predominance of the positivist approach is adequate for developing measurement, programming, and control competencies, but may prove insufficient when the professional faces problems that cannot be understood solely through quantitative indicators. This interpretation is consistent with Lysak [2], who warns that engineering education without sufficiently integrated philosophical foundations can generate epistemological and ethical limitations, especially in the face of technologies with greater autonomy. The proposal presented in Table 4 therefore broadens technical competencies through causal, interpretive, and environmental capabilities that can be combined as the complexity of the decision increases, in correspondence with dynamic-capabilities theory [18].

This need to broaden reasoning becomes more evident when an anomaly cannot be explained through the available data, since knowing what happened does not necessarily mean understanding why it happened. In response to this difference, critical realism contributes causal retroduction as a way of investigating the mechanisms that may generate a given event [6, 7], while hermeneutics makes it possible to extend the analysis toward the way operators and other actors interpret the situation within their context. This complementarity is consistent with approaches to human-centered design in Industry 4.0 and 5.0 [9, 10] and finds an operational expression in Algorithm 1, whose sequence is represented in Figure 5. In this way, the proposal connects the philosophical foundations with a procedure that guides when to measure, when to seek causes, and when to incorporate contextual interpretation.

Now, this integration takes on additional importance when artificial intelligence participates directly in recommending or executing decisions, since in these scenarios it is not enough to determine whether the system achieves a technically correct result, it must also be possible to question its reasoning and recognize its consequences. The literature warns that human oversight can lose effectiveness when the professional lacks sufficient knowledge to evaluate an algorithmic recommendation and ends up accepting it passively [3, 12, 4]. In response to this problem, the human-oversight point incorporated in Algorithm 1 seeks to preserve the professional's capacity for judgment, while the environmental dimension included in Table 4 extends that judgment toward ecological and future consequences [11]. Indeed, both elements make it possible to understand automation as a process in which efficiency, responsibility, and the capacity for questioning must remain interrelated.

Along the same lines, the results should be interpreted considering the documentary and conceptual scope of the study, given that the proposed relationships stem from the analysis and articulation of the sources organized in Table 2 and not from tests conducted with professionals or operating industrial systems. Consequently, both the integrated capability plan in Table 4 and Algorithm 1 constitute conceptual proposals grounded in the literature, but still require empirical evaluation to determine their behavior in real automation situations. This limitation, in turn, establishes a natural continuity for future research, which could apply the framework in industrial plants, analyze its usefulness against different types of anomalies, and assess whether professionals trained under these capabilities improve the explanation, interpretation, and oversight of automated decisions. In this way, future validation will make it possible to determine to what extent the proposed philosophical integration can be effectively translated from the conceptual level into industrial practice.

6. Conclusions

The purpose of this work was to analyze the relationship between philosophical currents and decision-making in intelligent industrial automation systems, with the aim of proposing an integrated capability framework for Industry 4.0. Based on the document analysis, it is concluded that positivism provides an indispensable basis for the measurement, verification, and control of processes, although its scope is limited when decisions require understanding non-evident causes, interpreting human situations, or responding to increasingly complex intelligent systems; in these scenarios, critical realism broadens the reasoning through the identification of causal mechanisms, while hermeneutics incorporates the understanding of context and of the interactions between people and technology. In addition, the articulation of these perspectives makes it possible to propose a professional training that is not limited to the technical domain, but integrates quantitative, causal, and interpretive capabilities to respond to problems of different complexity. To this is added environmental philosophy as a cross-cutting dimension, through which technological efficiency is related to the responsible use of resources, ecological consequences, and responsibility toward future scenarios. In this context, the study contributes a transdisciplinary perspective for strengthening professionals' capacity to understand, question, and oversee decisions in progressively automated industrial environments, keeping human judgment as a necessary element in the face of the growing participation of artificial intelligence.

As a future line of work, it is proposed to move from the conceptual construction developed in this study toward its validation in real industrial settings, through case studies or action-research processes with professionals involved in automation. This stage would make it possible to assess whether the proposed capabilities effectively contribute to recognizing anomalies, understanding their causes, interpreting situations of human–machine interaction, and strengthening the oversight of decisions supported by intelligent systems; for this purpose, interviews, direct observation, and other instruments could be used to contrast the framework with professionals' experience and with concrete plant situations. Likewise, future research could broaden the documentary corpus by incorporating other databases, languages, and industrial contexts, in order to determine whether the philosophical relationships identified retain their relevance across different traditions of engineering education and technological environments. In this way, it would be possible to progressively strengthen the practical validity and generalizability of the proposed framework.

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Statement on the Use of Artificial Intelligence. The authors used generative artificial intelligence tools exclusively to support the structural reorganization of the manuscript and the improvement of the text's style. The analysis, documentary interpretation, design of the proposed algorithm, and conclusions are the exclusive intellectual responsibility of the authors, who validated and approved the final version.

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