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KNOWLEDGE CAPTURE AS A CONTROL PROBLEM IN INDUSTRIAL OPERATIONS: AN ENGINEERING APPROACH TO OPERATIONAL KNOWLEDGE CAPTURE IN DYNAMIC SYSTEMS

CAPTURA DE CONHECIMENTO COMO UM PROBLEMA DE CONTROLE EM OPERAÇÕES INDUSTRIAIS: UMA ABORDAGEM DE ENGENHARIA PARA A CAPTURA DE CONHECIMENTO OPERACIONAL EM SISTEMAS DINÂMICOS

LA CAPTURA DE CONOCIMIENTO COMO PROBLEMA DE CONTROL EN OPERACIONES INDUSTRIALES: UN ENFOQUE DE INGENIERÍA PARA LA CAPTURA DE CONOCIMIENTO OPERACIONAL EN SISTEMAS DINÁMICOS

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Carolina Lago Pena Maia

ABSTRACT
Operational knowledge capture in connected industrial environments has often been discussed in recent literature through digitalization and knowledge management perspectives, yet without a technical framing that represents its temporal dynamics under real operating conditions. This article aims to propose an engineering approach that treats operational knowledge capture as a dynamic systems and control problem, enabling its description in terms of states, disturbances, and technical actuators. The methodology is theoretical and conceptual, based on an analytical review of studies published over the last five years and on the development of a conceptual model integrating cyber-physical systems foundations, human-in-the-loop architectures, adaptive automation, and cognitive support structures. The results organize the literature around a formalization of a “knowledge system”, defining states related to knowledge externalization, accessibility, and reuse, operational disturbances associated with variability and unexpected events, and technical actuators such as sensors, multimodal records, digital platforms, and AI- based assistance mechanisms. The discussion shows that purely manual processes tend to produce informational instability, low traceability, and recurring loss of operational learning, whereas integrated architectures support knowledge consolidation and reuse as part of production system behavior. It is concluded that formalizing knowledge capture as a technical problem strengthens analytical and design capabilities for self-learning industrial solutions, enhancing the integration between human cognition, automation, and operational performance.

Keywords: Operational Knowledge. Knowledge Capture. Dynamic Systems. Control Engineering. Human-In-The-Loop.

RESUMO
A captura de conhecimento operacional em ambientes industriais conectados é frequentemente abordada na literatura recente por perspectivas voltadas à digitalização e à gestão do conhecimento, porém sem um enquadramento técnico que represente sua

dinâmica ao longo do tempo em condições reais de operação. Este artigo tem como objetivo propor uma abordagem de engenharia que trata a captura de conhecimento operacional como um problema de sistemas dinâmicos e controle, permitindo descrevê- la por meio de estados, distúrbios e atuadores técnicos. A metodologia adotada é teórico-conceitual, baseada em revisão analítica de estudos publicados nos últimos cinco anos e na construção de um modelo conceitual que integra fundamentos de sistemas ciber-físicos, arquiteturas human-in-the-loop, automação adaptativa e estruturas de suporte cognitivo. Os resultados organizam a literatura em torno de uma formalização do "sistema de conhecimento", definindo estados associados à externalização, acessibilidade e reutilização do conhecimento, distúrbios operacionais ligados à variabilidade e eventos inesperados, e atuadores técnicos como sensores, registros multimodais, plataformas digitais e mecanismos de assistência por IA. A discussão evidencia que processos puramente manuais tendem a gerar instabilidade informacional, baixa rastreabilidade e perda recorrente de aprendizagem operacional, enquanto arquiteturas integradas favorecem consolidação e reutilização do conhecimento como parte do comportamento do sistema produtivo. Conclui-se que a formalização da captura de conhecimento como problema técnico amplia a capacidade de análise e projeto de soluções industriais autoaprendentes, fortalecendo a integração entre cognição humana, automação e desempenho operacional.

Palavras-chave: Conhecimento Operacional. Captura de Conhecimento. Sistemas Dinâmicos. Engenharia de Controle. Human-In-The-Loop.

RESUMEN

La captura de conocimiento operativo en entornos industriales conectados se aborda con frecuencia en la literatura reciente desde perspectivas centradas en la digitalización y la gestión del conocimiento, pero sin un marco técnico que represente su dinámica a lo largo del tiempo en condiciones operativas reales. Este artículo pretende proponer un enfoque de ingeniería que considera la captura de conocimiento operativo como un problema dinámico de sistemas y control, permitiendo su descripción mediante estados, perturbaciones y actuadores técnicos. La metodología adoptada es teórico-conceptual, basada en una revisión analítica de estudios publicados en los últimos cinco años y en la construcción de un modelo conceptual que integra fundamentos de sistemas ciberfísicos, arquitecturas con interacción humana (human-in-the-loop), automatización adaptativa y estructuras de soporte cognitivo. Los resultados organizan la literatura en torno a una formalización del «sistema de conocimiento», definiendo estados asociados con la externalización, la accesibilidad y la reutilización del conocimiento, perturbaciones operativas vinculadas a la variabilidad y eventos inesperados, y actuadores técnicos como sensores, registros multimodales, plataformas digitales y mecanismos de asistencia de IA. El análisis destaca que los procesos puramente manuales tienden a generar inestabilidad informativa, baja trazabilidad y pérdida recurrente de aprendizaje operativo, mientras que las arquitecturas integradas favorecen la consolidación y reutilización del conocimiento como parte del comportamiento del sistema productivo. Se concluye que formalizar la captura de conocimiento como un problema técnico amplía la capacidad de análisis y diseño de soluciones industriales de autoaprendizaje, fortaleciendo la integración entre la cognición humana, la automatización y el rendimiento operativo.

Palabras clave: Conocimiento Operacional. Captura de Conocimiento. Sistemas Dinámicos. Ingeniería de Control. Human-In-The-Loop.

1 INTRODUCTION

The growing complexity of contemporary industrial systems has increased the dependence on situated human decisions, made in real time, in environments marked by operational variability and intense coupling between physical and digital processes, which makes operational knowledge a structuring element of productive performance (Ciccarelli, 2023). In industrial architectures based on *cyber-physical systems*, this knowledge emerges as a distributed, dynamic, and strongly contextualized component, whose absence of formalization compromises the adaptability of the technical system as a whole (Harrison, 2021).

The knowledge acquired by experienced operators is progressively built from continuous interaction with the production process, manifesting itself through fine adjustments, anticipations, and interpretations that are rarely made explicit verbally or documentally (Ribeiro, 2022). This type of knowledge is implicit, situational, and experience-dependent, and is activated mainly in conditions not foreseen by formal operating models (Turner, 2021).

The Mechanisms documentation, how *Standard operating*
formal procedures and training, have historically been designed for contexts of operational stability and repetitiveness of tasks, assuming that knowledge can be completely described and transferred through static instructions (Iheukwumere- Esotu, 2022). In highly dynamic production systems, such mechanisms are limited in not capturing contextual variations, operational exceptions, and adaptations made at the level of everyday practice (Anshari, 2022).

The intensification of the pressure for productivity, associated with the reduction of operating margins and the increasing automation of processes, favors quick and improvised decision-making that remains restricted to the operator at the time of action (Chacón, 2021). Under these conditions, the knowledge generated during exception resolution tends to dissipate after the event, producing a systematic loss of organizational learning over time (Cimini, 2020).

The recurrent failure to capture this knowledge in real environments does not stem from the absence of digital technologies, but from the lack of a conceptual framework capable of representing the dynamics between operators, processes, and automated systems (Kalaboukas, 2021). The literature indicates that, without a model that integrates human cognition and technical control, *knowledge capture* initiatives remain fragmented and reactive, limiting their operational effectiveness (Lu, 2022).

Given this scenario, this paper proposes to treat operational knowledge capture as a control engineering problem, in which states, disturbances and actuators can be formally defined in dynamic industrial systems. The structure of the work includes a critical review of the literature, the proposition of a conceptual model and the discussion of its implications for the design of self-learning industrial systems based on *human-in-the-loop* and *Artificial Intelligence of Things*.

2 THEORETICAL FRAMEWORK

2.1 OPERATIONAL KNOWLEDGE IN INDUSTRIAL ENVIRONMENTS

Operational knowledge in industrial environments is made up of perceptions and interpretations that emerge in direct contact with production processes, where the reading of system signals, the understanding of process behavior, and the anticipation of events form a situated and continuously updated decision-making basis (Ciccarelli, 2023). In advanced automation scenarios, this knowledge manifests as human mediation over the operation, functioning as an interpretive layer that connects process data, production goals, and actual factory floor conditions (Turner, 2021).

The literature that discusses the workforce in Industry 4.0 describes the contemporary operator as someone inserted in digital ecosystems, with responsibilities that transcend the execution of tasks and move to coordination, supervision, and decision-making in contexts of operational variability (Ciccarelli, 2023). This transition reorganizes the nature of the knowledge required in the industrial environment, as operators start to deal with more opaque systems from a causal point of view, which amplifies the need for experience-based interpretations (Harrison, 2021).

When processes are modeled by connected architectures, the operation becomes mediated by digital layers that collect, aggregate, and display information, but the final reading still depends on the human ability to produce meaning from incomplete events and noise present in the measurements (Chacón, 2021). Therefore, operational knowledge tends to be associated with pattern recognition, situational diagnosis, and fine-tuning skills, characteristics that develop over time and stabilize as practical repertoires, rather than as formally teachable content (Ribeiro, 2022).

The perspective of dynamic systems applied to the industrial environment favors understanding operational knowledge as a temporal phenomenon, in which human decisions respond to disturbances, delays, and non-linearities that cross the production process, imposing continuous adaptations (Harrison, 2021). In this sense, the operator's knowledge can be seen as a latent variable that influences the performance of the system, as it acts on intervention choices, prioritization of actions, and interpretation of indicators that vary according to the state of the process (Cimini, 2020). In analyses of human mediation in automation, the worker's performance appears as an element that preserves the robustness of the operation when the automated system encounters unforeseen conditions, requiring contextual interpretation and selection of responses under time and resource constraints (Turner, 2021). This robustness, however, depends on knowledge that usually remains distributed in everyday practice and, therefore, is difficult to represent in static instructions or traditional documentary bases (Iheukwumere-Esotu, 2022).

The knowledge management literature connected to Industry 4.0 argues that digitalization changes the means of knowledge circulation, but it does not automatically solve the problem of transforming experience into shareable representation, as experience is indexed to the context and organized in tacit layers (Ribeiro, 2022). Thus, understanding operational knowledge requires recognizing its situation-dependence, its sensitivity to process changes, and its relationship to the ongoing interaction between humans and technical systems (Ciccarelli, 2023).

The concept of operator in recent industrial paradigms is also linked to the increase in interactions with digital interfaces, automated alerts, and model-generated recommendations, creating a scenario in which experience begins to dialogue with algorithmic outputs and synthesized representations of the process (Angulo, 2023). This dialogue produces a cognitive arrangement in which the operator maintains interpretive responsibility, selecting which signals are relevant, when to act, and how to adjust the operation in the face of uncertainties and imperfect data (Kalaboukas, 2021).

The operationalization of knowledge, in this sense, is associated with the ability to deal with variability and the contingent nature of decisions, since real production often includes micro-events that are not repeated with fidelity and require adaptive responses (Chacón, 2021). This phenomenon reinforces that operational knowledge is an emergent property of the coupling between individual, technology, and process, and not a fixed set of instructions stored in documents (Horejši, 2020).

The notion of self-adjusting systems suggests that the industry is moving towards architectures capable of reconfiguration and adaptation, but such a movement increases the complexity perceived by operators, as the behavior of the system can vary due to internal logics, rules, and built-in models (Harrison, 2021). As a result, operational knowledge becomes even more valuable when the operator needs to infer causalities, validate recommendations, and interpret behavioral changes in connected and dynamic systems (Lu, 2022).

The literature on cognitive *digital twins* indicates that digital representations of the process can incorporate models, histories, and inferences to support decisions, but the usefulness of these representations depends on how they align with the operator's practical knowledge, at the risk of producing an additional layer of informational complexity (Kalaboukas, 2021). In this approach, operational knowledge is also understood as a criterion for validating and adjusting the digital twin itself, since the operator compares representations and observed results to identify inconsistencies and calibrate interpretations (Lu, 2022).

The connected industrial environment tends to record events, sensors, and logs, but the existence of data does not imply the existence of shareable knowledge, as knowledge requires an interpretive structure, a link to action, and situational relevance to sustain interventions (Angulo, 2023). Therefore, the literature reinforces that operational knowledge remains a resource that is developed in practice and expressed at the time of decision, requiring models that consider temporality, variability, and human-machine interaction (Cimini, 2020).

2.2 CAPTURING, EXTERNALIZING AND REUSING KNOWLEDGE

Knowledge capture in industrial operations can be understood as a set of mechanisms aimed at transforming situated experiences into communicable representations, capable of being stored, shared, and reused in future decisions (Iheukwumere-Esotu, 2022). In the context of Industry 4.0, this process tends to be reconfigured by connected technologies, as sensors, traceability, and digital platforms expand the ability to record events, although the question remains of how to convert records into useful explanations for action (Ribeiro, 2022).

Externalization of knowledge is often treated as conversion of what is implicit in practice to explicit artifacts such as descriptions, procedures, and models, but this conversion faces difficulties when knowledge is produced by fine-tuning and context-dependent heuristics (Turner, 2021). Thus, the literature points out that externalizing operational knowledge requires understanding how operators interpret signals and how they make decisions under uncertainty, which requires representation structures aligned with human cognition and process behavior (Ciccarelli, 2023).

The reuse of knowledge, in turn, depends on the ability to retrieve pertinent information at the time of need, which involves indexing, contextualization, and search mechanisms that preserve the relationship between the event, the condition of the process, and the intervention carried out (Iheukwumere-Esotu, 2022). In connected production systems, this reuse can be supported by intelligent architectures capable of recommending actions, but such recommendations require criteria that integrate history, current state, and operational objectives to avoid generic suggestions (Angulo, 2023).

The literature on *human-in-the-loop* indicates that knowledge capture gains power when it incorporates the operator as an active element of curation, validation, and refinement of records, as the operator is able to attribute meaning and relevance to events that, in isolation, appear as noise in databases (Cimini, 2020). In this arrangement, externalization is not a mere transcription of actions, but a process of constructing representations that connect observed conditions, hypotheses of cause, and justifications for intervention, favoring future use in analogous situations (Turner, 2021).

The *cognitive digital twin* approach offers a framework in which the captured knowledge can be incorporated into models that evolve with the system, uniting operational data, process structure, and inferences for decision support (Lu, 2022). In this case, the reuse of knowledge becomes a function of the digital twin itself, which integrates event history and responses to suggest paths and predict consequences, as long as the representations are consistent with operational practice (Kalaboukas, 2021).

In connected and agile networks, knowledge capture needs to consider that decisions do not occur in isolation, but in chains of interdependence between production units, logistics, and supplies, which amplifies the need to represent cause-and-effect relationships at different scales (Kalaboukas, 2021). The literature suggests that operating models that combine connectivity and intelligence can structure knowledge capture as a continuous flow, in which events are interpreted, aggregated, and transformed into reviewable rules, parameters, or recommendations (Harrison, 2021).

Knowledge conversion can also be analyzed through collaborative platforms that organize operational content, procedures, and maintenance learning, allowing knowledge to consolidate itself as a living and continuously updated repository (Iheukwumere-Esotu, 2022). Even so, the effectiveness of this type of platform depends on integration with the context of use, because if the information is not actionable and contextualized, it tends to become a file consulted only in audits or formal training (Ribeiro, 2022).

The literature also shows that the capture of operational knowledge finds limits when the focus falls exclusively on textual documentation, as a significant part of the experience is manifested in gestures, inspection sequences, interpretation of sounds, vibrations, and temporal patterns perceived during the operation (Angulo, 2023). This favors the use of multimodal records and contextual annotation mechanisms, integrating media and process data to bring knowledge closer to the way it is actually produced and mobilized (Horejši, 2020).

The externalization of knowledge can be strengthened when associated with cognitive assistance systems that guide the operator during execution and, simultaneously, record decisions, justifications, and system conditions, creating interpretable traces of the decision-making process (Angulo, 2023). This type of approach allows knowledge to be recorded not only after the event, but during the action itself, preserving temporality, context, and practical reasoning that would otherwise be lost in retrospective reports (Ciccarelli, 2023).

The Industry 4.0 and knowledge management literature also highlights that reuse depends on informational governance, as the multiplication of data and records can produce excess information, reducing the ability to locate relevant learning at the right time (Anshari, 2022). Thus, knowledge capture requires criteria for curation, validation, and continuous updating, allowing records to remain connected to the state of the system and actual operating conditions (Ribeiro, 2022).

The formalization of knowledge in industrial systems can take the form of operational models capable of representing processes, states, and interventions, bringing knowledge capture closer to a modeling and control problem in dynamical systems (Harrison, 2021). This approach opens space to treat knowledge as part of an architecture that feeds back into the system's performance, incorporating records and inferences in cycles of adjustment and learning over time (Chacón, 2021).

2.3 SOPS, FORMAL TRAININGS, AND MANUAL DOCUMENTATION

Standard *operating procedures* and formal training are traditional standardization practices that seek to stabilize execution and reduce performance variations, structuring knowledge under prescriptive and sequential formats (Iheukwumere-Esotu, 2022). This type of documentation usually works best when the process is relatively predictable and when the operating conditions remain close to the hypotheses used to construct the procedure (Chacón, 2021).

In Industry 4.0, the growing presence of automation and connectivity reorganizes the relationship between prescription and execution, as operators interact with systems that can change parameters and states quickly, making strict adherence to fixed procedures less compatible with operational reality (Harrison, 2021). The literature on automation mediator worker describes that, in scenarios with high variability, documented procedures tend to be reinterpreted, adapted, or temporarily ignored in favor of responses more aligned with the real state of the system (Turner, 2021).

Formal trainings often impart operating models based on optimal flows, leaving gaps when the operator needs to act under unforeseen conditions, such as intermittent failures, raw material variations, response delays, and contradictory signals (Ciccarelli, 2023). In this sense, the literature points out that the knowledge transferred in training tends to privilege general rules, while operational knowledge is consolidated as a repertoire of exceptions, adjustments, and heuristics that arise in prolonged contact with the process (Ribeiro, 2022).

Manual documentation is also crossed by practical limitations related to the time available to record occurrences, the vocabulary used, and the difficulty of translating sensory perceptions and reasoning situated in standardized language (Iheukwumere-Esotu, 2022). In real operations, writing tends to be later than the event and, therefore, loses temporal and contextual elements, resulting in incomplete records that rarely capture the logic that motivated the operator's decision (Angulo, 2023).

The presence of digital systems can expand the production of records, but this does not mean that documentation automatically becomes more useful, as the operational value of the record depends on its link with system states, initial conditions, intervention performed, and observed effects (Lu, 2022). The literature on *cognitive digital twins* suggests that documentation becomes more actionable when connected to models that recover relationships between events and consequences, allowing the record to move from narrative to being structured in terms of states and transitions (Kalaboukas, 2021).

Training based on fixed content can also disregard the rapid evolution of technologies and interfaces, which tends to generate a mismatch between what is taught and what is experienced in the connected productive environment (Anshari, 2022). Therefore, discussions on recent industrial paradigms indicate the need for cognitive support approaches that accompany execution and assist the operator during action, transforming learning into a continuous process associated with operation (Horejši, 2020).

The *human-in-the-loop manufacturing* literature highlights that standardized procedures can coexist with flexibility mechanisms when there are control architectures that incorporate human intervention as part of the system, allowing structured adjustments without abandoning traceability (Cimini, 2020). In this context, documentation can be rethought as a component of a control and learning architecture, in which the operator records interventions and reasoning in an integrated way with the system, reducing knowledge loss and increasing reuse (Turner, 2021). Purely manual records tend to prioritize the description of what was done, while what makes knowledge reusable is the understanding of why it was done, under what conditions, and with which discarded alternatives, dimensions that are difficult to standardize in traditional forms (Ciccarelli, 2023). For this reason, connected cognitive assistance systems can help transform documentation into a guided process, in which the operator structures the record with the support of prompts, categories, and automatic links with process data (Angulo, 2023).

Even when procedures are well described, their usefulness depends on the way they are found and applied, since, in operations with time constraints, the operator tends to resort to what is immediately accessible, favoring tacit knowledge and informal networks to the detriment of long manuals (Ribeiro, 2022). Thus, manual documentation, when disconnected from recommendation and contextualization systems, tends to operate as a compliance and audit file, and not as a daily decision support instrument (Iheukwumere-Esotu, 2022).

When documentation is integrated with adaptive automation architectures, it can become a reconfiguration resource, as rules, parameters, and records start to feed cycles of improvement and operational adjustment (Harrison, 2021). In this type of approach, procedures are no longer exclusively prescriptive and become components of a dynamic representation of the process, with the possibility of continuous updating based on captured operational experience (Chacón, 2021).

2.4 STRUCTURAL LIMITATIONS OF PURELY MANUAL PROCESSES

Purely manual processes of capturing and recording knowledge have structural limitations linked to dependence on human memory, fragmentation of the record, and low interpretative standardization, which compromises consistency and traceability over time (Ribeiro, 2022). In industrial environments with high variability, the absence of automatic contextualization mechanisms favors the emergence of generic records that do not preserve the link between event, system state, and applied response (Chacón, 2021).

The time limitation is recurrent, as the operator usually records only the minimum necessary to resume the production flow, failing to explain the reasoning, hypotheses, and signs that motivated the intervention, elements that are precisely the ones that would support future reuse (Turner, 2021). The literature on operator in Industry 4.0 indicates that the cognitive load associated with the supervision of automated systems makes it even less likely that the operator will produce detailed records without technological support, as their attention is consumed by the operation itself (Ciccarelli, 2023).

The multimodal nature of operational knowledge also imposes limits on the manual, since part of the experience involves sounds, vibrations, microvariations in time, and reading temporal patterns that are hardly accurately described in text, especially when the available language is standardized and restricted (Horejši, 2020). As a result, the knowledge that remains as perception tends to be lost when the record does not capture the sensory and temporal context in which the decision occurred (Angulo, 2023).

The lack of integration between records and process data reduces the ability to reconstruct causalities, since, without association with time series, setpoints, alarms, and operating conditions, human reports remain narratives disconnected from the actual behavior of the system (Lu, 2022). The literature on cognitive digital twins points out that the usefulness of the record grows when it is indexed to observable states and variables, allowing working memory to be reconstructed as a sequence of events linked to process conditions (Kalaboukas, 2021).

Manual processes also tend to generate heterogeneity of writing and vocabulary, which hinders standardization and subsequent search, as different operators describe similar events with different terms, reducing the ability to consolidate knowledge on a common basis (Iheukwumere-Esotu, 2022). This phenomenon reinforces that, without note-taking and curation structures, manual outsourcing favors dispersion and low reuse, even when there is an organizational intention to record learning (Ribeiro, 2022).

When the capture is done retrospectively, memory tends to reorganize the report, omitting uncertainties and intermediate attempts, which makes the record less faithful to the real dynamics of the decision and reduces its usefulness to guide future responses in similar situations (Turner, 2021). Thus, approaches that capture knowledge during execution, with the support of connected systems, preserve temporality and justifications, bringing the record closer to the practical logic used by the operator at the time of intervention (Angulo, 2023).

The adaptive automation literature also indicates that manual processes do not keep up with the speed of change of reconfigurable systems, as procedures can quickly become obsolete when the technical architecture itself is updated, changing parameters, interfaces, and operation flows (Harrison, 2021). In this scenario, manual records that are not updated in short cycles tend to lose adherence to the real system, reinforcing the dependence on local expertise and reducing consistency across shifts, teams, and plants (Chacón, 2021).

In addition, manual processes do not offer reliable automatic validation mechanisms, which allows incorrect or incomplete records to remain as a reference and be reused inappropriately, increasing operational risk and performance variability (Cimini, 2020). In architectures that incorporate model-based supervision and recommendation, it becomes possible to validate record coherence with process data and identify inconsistencies, transforming knowledge capture into a verifiable component of the operation (Lu, 2022).

The limitation of scale is equally evident, as industrial operations produce a large volume of micro-events and exceptions that cannot be fully recorded by human effort, generating selective sampling that leaves gaps in the points of greatest complexity (Iheukwumere-Esotu, 2022). For this reason, connected systems that automatically record events and allow guided contextual annotation can expand coverage, maintaining a link between occurrence and operating conditions, which favors consolidation of more complete operational memory (Angulo, 2023).

When knowledge capture is considered as dynamic, it becomes evident that manual processes introduce delays and noise in the feedback of the system, as the recording occurs outside the time of the operation and without guarantees of completeness, interfering with the ability to learn from operational disturbances in a systematic way (Harrison, 2021). This reading brings the problem closer to a control perspective, in which measurement delays and loss of information compromise stability and performance, reinforcing the need for more integrated technical capture mechanisms (Cimini, 2020).

2.5 CYBER-PHYSICAL SYSTEMS AND HUMAN-IN-THE-LOOP SYSTEMS

Systems based on *cyber-physical systems* integrate physical elements, sensors, connectivity, and digital decision layers, enabling continuous monitoring, reconfiguration, and coordination of processes in real time (Harrison, 2021). In this arrangement, human presence remains a component of decision and supervision, especially in conditions of uncertainty, where contextual interpretation and selection of interventions still require cognitive mediation (Turner, 2021).

The *human-in-the-loop manufacturing literature* describes architectures in which the operator is incorporated as a functional element of the control system, participating in decision-making and process adjustment in a structured and traceable way (Cimini, 2020). This incorporation makes it possible to treat human intervention as part of a feedback loop, in which operator decisions are recorded, evaluated, and potentially integrated into automated recommendation and adjustment mechanisms (Chacón, 2021).

The notion of operator 4.0 emphasizes that digital technologies expand human capabilities through assistance, intelligent interfaces, and contextualization resources, reorganizing work towards a more analytical and mediating profile (Ciccarelli, 2023). In this logic, cognitive support systems provide structured information and recommendations, but rely on human curation and validation to ensure adherence to the real context of operation and avoid inappropriate automatic interpretations (Angulo, 2023).

The concept of cognitive digital twin broadens this perspective by proposing representations that combine process models, operational data, and inferences, capable of supporting decisions and updating interpretations over time (Lu, 2022). In connected and agile networks, such twins can act as coordination infrastructure and operational memory, integrating event history and responses to provide contextualized support to the operation (Kalaboukas, 2021).

Solutions based on *virtual reality* and *augmented reality* also appear as mechanisms to support execution and situated learning, as they allow overlapping information and contextual guides directly in the work environment (Horejši, 2020). When combined with multimodal records and integration with process data, these technologies favor knowledge capture during action, reducing loss of context and increasing the quality of operational records (Angulo, 2023).

The integration between human and technical system, in this context, presupposes architectures that recognize the limits and capabilities of both, distributing perception, decision, and intervention functions in a way that is compatible with the reliability and response time of the system (Harrison, 2021). Therefore, models that treat the operation as a dynamic system tend to consider the operator as a component that can stabilize the overall behavior when the process deviates from the predicted conditions, as long as their intervention is structured and recorded (Cimini, 2020).

The literature on digital platforms for maintenance shows that connectivity can organize knowledge as an active repository, integrating records of activities, occurrences, and responses into structures that facilitate search and continuous learning (Iheukwumere-Esotu, 2022). By connecting these repositories with recommendation layers and process status, a basis is created for real-time reuse of operational knowledge, aligned with the operator's concrete needs during execution (Ribeiro, 2022).

Control architectures applied to continuous processes in Industry 4.0 indicate that connectivity enables extended observability and coordination between components, but requires models that represent how human and automatic interventions interact under disturbances and state changes (Chacón, 2021). This need brings the topic of control engineering closer by suggesting that the captured knowledge should be structured as part of the system's behavior, allowing events and interventions to be treated as signals that feed back into future decisions (Harrison, 2021).

The Artificial Intelligence of Things *connected cognitive assistance perspective* describes systems capable of guiding operators through contextualized recommendations, integrating sensors, history, and models to reduce uncertainty during operation (Angulo, 2023). This support is most effective when the operator can interact, correct, and complement the recommendation, generating a learning cycle in which the system gradually incorporates operational standards validated in practice (Ciccarelli, 2023).

When the focus shifts to connected supply networks, the logic of cognitive digital twins suggests that local decisions can be influenced by global states and that knowledge capture should preserve relationships between events, constraints, and consequences at different levels of the system (Kalaboukas, 2021). In this reading, the capture of operational knowledge takes on the contours of coordination and distributed control, in which the system's memory needs to be consistent, contextual, and accessible to support decisions that involve multiple interdependent components (Lu, 2022).

2.6 FUNDAMENTALS OF DYNAMICAL SYSTEMS AND CONTROL

Dynamical systems theory offers a mathematical framework to represent industrial processes as sets of states that evolve over time under the influence of inputs, perturbations, and feedbacks, allowing the analysis of behavior, predictability, and system response to operational variations (Harrison, 2021). In the contemporary industrial context, this approach supports the modeling of production processes as dynamic entities coupled to sensors, actuators, and computational layers that continuously monitor and adjust the operation (Chacón, 2021).

Control engineering uses dynamic models to describe causal relationships between variables, defining intervention strategies that seek to keep the system within desired operational regions even in the face of uncertainties and fluctuations (Lu, 2022). In connected industrial environments, such models start to incorporate real-time data and distributed computational logic, expanding the capacity for observation and intervention in complex processes (Kalaboukas, 2021).

The mathematical formalization of production systems allows abstracting the operation in terms of observable and unobservable states, which favors analyses on transient behavior, permanent regime, and response to external events (Harrison, 2021). This formalization also creates the basis for integrating human decisions as variables that influence the dynamics of the system, bringing together technical control and operational cognition in the same conceptual framework (Cimini, 2020).

The literature on adaptive automation indicates that modern industrial systems tend to operate in non-stationary conditions, requiring models capable of handling structural changes and frequent reconfigurations (Chacón, 2021). In this scenario, control fundamentals provide instruments to analyze how continuous adjustments and local decisions affect the overall behavior of the system over time (Turner, 2021).

By treating industrial processes as dynamic systems, it becomes possible to analyze how delays, measurement noise, and human interventions alter state trajectories and influence operational outcomes (Harrison, 2021). This reading supports the approximation between control and knowledge capture, as recorded decisions can be interpreted as signals that modify the future dynamics of the system (Angulo, 2023).

2.7 STABILITY, DISTURBANCES AND PERFORMANCE IN SYSTEMS UNDER CONTROL

The concept of stability in systems under control refers to the ability of the system to return to predictable behavior after experiencing internal or external disturbances, keeping its variables within acceptable limits (Harrison, 2021). In industrial environments, this property is directly associated with the robustness of the operation in the face of load variations, configuration changes, and unexpected events (Chacón, 2021).

Operational disturbances can take multiple forms, including raw material fluctuations, intermittent equipment failures, and variations in demand, affecting the dynamic behavior of the system (Lu, 2022). Control theory provides instruments to model these disorders and assess how intervention strategies mitigate their effects on performance and reliability (Kalaboukas, 2021).

The performance of controlled systems is usually evaluated based on criteria such as response time, steady-state error, and resource consumption, which depend on both the structure of the controller and the quality of the information available (Harrison, 2021). In connected industrial systems, human presence influences these criteria by introducing adaptive decisions that can compensate for limitations of automatic control in unforeseen situations (Turner, 2021).

The *human-in-the-loop* literature suggests that human interventions function as adjustment mechanisms capable of stabilizing the system when automatic models lose adherence to real operating conditions (Cimini, 2020). These interventions, when understood as part of the control system, can be analyzed in terms of impact on stability and overall performance (Angulo, 2023).

The integration of operational records with control models allows the identification of recurring patterns of disturbances and responses, favoring structural adjustments that reduce variability over time (Chacón, 2021). Thus, stability is no longer treated only as a technical property and starts to incorporate cognitive dimensions associated with the experience accumulated in the operation (Ciccarelli, 2023).

2.8 COGNITIVE MODELS OF ABILITY, RULES AND KNOWLEDGE

Cognitive models of skill, rules, and knowledge describe distinct levels of human processing during the execution of tasks, differentiating between automated actions, guided procedures, and decisions based on conceptual understanding (Ciccarelli, 2023). These models provide a framework for understanding how operators transition between quick responses and analytical reasoning as the operational situation changes (Turner, 2021).

At the skill level, the action occurs almost automatically, supported by repeated practice and direct perception of signals from the environment, which reduces cognitive load during normal operation (Ribeiro, 2022). In dynamic industrial systems, this level is often mobilized in routine tasks, allowing for agile response to small and predictable variations (Harrison, 2021).

The rule-based level involves the application of learned procedures, instructions, and heuristics that guide action when the situation falls within known patterns (Iheukwumere-Esotu, 2022). This type of processing is typical of formal training and operational documentation, although its effectiveness depends on the adherence between prescribed rules and actual process conditions (Chacón, 2021).

The knowledge-based level is activated when the situation deviates from known patterns, requiring diagnosis, hypothesis formulation, and evaluation of alternatives before intervention (Ciccarelli, 2023). In these cases, the operator uses mental models of the process to interpret ambiguous signals and decide actions under uncertainty (Lu, 2022).

The literature indicates that advanced industrial environments require frequent transitions between these cognitive levels, as automation changes the nature of tasks and exposes operators to less repetitive situations (Turner, 2021). Understanding these transitions is relevant to structuring support systems that respect cognitive limits and favor decisions aligned with the behavior of the technical system (Angulo, 2023).

2.9 INTEGRATION BETWEEN HUMANS AND TECHNICAL SYSTEMS

Integration between humans and technical systems in industrial settings occurs through interfaces, information flows, and shared decision mechanisms that connect human cognition and automated control (Harrison, 2021). This integration defines how data is presented, how decisions are made, and how human interventions affect the behavior of the system (Cimini, 2020).

Human-in-the-loop *architectures* structure this relationship by incorporating the operator as a functional component of the system, allowing human decisions to be recorded, evaluated, and integrated into control cycles (Turner, 2021). This arrangement favors greater alignment between human action and technical response, reducing asymmetries between model and actual operation (Chacón, 2021).

The literature on cognitive assistance highlights that intelligent interfaces can support the interpretation of complex data, synthesizing information and guiding the operator's attention during execution (Angulo, 2023). The usefulness of this support depends on the ability of the system to adapt to the context and on the operator's ability to validate and adjust recommendations according to their experience (Ciccarelli, 2023).

Technologies such as *digital twins* extend integration by offering dynamic representations of the process that combine data, models, and operational history (Lu, 2022). When aligned with the operator's practice, these representations strengthen the coordination between human and technical system, as they allow simulating consequences and comparing scenarios before the intervention (Kalaboukas, 2021).

Effective integration also requires considering human limitations, such as cognitive load and response time, distributing functions in a way that is compatible with technical and cognitive capabilities (Harrison, 2021). This distribution directly influences the way operational knowledge is produced, recorded, and reused within the system (Ribeiro, 2022).

2.10 GAPS IN THE LITERATURE: LACK OF FORMALIZATION OF THE PROBLEM

The literature on knowledge management and Industry 4.0 recognizes the relevance of operational knowledge, but tends to treat it in a descriptive way, without a formal framework that allows a systematic analysis of its behavior over time (Ribeiro, 2022). This absence of formalization limits the ability to compare approaches, assess impacts, and integrate captured knowledge into technical control architectures (Harrison, 2021).

Studies on *human-in-the-loop* and operator 4.0 explore human mediation and supporting technologies, but rarely model knowledge capture as part of a dynamic system with defined states, inputs, and outputs (Ciccarelli, 2023). As a result, human interventions remain treated as isolated events, and not as signals that influence the evolution of the production system (Cimini, 2020).

The literature on *digital twins* and cognitive systems advances the integration between data and models, but often assumes that the necessary knowledge is already available or can be extracted directly from operational records (Lu, 2022). This assumption disregards the implicit and contextual nature of the knowledge produced in practice, making it difficult to incorporate it consistently into digital models (Kalaboukas, 2021).

Documentation-based approaches and registration platforms expand the availability of information, but lack a conceptual framework that relates records, decisions, and system behavior in an integrated way (Iheukwumere- Esotu, 2022). Without this framework, knowledge capture remains fragmented and disconnected from the dynamics of operation control (Chacón, 2021).

In view of these gaps, there is a need for a framework that treats the capture of operational knowledge as a technical problem that can be modeled, analyzed, and designed, aligning human cognition and control of dynamic systems (Angulo, 2023). Such a framework creates conditions to integrate decision records into self-adjusting industrial architectures, bringing control theory and operational practice together in a consistent way (Turner, 2021).

3 METHODOLOGY

The methodological approach adopted is of a theoretical-conceptual nature, based on an analytical review of the recent literature, oriented to the construction of an explanatory model capable of reinterpreting the capture of operational knowledge under a technical framework. This type of approach is appropriate when the objective is to reorganize existing concepts and propose new analytical articulations based on foundations already consolidated in different fields of knowledge (Lakatos, 2021).

The theoretical framework is based on the integration between control engineering, dynamic systems, and literature on operational knowledge in connected industrial environments, allowing human decisions to be treated as elements that influence the evolution of the system over time (Gil, 2019). The choice for a conceptual model is justified by the need to represent abstract relationships between states, interventions, and observed effects, which favors structured analysis without resorting to direct empirical experimentation (Lakatos, 2021).

The conceptual modeling of knowledge capture as a dynamic system was built from the identification of recurrent variables described in the literature, organized as system states, external inputs, and technical action mechanisms (Gil, 2019). This strategy allows us to represent the dynamics of operational knowledge as a process subject to temporal variations, influenced by internal and external conditions of the operation (Lakatos, 2021).

The definition of the states of the knowledge system considered different levels of externalization, accessibility, and reuse of knowledge, understood as observable conditions that vary according to operational practices and available technological support (Gil, 2019). These states were organized in such a way as to allow analysis of transitions over time, associated with human interventions and techniques described in the literature (Lakatos, 2021).

The identification of operational disturbances was based on the recurrence of factors that negatively affect the consolidation of knowledge, such as process variability, time constraints, and unexpected events, consistently described in the studies analyzed (Gil, 2019). These disorders were treated as external inputs to the knowledge system, capable of altering its trajectory and compromising informational stability (Lakatos, 2021).

The characterization of the technical actuators included digital technologies, recording systems, sensors, and cognitive support mechanisms, considered as means of intervention that directly influence the states of the system (Gil, 2019). These actuators were analyzed for their ability to reduce informational losses and favor structured retention of operational knowledge (Lakatos, 2021).

The criteria for analyzing the stability and performance of the system were defined based on classic concepts of control theory, reinterpreted for the domain of knowledge capture, allowing the evaluation of consistency, continuity, and reusability over time (Gil, 2019). This methodological adaptation makes it possible to treat knowledge as a dynamic variable subject to degradation or consolidation according to the architecture of the system in which it is inserted (Lakatos, 2021).

4 RESULTS AND DISCUSSION

Table 1 presents a synthesis of the main findings of the authors analyzed, organizing their contributions in relation to operational knowledge, human-system integration, technical architectures and conceptual foundations that support the proposal of this article.

Table 1

Synthesis of the main findings of the literature analyzed

Author (year)	Central contribution

Angulo (2023)	It analyzes the design of cognitive assistants integrated with Artificial *Intelligence of Things*, discussing how multimodal records, contextual inference, and human-system interaction can support operators in decision-making and the continuous capture of operational knowledge.
Anshari (2022)	It discusses the relationship between knowledge management and the paradigms of the Fourth Industrial Revolution, showing how digital technologies reconfigure informational flows without ensuring, by themselves, the consolidation and reuse of organizational knowledge.
Chacón (2021)	It proposes a control architecture for continuous industrial processes based on Industry 4.0 principles, demonstrating how connected systems can integrate monitoring, decision-making, and intervention in complex operating environments.
Ciccarelli (2023)	It reviews the concept of Operator 4.0, highlighting the cognitive mediation exercised by workers in advanced industrial environments and the expansion of their functions for supervision, interpretation and coordination.
Cimini (2020)	It features a *human-in-the-loop* control architecture for manufacturing systems, in which human intervention is treated as a functional component of the system, allowing greater flexibility and adaptation to operational variability.
Harrison (2021)	It discusses fundamentals of adaptive automation and dynamic systems, addressing how reconfigurable architectures can maintain operational stability in the face of structural changes and unanticipated conditions.
Horejši (2020)	It explores the use of *augmented reality* and *virtual reality* in smart assembly lines, analyzing how these technologies support execution, situated learning, and interaction between operators and digital systems.
Iheukwumere-Esotu (2022)	It develops a digital knowledge management platform applied to industrial maintenance, highlighting the potential and limitations of systems based on collaborative records and web for the retention of technical knowledge.
Kalaboukas (2021)	It proposes an operational model of *cognitive digital twins* applied to connected supply networks, integrating data, models, and inference to support coordination and decision-making in distributed systems.
Lu (2022)	Analyzes the concept of cognitive digital twin from systems engineering model-based, discussing conceptual foundations, levels of abstraction, and integration between models, data, and intelligence.
Ribeiro (2022)	It presents a critical analysis of the relationship between knowledge management and Industry 4.0, highlighting the limits of existing approaches and pointing out the absence of models that integrate operational knowledge with the dynamics of production systems.
Turner (2021)	Examines human mediation scenarios in advanced automation, discussing how workers influence performance, reliability, and adaptation of highly automated industrial systems.

Source: Prepared by the author (2024)

From Angulo (2023), it is observed that knowledge capture can be interpreted as a continuous process mediated by intelligent technologies, while Chacón (2021) demonstrates that industrial architectures already operate according to dynamic control logics that can incorporate human decisions as system variables. Ciccarelli (2023) complements this reading by showing that the contemporary operator acts as a cognitive mediator, connecting technical information and operational context in real time.

According to Cimini (2020), *human-in-the-loop systems* allow human intervention to be structured as a functional part of the operation, while Harrison (2021) shows that stability in adaptive systems depends on the integration between automatic control and situated decisions. Ribeiro (2022) reinforces that the absence of formal structures to capture this knowledge maintains the dependence on informal and local practices.

While Turner (2021) highlights that human mediation sustains performance in situations of variability, Iheukwumere-Esotu (2022) demonstrates that digital platforms expand registration, but lack dynamic contextualization to favor reuse. Lu (2022) and Kalaboukas (2021) broaden the debate by proposing *cognitive digital twins* as structures capable of integrating data, models, and operational experience.

Horejši (2020) shows that immersive technologies favor capture during action, while Anshari (2022) points out that digital transformation reorganizes knowledge flows without ensuring their consolidation. The articulation between these authors shows that knowledge capture can be formalized as a control problem, in which desired states, disturbances, and actuators are clearly identifiable. In this framework, the desired state corresponds to the existence of externalized, accessible, and reusable knowledge, as indicated by Ribeiro (2022), while Angulo (2023) suggests that cognitive assistants can act as mediators of this consolidation. Chacón (2021) and Harrison (2021) indicate that operational disturbances alter the trajectory of the system, requiring interventions that stabilize both the physical process and working memory.

According to Cimini (2020), technical actuators such as sensors and structured records allow human interventions to be treated as system signals, while Turner (2021) reinforces that these interventions directly influence overall performance. The absence of such mechanisms, as discussed by Iheukwumere-Esotu (2022), maintains informational instability and recurrent learning loss.

By articulating control theory and cyber-physical systems, Lu (2022) and Kalaboukas (2021) demonstrate that knowledge can be incorporated into self-adjusting architectures, as long as it is formalized as part of the system's dynamics. This body of evidence supports the proposal to treat knowledge capture as a technical problem, integrating human cognition, automation, and operational performance in a consistent way.

5 FINAL CONSIDERATIONS

This paper presented a conceptual approach that interprets the capture of operational knowledge as an engineering problem, structured according to the fundamentals of dynamic systems and control. This perspective allows us to reorganize the debate by shifting knowledge from the exclusively managerial field to a technical and modelable domain.

The proposed advance consists of treating human decisions, records, and technologies as components of a system subject to states, disturbances, and intervention mechanisms. This reading favors greater integration between industrial automation and operational learning processes.

The implications for control engineering include broadening the traditional scope of analysis by incorporating cognitive and informational variables into the design of connected industrial systems. This movement brings theory and practice closer together by recognizing operational experience as part of the system's behavior.

Among the limitations, the conceptual character of the model stands out, which demands future validation in empirical contexts and specific industrial applications. Still, the framework presented provides a solid basis for further investigation.

Future research may explore the operationalization of the model in real systems, as well as the development of formal metrics to assess stability and performance of knowledge over time. The integration between control, cognition and technology remains a fertile field for theoretical deepening and practical application.

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