IEEE Access
Multidisciplinary ⁝ Rapid Review ⁝ Open Access Journal

Received 30 August 2022, accepted 17 September 2022, date of publication 21 September 2022, date of current version 29 September 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3208250

RESEARCH ARTICLE

Identifying the Dynamics of Intangible Resources for Industry 4.0 Adoption Process

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ABSTRACT Industry 4.0 is a socioeconomic phenomenon that affects all industries, transforming not only products, processes, and services, but also business models, organizational structures, and strategies, placing human beings at the center of this digital transformation. Researchers have already demonstrated the importance of intangible resources in the Industry 4.0 adoption process. Nevertheless, there is still a gap in empirical research on how these factors evolve during the process. Therefore, the main objective of this study is to identify how these factors influence each other across different Industry 4.0 maturity levels. To achieve this goal, a qualitative approach was used with multiple case studies comparing responses from companies at higher Industry 4.0 maturity levels and contrasting them with the responses from companies at lower levels, distilling aggregate dimensions through an inductive coding procedure. Experts evaluated the results to find relations between the aggregate dimensions, their evolution and influence on each other. As a result, a conceptual framework was developed that demonstrates the dynamics of intangible factors that could be used by any company to nurture its own Intellectual Capital as a groundwork for the adoption of Industry 4.0. Among these dynamics, the central role of engaged leaders was highlighted in developing structural capital factors. Future studies should conduct interviews with more companies from other industrial sectors as well as on the implementation and management of Intellectual Capital in manufacturing companies to assess the applicability of the proposed conceptual framework.

INDEX TERMS Fourth industrial revolution, industry 4.0, intangible resources, intellectual capital, maturity assessment, smart manufacturing, smart working.

I. INTRODUCTION

The Fourth Industrial Revolution is based on the digital revolution, transforming society and the global economy [1]. Digital transformation is a phenomenon that affects all sectors, where traditional products are replaced by similar digital ones, or at least equipped with digital functionalities [2]. A new manufacturing paradigm, Industry 4.0 refers to the digitization and connection of the industrial value creation process [3], [4]. Industry 4.0, a concept coined in 2011 by an initiative of the German federal government with universities and private companies, was a strategic program to develop advanced production systems with the aim of increasing the productivity and efficiency of the national industry [3]. Industry 4.0 integrates a stream of research concerned with industrial processes which has paid significant attention to smart manufacturing and its base technologies, including the Internet of Things (IoT), cloud, big data, analytics, and artificial intelligence [5]. Researchers and practitioners believe that Industry 4.0 empowers companies to increase their operational efficiency and innovate faster [6], [7]. In this sense, the ultimate goal is to become a learning, agile company capable of continuous adaptation to a changing environment [8], [9].

However, addressing the developments associated with the Fourth Industrial Revolution from a technological perspective is insufficient. Companies also need to transform their

The associate editor coordinating the review of this manuscript and approving it for publication was Justin Zhang.

organizations and cultures [8]. Digital transformation affects not only physical products, but also the nature of the business, organizational structure, and strategy. In this context, human factors are crucial for the implementation of Industry 4.0 [2], [10]. Thus, Industry 4.0 is changing the basis of competitive advantage from tangible to intangible resources [7], [11]. In this regard, successful digital transformation requires organizations to re-examine their strategies for approaching Intellectual Capital (IC) [7]. IC stands for the study of the roots of a company's value, a measurement of the hidden dynamic factors that underlie the visible company of buildings and products [12].

Prior research on intangible resources and Industry 4.0 has mainly focused on contributions to the development of sociotechnical factors on Industry 4.0 maturity levels [13], and on discussing some factors that influence the implementation process of Industry 4.0 [13], [14], [15]. However, studies have seldom questioned how these factors evolve from lower to higher Industry 4.0 maturity levels and how they interrelate in order to reach higher maturity levels. Moreover, there is a lack of studies that provide empirical evidence on how Industry 4.0 is adopted in manufacturing companies from a sociotechnical perspective [2], [5], [13], [15], [16].

Thus, this study aimed to identify the dynamics of intangible resources and how they influence each other in order to reach higher maturity levels in Industry 4.0. The main contribution of this study is the development of a conceptual framework that represents the dynamics of intangible factors from companies with lower to higher levels of maturity. It is expected to serve as a managerial tool for manufacturing companies seeking to nurture their own intangible assets towards higher maturity levels in Industry 4.0.

In order to achieve this research goal, case studies were conducted with eight companies from the Brazilian automotive supply chain that have participated in an Industrial Policy program named "Route 2030", developed by the Brazilian Ministry of Economy. This program, conducted by the National Service of Industrial Training (SENAI), was designed to foster innovative projects and productivity gains, especially for small and medium-sized enterprises (SMEs). These companies answered an Industry 4.0 maturity model questionnaire as the first step of the program. Then, aggregate dimensions were distilled from the data analysis process, and relations among them were suggested by a team of Intellectual Capital and Industry 4.0 experts based on how they evolve and influence each other from lower to higher Industry 4.0 maturity levels. Finally, associations between the aggregate dimensions and harmonized IC factors were suggested. The relevance and novelty of this research is bridging a gap suggested by recent studies, which, after analyzing 4.973 publications on the topic of Industry 4.0, spanning a period of ten years, found that only 6.4% of those papers explored the "smart working" dimension, i.e., the role of workers and sociotechnical aspects in manufacturing companies, highlighting that this is one of the most promising fields for future research [17], [18].

This paper is divided into five sections. First, we conceptualize intangible resources within the scope of Industry 4.0. Section 3 presents the methodology employed to identify the intangible factors in companies with higher Industry 4.0 adoption levels and how they influence each other. Section 4 presents and discusses the results and the proposed conceptual framework of this study. In section 5, we conclude with the findings and implications of this study.

II. THEORETICAL BACKGROUND

This section presents two different theoretical lenses for examining the role of intangible resources within the scope of Industry 4.0. Initially, the concept of IC and its factors are presented. The sociotechnical factors identified in previous studies are also highlighted.

A. INTELLECTUAL CAPITAL FACTORS

In the modern age, organizations find themselves in complex environments of ever-increasing dynamism and uncertainty. Developing and acquiring tacit resources and knowledge is vital for the success of an organization [17], [19]. A modern organization is composed of a fluid structure, strategic partnering, empowered employees, groupware, multimedia network marketing, and vital reservoirs of human intellectual resources [12]. These factors are hidden to investors. One emerging paradox is that investing in the areas of human capital and IT leads to a short-term deterioration of profits, reducing the value of the balance sheet, and consequently the book value of the organization. To put it briefly, the paradox is that the more an organization invests in knowledge upgrading and IT, the lower its value [20].

One way to appreciate the role of IC is metaphorical, by picturing a company as a living organism, as a tree [12]. Organizational charts, annual reports, quarterly statements, company brochures, and other documents would be its trunks, branches, and leaves. However, assuming these to be the entire tree, because they represent everything visible, is obviously a mistake. Half of a tree – or sometimes more – is underground, in its root system. Instead of studying its fruits and leaves, which provide evidence of how healthy the tree is today, understanding what is going on in its roots is a far more effective way to learn how healthy the tree will be in the years to come. This points to the importance of IC – the study of a company's roots, the measurement of the hidden and dynamic factors that form the basis of a company's tangible assets. According to the collective research project "Intellectual Capital Statement – Made in Europe": human capital, structural capital, and relational capital [21], these hidden factors typically comprise three dimensions:

Human Capital (HC) is defined as "what the single employee brings into the value adding processes" [21]. The combined knowledge, skill, innovativeness, and ability of the company's individual employees to fulfill the task at hand. It also includes a company's values, culture, and philosophy. A company cannot own human capital [12].

TABLE 1. List of harmonized IC factors [27].

Human Capital (HC)
(HC1) Professional Competence
(HC2) Social Competence
(HC3) Employee Motivation
(HC4) Leadership Ability
Structural Capital (SC)
(SC1) Internal Cooperation and Knowledge Transfer
(SC2) Management Instruments
(SC3) IT and Explicit Knowledge
(SC4) Product Innovation
(SC5) Process Optimization and Innovation
(SC6) Corporate Culture
Relational Capital (RC)
(RC1) Customer Relationships
(RC2) Supplier Relationships
(RC3) Public Relationships
(RC4) Investor Relationships
(RC5) Relationships to Cooperation Partners

Structural Capital (SC) is defined as "what happens between people, how people are connected within the company, and what remains when the employee leaves the company" [21]. The hardware, software, databases, organizational structure, patents, trademarks, and everything else in organizational capability to support the productivity of employees. Unlike HC, SC can be owned and traded [12]. Returning to the tree metaphor, SC can be compared to a tree trunk, which grows in rings over the years. Each year, the organization codifies something beyond its team. More and more structure emerges. Thus, the key role of a leader is to transform HC into SC [20].

Relational Capital (RC) is defined as "the relations of the company to external stakeholders" [21]. Relationships to former, current, and potential customers and suppliers; relationships to the public, including former and potential employees; all relations to investors, internal and external; and relations to cooperation partners, such as research and development (R&D) partnerships and networking activities [22].

To support companies in nurturing their IC, we developed a set of 15 harmonized factors, listed in Table 1, which covers between 80 and 90 per cent of the factors initially used by 25 German SMEs [23]. This list has been applied to more than a thousand companies and has been continuously reviewed [23], [24], [25], [26], [27].

Researchers have clarified that the development of IC factors can enable a company to maintain a balance between innovation capacity and operational efficiency, which is also the goal of Industry 4.0 [8], [9]. The goal of IC management is to leverage HC, SC, and RC simultaneously, improving the ability to generate value by identifying, capturing, leveraging, and recycling the IC. This includes both value creation and value extraction [21].

IC management goes further, seeking to develop intangible assets so that a company may learn and adapt [12]. In addition, IC management was originally designed for service companies [21], but has recently been applied to manufacturing companies as intangible assets have become critical in the context of Industry 4.0 [28]. However, only a few studies have examined the relationship between IC and Industry 4.0 [7].

B. SOCIOTECHNICAL DIMENSIONS AND INDUSTRY 4.0

This study considered prior research examining the influence of sociotechnical dimensions on the Industry 4.0 adoption process. First, it considered a cluster analysis performed to identify four sociotechnical dimensions – social, technical, work organization, and environmental [13] as the basis for this study. Additionally, multi-case studies were used to highlight the lessons learned that influence companies in the adoption of Industry 4.0 technologies [14], [15]. These lessons reveal that, for the successful implementation of Industry 4.0, social aspects (people, organization) are as important as technical factors [29]. Thus, the following intangible factors were considered in this study:

Social subsystem: The social subsystem encompasses people involved in the organization [13], [30], emphasizing the need for openness for the engagement of employees in ideation processes, problem solving, and open communication within the company [13], [14]. It sheds light on the role of leaders in strategy development, supporting initiatives for new technology adoption and for a decentralized decision-making process [13], [15].

Technical subsystem: This subsystem comprises elements of the production operation and how it is performed [13], [30]. This dimension highlights the importance of small pilot projects with limited budgets, focusing on testing and understanding the cause-effect relationship between new technologies, innovative capacities, and performance gains in the manufacturing process [13], [14], noting the importance of lean manufacturing tools in a 'chicken or egg' dilemma, more mature companies have implemented lean tools as the basis for digitization [13].

Work organization subsystem: Work organization considers the way in which work is designed in a firm, comprising aspects such as rules, operational procedures, work instructions, information flow, team organization, employee shifts, training for operation, task planning and integration, and other aspects of the work to be conducted [13], [30]. It emphasizes the role of project teams in new technology adoption, pilot projects, strategy development, and engagement with the decision-making process [13], [14]. It also highlights the importance of corporate culture, including aspects such as openness to the new, acceptance of failures, open communication, and encouragement of creative activity [14], [15].

Environmental subsystem: The environmental subsystem can be viewed through two lenses: external and internal environmental factors [13], [30]. Among the internal factors, the role of knowledge management is highlighted through the ideation process, best-practice sharing, and cross-functional communication, enhancing the exchange of experiences [13], [14], [15]. Regarding external environmental factors, the role of reliable partners, such as technological partners, is also important for benchmarking with suppliers, customers, and even competitors [14], [15].

III. RESEARCH DESIGN

To achieve the goal of this research, a qualitative approach with multiple case studies was used to identify the intangible resources that influence Industry 4.0 maturity levels the most, and how they influence each other in order to reach higher Industry 4.0 levels. Considering that previous studies have already identified some intangible factors and their role in the Industry 4.0 adoption process, this qualitative research aims to provide deep-rooted information and explain "how" these factors evolve and "why" they influence each other. Additionally, a qualitative approach is commonly used in situations where complex and novel phenomena are studied within their real-life, social, and organizational environments, as is the case for the Industry 4.0 adoption process [2], [31].

Semi-structured interviews were then conducted to explore this new phenomenon and understand the dynamics of the identified intangible resources in the adoption of Industry 4.0, thus developing an in-depth analysis of the field and allowing for new concepts to be built [32], [33]. In addition, this study was based on multiple cases, which increased the accuracy, robustness, reliability, and generalizability of the results [31].

A. CASE STUDY SELECTION

To select cases for this study, we used the data collected and provided by SENAI through an Industry 4.0 maturity model developed by the Technological Institute of Aeronautics (ITA) [34], inspired by the ACATECH Industry 4.0 maturity model [8]. This method evaluates the maturity levels of companies in five stages, where Level One is the least mature and Level Five as the most mature. This Industry 4.0 maturity model uses a questionnaire comprising 21 questions, which are grouped into three dimensions: "Strategy and Organization"; "Manufacturing and Supply Chain"; and "Business Models, Products and Services."

The maturity level of a company was obtained from the general average of the total responses. It is important to note that the three dimensions in this questionnaire were used as inputs to develop the semi-structured questionnaire used in this research, as detailed in Table 2. As a requirement of the "Route 2030" program, the maturity assessment questionnaire was answered by at least a senior manager that was close to or responsible for Industry 4.0 adoption pilots and/or projects, and had awareness of the company's strategic orientation. All companies that participated in the "Route 2030" program went through Industry 4.0 workshops and online lectures during a preparation phase for the maturity assessment. Subsequently, the companies conducted their maturity assessment with the support of an online platform. The results were then presented to each company by a SENAI expert, in order to give them the opportunity to adjust their understanding of Industry 4.0 concepts and their level of maturity, based on observations of the SENAI consultant. Consequently, the reliability of this study was strengthened [35].

TABLE 2. Semi-structured questionnaire.

Questions
1) Company basic information:
- Size of the company, industrial segment, main customers
- Governance and organizational structure
- Date of establishment, current location(s)
- Number of employees
2) Strategy and Governance:
- Is there governance and leadership directly involved in the adoption of Industry 4.0 technologies?
- Is the adoption of Industry 4.0 technologies related to the company's strategic objectives?
- Is there a structure of teams dedicated to these initiatives?
(3) Manufacturing technologies
- How is your company adopting Industry 4.0 technologies?
- How are the learnings of an experiment shared with other teams/other pilots?
- What is the management and technology structure currently in place to adopt new technologies?
(4) Business Models, Products and Services:
- How does the company engage with the value chain (suppliers) to develop new value propositions?
- How does the company relate with clients to develop new value propositions?
- How does the company relate with technological partners to accelerate technology adoption?
(5) Barriers and obstacles:
- What are the main barriers and obstacles for the adoption of new technologies?

Therefore, eight companies at different levels of maturity levels were randomly selected by theoretical sampling, with the aim of building results reflecting the contrasts between the different levels of maturity in the adoption of Industry 4.0. The goal was to provide a broader view of how intangible factors bear influence and evolve across different levels of maturity in Industry 4.0, thus facilitating the generalization of results, avoiding sampling bias, and ensuring the validity of this research [31], [36].

These companies were contacted by e-mail, and then by video calls, to explain the goals of this research, as well as to discuss their interest in participating. All contacted companies initially accepted to participate as part of this study, and interviews were scheduled. As a result, eight companies were selected to respond to a semi-structured questionnaire, as presented in Table 3. Amongst them, one is at a very low maturity level while five represent the highest Industry 4.0 maturity level. The names of the companies were kept confidential.

B. DATA COLLECTION

To identify the hidden dynamic factors (i.e., the intangible factors that influence companies the most toward achieving higher Industry 4.0 maturity levels) and how they influence each other across different maturity levels, semi-structured interviews were used as primary data collection method. This kind of interview allows for structured data collection while maintaining an adequate and necessary level of

TABLE 3. List of interviewed companies.

Maturity Level	Company Name	Company short description
1,48	A	Small-sized company, producer of plastic and rubber parts for motorcycles.
1,78	B	Medium-sized company, producer of polished parts for automotive vehicles.
2,48	C	Medium-sized company, producer of molds, injected plastic parts and complex door panels.
2,86	D	Medium-sized company, producer of screws for automotive vehicles.
3,32	E	Medium-sized company, producer of electrical parts for automotive vehicles.
3,99	F	Large-sized company, producer of steel and mining parts.
4,37	G	Large-sized company, producer of stamped parts, welded assemblies, seat frames, shock systems, support panel cross section.
4,52	H	Medium-sized company, manufacturer of seats and seat frames, panels and plastic injected parts, and exhausts.

openness to allow for the emergence of unexpected and novel knowledge [2], [31].

First, four open questions were designed considering the main questions of the Industry 4.0 maturity model used in this study [34]. A preliminary version of the interview script was tested with two manufacturing companies for fine tuning before the main interviews were conducted (see Table 2 for the interview script). Since these constituted preparation work for the official interviews, both results were discarded. In this phase, it was observed that interviewing only one person per company would generate enough information to draft the conceptual framework. The interviewees were all managers or directors of operations from the companies selected for this research. The interviews were preceded by a presentation about each company's Industry 4.0 maturity results, a brief introduction to our research goals, and an explanation of the semi-structured questionnaire. Each interview lasted approximately ninety minutes and was conducted by videoconference. In order to maintain an open atmosphere, giving more space for spontaneous answers, the interviews were not recorded.

Three researchers took notes during the interviews, which allowed us to confront interview impressions and obtain a complete view of each case, also reducing observer bias [2], [31]. To ensure reliability, the interview transcripts were analyzed, and a final report was sent to the interviewees of each company for review and formal approval.

C. DATA ANALYSIS

Data analysis followed an inductive coding procedure to allow for new concepts to emerge without the inherent limitations of predefined hypotheses [2], [37]. This contributed to theory building by evidencing consistencies and patterns in the collected data [2], [14], [31], [32], [37].

The coding procedure started with a first-order analysis, contrasting responses from companies at higher maturity levels in Industry 4.0 with the responses from companies at lower maturity levels. The four sociotechnical dimensions previously presented in this study were considered as a ground concept model [13]. The first aggregation was created following the terms reliably reported by the interviewees. Next, these categories were synthesized into second-order themes to further converge the similarities and contrast differences between them. Subsequently, the emerging second-order themes were distilled into aggregate dimensions. Obtaining a set of emergent categories related to second-order themes and aggregate dimensions provides a basis for constructing a data structure, which is a key component for demonstrating rigor in qualitative research [14], [37]. This entire process was conducted by a research team comprising the six authors of this paper as experts on both themes: Industry 4.0 and Intellectual Capital management, which certainly increases the validity and objectivity of the coding procedure [38].

Finally, the experts involved in this research developed a relationship between all the aggregate dimensions, revealing how each factor influences the others toward higher levels of Industry 4.0 maturity. The authors also suggested relationships between the aggregate dimensions and the list of harmonized IC factors presented in Table 1. These suggestions were made according to their previous experience in assessing and implementing intellectual capital statements in more than 1,000 SMEs in Europe [22], [23], [24], [25], [26], [27], [39], [40], [41], [42]. The IC factors related to each aggregate dimension, as presented in Table 4, are the most likely to be nurtured to develop the corresponding aggregate dimension. However, practitioners and researchers are encouraged to begin replicating this study from these suggestions but also to expand to other IC factors as well.

IV. RESULTS

The results based on the semi-structured interviews distilled eight aggregate dimensions and thirteen second-order themes that were related to the list of harmonized IC factors to present a suggested correlation between them. This data structure, presented in Table 4, was used to suggest a conceptual framework summarizing how the aggregate dimensions interact with each other to achieve higher Industry 4.0 maturity levels.

A. EMPOWERED EMPLOYEES

The first distilled dimension was distilled from the social subsystem dimension, as the interviewees highlighted that successful adoption of Industry 4.0 requires systematic employee training, not only for technical re-skilling, for instance, in areas such as automation and data science, but also for the development of socioemotional skills like collaboration, communication, and leadership problem-solving skills. It was possible to observe that employees feel more confident when they can share ideas, lessons learned, and aspects related to initiatives to implement new technologies. They understand that these initiatives could be an opportunity to move forward in their careers rather than a threat. They also gain a better understanding of the causes and effects of technology adoption which can be combined with pre-existing knowledge from the current manufacturing process. As one interviewee stated, ''We must not fail to listen to the staff'.''

In contrast, less developed companies did not have a systematic approach to employee training; instead, training was only sporadic, upon acquisition of new machinery, for instance. Therefore, employees feel less prepared to suggest ideas for the adoption of new technology. They normally see this as a threat to their current role in the manufacturing process and jobs.

Consequently, it is thus suggested that ''empowered employees'' is an important aggregate dimension for manufacturing companies to achieve greater Industry 4.0 maturity levels, as it was observed that it has positive effects on the following aggregate dimensions: (4) Bottom-up approach; and (3) Strategy & governance. The authors of this study also suggest that the development of this aggregate dimension could be achieved by nurturing the following IC factors: professional competence (HC1), social competence (HC2), employee motivation (HC3), internal cooperation and knowledge transfer (SC1), and corporate culture (SC6).

B. ENGAGED LEADERS

The second aggregate dimension was also extracted from the social subsystem dimension, focused on the role of leaders. It was observed that companies at higher maturity levels have engaged leaders focused on internal subjects, such as promoting dialogue and the exchange of experiences and ideas within the staff, as well as with external subjects, by seeking novelties from suppliers, co-creation with clients, and inspiration from similar companies and/or companies of the same corporate group. It was also observed that engaged leaders promoted knowledge updating and recycling for their employees and took ownership of the definition and implementation of their companies' strategies. They also play a critical role in the implementation of knowledge management systems and processes, thereby promoting both bottom-up and top-down processes.

In contrast, companies at lower maturity levels have leaders who are not very engaged. Consequently, employees do not have an open communication channel and face internal resistance to new ideas. Leaders generally do not debate new strategies internally or exchange information that induces new strategies with clients and suppliers. Their decisions are usually arbitrary and based on intuition rather than data or information.

It is therefore suggested that ''engaged leaders'' is a central aggregate dimension for manufacturing companies to achieve higher Industry 4.0 maturity levels, as it was observed that it has positive effects on the following aggregate dimensions: (1) Empowered Employees, (3) Strategy & governance and (6) Knowledge sharing. It is also suggested that the development of this aggregate dimension can be achieved by nurturing the following IC factor: leadership ability (HC4).

C. STRATEGY & GOVERNANCE

The third distilled dimension was identified from the work organization subsystem dimension, considering that the most mature companies presented clear and well-defined strategies for the adoption of Industry 4.0, which were mostly to improve process efficiency and quality levels. It was possible to identify that these companies had dedicated cross-functional teams that met frequently, with clear objectives to be achieved. They had well-defined action plans and KPI boards that communicated to stakeholders. Ideas and lessons learned were shared among them and with the board as part of the decision-making process. The manufacturing staff often requested new ideas as a source for the development of action plans. Good practices were shared across the company and implemented as standardized processes or procedures. Problems were discussed openly with the support of cross-functional representatives and external experts.

In contrast, the least mature companies were unable to present a strategy for Industry 4.0 adoption. They showed great interest and curiosity on the topic but lacked a clear vision of the expected cause-effect relationship of its implementation on the company's strategy. In addition, they were not able to present a clear decision-making process. This was mainly performed by the executive director but with no clear criteria or requirements. Notably, there are no dedicated teams, action plans, or KPIs for new initiatives. Industry 4.0 is often a theme studied by only one or two employees. However, there were complaints about barriers such as lack of trustful information, channels to share new ideas, and available resources. Most of the times, initiatives are only good ideas that never come to be entirely implemented.

Thus, it is suggested that ''strategy & governance'' is an important aggregate dimension for manufacturing companies to achieve greater Industry 4.0 maturity levels, as it was observed that it has positive effects on the following aggregate dimensions: (4) Bottom-up approach, (5) Learn by doing and (6) Knowledge sharing. The authors of this study also suggest that the development of this aggregate dimension could be achieved by nurturing the following IC factors: leadership ability (HC4), internal cooperation and knowledge transfer (SC1), management instruments (SC2), and IT and explicit knowledge (SC3).

D. BOTTOM-UP APPROACH

The fourth aggregate dimension was distilled, once again, from the social subsystem dimension, as it was observed that initiatives to collect, analyze, and implement new ideas, mostly related to manufacturing process improvement, were normally taken in companies at higher maturity levels. According to the interviewees, employees were encouraged to share their ideas and were rewarded when these ideas were successfully implemented. These ideas are often aggregated into the company's action plan to implement Industry 4.0, which is connected through the governance and leaders of the interviewed companies. These initiatives are considered pilots, so the results are measured to verify the causes and

TABLE 4. Data structure developed from the results of semi-structured interviews through inductive coding procedure.

Aggregate dimensions	Sociotechnical dimension	Second-order themes	First-order categories	Related IC Factors
(1) Empowered employees	Social subsystem	Systemic trainings	There are several trainings to change the mindset; and to upgrade statistics / data science	HC1
			Teams are prepared to develop business models and present their ideas	HC2
			There is fear of job loss, but training generates professional growth, and the situation is reversed	HC3
		Empowered teams	Team culture and "accountability" - "empowered" employees, who ask for new technologies	SC6
			There is a culture of lessons learned, and acceptance of mistakes	SC1; SC6
(2) Engaged leadership	Social subsystem	Engaged leadership	CEO is the leader of Industry 4.0 initiatives	HC4
			Lessons learned are taken to the board of directors. If they are positive, they are disseminated in the company along other lines	HC4
(3) Strategy & governance	Work organization subsystem	Governance & decision making process	There is governance around the topic of Industry 4.0	SC2
			There is a development team directly involved / responsible for the adoption of technologies	SC1
			Weekly follow-ups are performed according to metrics that track local actions and goals	SC2
			All business areas have dashboards with standardized KPIs for decision making	SC3
		Strategy driven	There is a strategic plan for the adoption of Industry 4.0	HC4; SC2
			Focus on meeting strategic objectives	HC4; SC2
			The company is starting to design its Industry 4.0 strategy, based on lessons learned from pilot projects	SC1
(4) Bottom-up approach	Social subsystem	Bottom-up approach	Pilot projects originate from an internal program of ideas	SC5; SC4; SC3; SC2; SC1
			Pilots are proposed "bottom-up" to convince the board of directors about the need to adopt new technologies	SC1
(5) Learn by doing	Work organization subsystem	Innovation pilots	Pilots are conducted to verify technical feasibility (cause-effect relationship) in partnership with external parties / stakeholders	SC5; RC1; RC2; RC5; SC4
			These need to be pragmatic, proving that the technology solves problems or increases productivity levels	SC1; SC5
		Hands-on approach	Company has its own R&D center	SC4
			There is a "rollout" process for the areas that will diffuse into the corporate group	SC2; SC4; SC5
			It has an environment (workshop) for developing new machines	SC4; SC5
(6) Knowledge sharing	Environmental subsystem (internal factor)	Knowledge management	The results of the pilots are shared with all employees in the company	SC1; SC3
			Knowledge is (more) distributed in the company ("nobody does anything alone")	SC1; SC6; HC2; HC4
			There is no division/room between departments, all on the same floor to increase the flow of information and facilitate decision making	SC1; SC6
(7) Productivity and quality tools as Groundwork	Technical subsystem	Lean and digital thinking	Company has already adopted a lean manufacturing culture	SC5; SC6
			Company has implemented MES	SC3
			Company is trying out new technologies	SC5
			Data is used for production monitoring	SC3; SC5
(8) Go and see	Environmental subsystem (external factor)	Customer relationship	Company has a good relationship with customers, acting in an open and collaborative way	RC1
			Suppliers are often the customers themselves	RC1; RC2
		Supplier relationship	Suppliers are sources of technological updates	RC2
			Try-out is performed using equipment on loan from suppliers	RC2
		Knowledge partners	Benchmarking visits are made to other companies in the corporate group	RC5
			There is collaboration with companies of the same sector and size. There is a curatorship to identify common pains	RC5
			Pilot project underway through a public policy program, connecting with startups and research and technology organizations	RC3; RC5

effects of adopting a new technology in the current manufacturing processes. The learning from these pilots is shared across departments and/or companies of the same corporate group. New ideas can be combined with ideas from other employees and/or departments to develop greater initiatives.

On the other hand, companies at lower maturity levels do not develop processes for generating and managing internal ideas. There are no clear channels or evaluation processes for new ideas. Normally, there are no incentives to sharing or combining ideas from different departments. In addition, there is no connection to the development and implementation of company strategies. Furthermore, employees do not learn from the pilots and do not feel motivated to propose new ideas.

Considering these observations, the authors suggest that a ''bottom-up approach'' is an important aggregate dimension for manufacturing companies to achieve greater Industry 4.0 maturity levels since it has positive effects on the following aggregate dimensions: (3) Strategy & governance and (5) Learn by doing. The authors of this study also suggest that the development of this aggregate dimension could be achieved by nurturing the following IC factors: internal cooperation and knowledge transfer (SC1), management instruments (SC2), IT and explicit knowledge (SC3), product innovation (SC4), and process optimization and innovation (SC5).

E. LEARN BY DOING

The fifth aggregate dimension was extracted based on the work organization subsystem, as it was observed that most mature companies conduct projects to learn by doing, understanding how the adoption of new technologies influences existing manufacturing processes. These pilots are usually short-term projects with lower budgets as a strategy to learn faster. The results are measured, learnings are shared, and employees are trained, rewarded, and given more responsibility. Failures are not criticized; instead, they are shared as learning so that they are not repeated. These initiatives are usually driven by a research and development team, with full or part-time dedication, which has sufficient and perennial resources to implement pilots. The teams conducted their activities with the support of some kind of infrastructure, which could be as simple as a machine repair workshop and/or laboratory - especially in small businesses – or as big as dedicated R&D centers. In these companies, successful ideas usually go through a ''roll-out'' phase; that is, they are implemented by an engineering team in other manufacturing processes of the company. Finally, most mature companies - regardless of their size - are more open to connect with external experts, such as research and technology organizations (RTOs), technology-based companies, and startups through pilots, as they pose less risk to company operations in case of failures.

In contrast, companies at lower Industry 4.0 maturity levels do not evaluate new technology adoption through pilots. Initiatives are generally implemented by external consultants, normally from suppliers selected by the main customers. These initiatives tend to be conducted without involving employees; therefore, learning is not shared across the company. These contracts have larger budgets, and higher risks; thus, failures are not welcome. There are no pilots, and new technology is often implemented without a clear understanding of its effects on the current manufacturing system. Therefore, there is not enough internal knowledge to criticize the implementation effort, and failure is not accepted. When measured, results are typically below expectations. The adoption of new technologies is regarded as an expense rather than an investment and tends to be disconnected from the company's reality and strategy.

Consequently, it is suggested that ''learn by doing'' is an important aggregate dimension for manufacturing companies to achieve greater Industry 4.0 maturity levels, as it was observed that it has positive effects on the following aggregate dimensions: (6) Knowledge sharing and (8) Go and see. The authors of this study also suggest that the development of this aggregate dimension could be achieved by nurturing the following IC factors: internal cooperation and knowledge transfer (SC1), management instruments (SC2), product innovation (SC4), process optimization and innovation (SC5), customer relationships (RC1), supplier relationships (RC2), and relationships with cooperation partners (RC5).

F. KNOWLEDGE SHARING

The sixth aggregate dimension was distilled from the environmental subsystem as an internal factor. According to the interviewees, companies with higher Industry 4.0 maturity levels have well-established knowledge processes and systems that support employees in sharing their learning across departments. Additionally, those companies presented flatter hierarchies, ''war rooms'' for initiatives, with KPI boards and updated information. In addition, working stations are placed without separation, promoting an open culture where people integrate to exchange ideas and solve problems quickly. As one representative said, ''nobody does anything alone.'' Thus, knowledge and decision-making processes are distributed in the company with the support of their governance and leaders.

Companies with lower maturity levels presented more vertical hierarchical structures, with knowledge and decisions concentrated on fewer individuals. Companies often do not have a process for registering and sharing information that could be useful in improving their business and manufacturing processes. As knowledge is not shared across the company, only a few key persons are able to connect with external partners such as suppliers, customers, and RTOs which could provide new insights to improve the manufacturing process.

Thus, it is suggested that ''knowledge sharing'' is an important aggregate dimension for manufacturing companies in order to achieve greater Industry 4.0 maturity levels, as it was observed that it has positive effects on the following aggregate dimensions: (4) Bottom-up approach and (5) Learn by doing. The authors of this study also suggest that the development of this aggregate dimension could be achieved by nurturing the following IC factors: internal cooperation and knowledge transfer (SC1), IT and explicit knowledge (SC3), corporate culture (SC6), social competence (HC2), and leadership ability (HC4).

G. PRODUCTIVITY AND QUALITY TOOLS AS GROUNDWORK

This dimension aggregates a set of tools and methods that are considered important for the adoption of new technologies at the shop floor of manufacturing companies. Moreover, the authors developed it by considering the factors observed in the technical subsystem dimension for Industry 4.0.

Among others, it was possible to identify that all companies at higher maturity levels have productivity and quality management tools implemented, such as Lean Manufacturing, i.e., Gemba, Kanban, Plan Do Check Act (PDCA), and Ishikawa analysis, in most of their manufacturing systems. Therefore, it is suggested that these tools foster a culture of information sharing, greater collaboration among team members, openness to new ideas, and better timing for communication, which all lead to a mindset oriented to problem-solving rather than to pointing out people's mistakes. Those are sociotechnical factors suggest by the authors to be related to structural capital (SC) factors. Additionally, those companies stated that they had already implemented manufacturing execution systems (MES), so they already have some data science initiatives and real-time data for quick responses and decision-making. Data were collected and analyzed mostly for machinery performance and failure analyses. Action plans have been developed to respond to this information. Thus, companies know where bottlenecks are located and their possible impact on production plans. Improving manufacturing processes are "fine tuning" procedures, that demand in-depth analysis and engagement of cross-functional experts.

In contrast, it was observed that companies at lower maturity levels are still partially implementing Lean Manufacturing tools, mostly the simpler ones such as 5S. In general, these companies collect data manually and analyze them by the end of the day to understand if the planned production goals were achieved. In addition, there is a lower perception of the value of adopting Industry 4.0-related technologies in those manufacturing processes. Since they present low efficiency and quality levels, any cheaper and simpler method or technology presenting reasonable results will generate a better perception of return on investment as compared to more advanced and expensive technologies.

Therefore, it is suggested that "productivity and quality tools as groundwork" is an important aggregate dimension for manufacturing companies to achieve greater Industry 4.0 maturity levels given its positive effects on SC factors, which are the backbone of the Industry 4.0 adoption process. The authors of this study also suggest that the development of this aggregate dimension could be reached by nurturing the following IC factors: IT and explicit knowledge (SC3), process optimization and innovation (SC5), and corporate culture (SC6).

H. GO AND SEE

The last aggregate dimension, called "go and see," represents one of the factors that companies at higher maturity levels use to explore new ideas: they connect with customers, suppliers, and knowledge partners. It is also highlighted as an important sociotechnical factor in the environmental subsystem from an external perspective. Interviewees highlighted that once connected with external partners, they visit them to see applications of Industry 4.0, technologies in real-life, similar cases. They normally develop networks with companies from the same corporate group or, in the case of family-based companies, with companies located in the same industrial district, sometimes even competitors. They are able to create communities of practices, visit each other and meet often to share common pains, learn from each other's pilots and share their good and bad experiences with technology suppliers. These transformation networks are useful for exploring new possibilities connected with the bottom-up approach and employee empowerment. It was also observed that shared learning made innovation pilots more efficient and improved their outcomes.

However, companies at lower maturity levels have poor or no connections with customers, suppliers, and other partners. They are usually isolated from the communities of companies that learn from each other. Consequently, they do not have access to reliable information from suppliers, and do not collaborate with customers. This makes it even harder for employees to suggest new ideas because they have never seen them at work before. In this sense, they are less empowered to support their companies.

It is thus suggested that "go and see" is an important aggregate dimension for manufacturing companies to achieve greater Industry 4.0 maturity levels, as it has shown positive effects on the following aggregate dimensions: (4) Bottom-up approach, (6) Knowledge sharing, (5) Learn by doing, and (1) Empowered employees. The authors of this study also suggest that the development of this aggregate dimension could be achieved by nurturing the following IC factors: customer relationships (RC1), supplier relationships (RC2), public relationships (RC3), and relationships to cooperation partners (RC5).

I. CONCEPTUAL FRAMEWORK

Once this research was able to identify the aggregate dimensions distilled from the semi-structured interviews, observing how they evolved from lower to higher levels of Industry 4.0 implementation, and how they influenced each other, it was possible to develop a conceptual framework representing these dynamics. The main goal of this concept development is to illustrate the importance of such hidden dynamic factors to support manufacturing companies in developing their own action plans for adopting new technologies and also to nurturing their intangible assets.

The figure of a wheel was suggested to account for the fact that it was not possible to identify where a company should start, much like in "the chicken or the egg" dilemma. This proposal suggests that the aggregate dimension (7) Productivity and quality tools as groundwork should be a priority, so it is placed at the beginning of the framework. In the central part of the wheel, appears the aggregate dimension (2) Engaged leaders, as it has a positive impact on three other dimensions, namely: (1) Empowered employees; (3) Strategy & governance; and (6) Knowledge sharing. At the peripherical part of the wheel the aggregate dimensions (4) Bottom-up approach; (5) Learn by doing and (8) Go and see are placed, suggesting that they have more connections with external partners, customers and suppliers, while also speeding up the inner

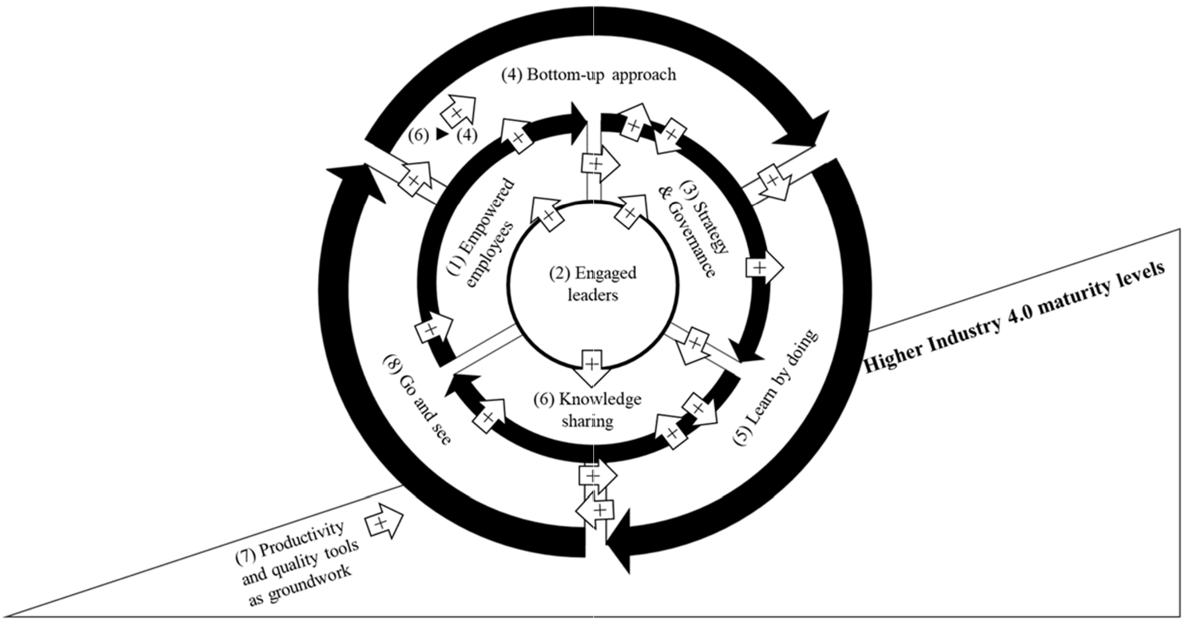

FIGURE 1. **Suggested conceptual framework, showing how intangible factors influence each other to achieve higher Industry 4.0 maturity levels.**

dimensions by fostering the development of intangible assets. By nurturing these eight aggregate dimensions, this research suggests that companies would prepare themselves to achieve higher Industry 4.0 maturity levels, as shown in Fig. 1.

V. DISCUSSION

The findings of this research shed light on the dynamics of manufacturing companies' intangible resources, the aggregate dimensions in Table 4, showing how they influence each other from lower to higher maturity levels. In this sense, although prior studies have considered sociotechnical and IC factors and their influence on companies adopting Industry 4.0 [7], [13], [14], this study is the first to reveal how these factors evolve and influence each other. Additionally, this research suggests valuable connections between the aggregate dimensions and harmonized IC factors that could be assessed and managed by companies of any size and investment capacity.

One important aspect evidenced is that companies at higher maturity levels presented mostly well-developed SC factors, as shown in Table 4. Among the aggregate dimensions, it is possible to observe that they presented well-established (3) strategy and governance, (4) a bottom-up approach, (5) learning-by-doing behavior, (6) knowledge sharing culture and process, and last but not least, (7) productivity and quality tools as groundwork for Industry 4.0 new technologies. These aspects are in line with the findings of previous research [13] that pointed to the importance of an alignment between strategy and Industry 4.0 adoption, considering it the strongest dimension of the sociotechnical view in terms of differentiation between lower- and higher-level adopters. Concurrent to prior studies [14], it has been observed that decentralized decision making and flat hierarchies, open information exchange, and open discussions are key aspects for Industry 4.0 implementation, as information is highly valuable in future value creation. This study also sheds light on the importance of generating experiences and lessons learned within a company [14]. The researchers observed that some companies employed small projects, using cost-benefit analysis in their companies, learning quickly from mistakes, and testing new approaches to develop and offer effective solutions. In this sense, concrete information about costs and potential was obtained from the pilot projects. In addition, it was possible to highlight the role of lean manufacturing [14], which benefits companies not only in terms of organizational agility but also in fostering the development of a smooth data flow based on interconnected systems. Therefore, it can be said that SC is the backbone of companies at higher Industry 4.0 maturity levels [27]. This observation is in line with previous studies that emphasize the importance of the work organization and technical subsystems [12], [13], [14] based on a socio-technical perspective [30] as groundwork for the Industry 4.0 adoption process.

Another important aspect is that relational capital factors make a critical contribution for companies at higher Industry 4.0 maturity levels. The aggregate dimension (8) "go and see" highlighted the importance of connecting with customers and suppliers, maintaining a collaborative relationship with them, and enabling firms to expand their horizons and absorptive capacity [7]. This fundamentally revolutionizes the way organizations interact with their customers and suppliers. Connecting with the end customers during all stages of the value-added process offers companies the opportunity to develop new, strongly service-oriented business models [14]. Additionally, close collaboration between universities and schools ensures that future employees acquire relevant skills. In this sense, relational capital plays a positive role in the development of SC in mature firms [12], [21]. This observation is in line with previous studies that emphasize the importance of an Environmental subsystem, [13], [14], [15] according to a socio-technical perspective [30], to accelerate the Industry 4.0 adoption process [7].

Furthermore, it was possible to observe the importance of human capital factors in companies at higher Industry 4.0 maturity levels. The first aggregate dimension, "empowered employees," consolidates the importance of systematic training to motivate employees to develop technical and social skills. These findings are in line with previous research [13], [14], [15] which showed that Industry 4.0 requires additional employee skills and competencies, such as ICT know-how, interdisciplinary competencies, and special personality traits. To develop these competencies, education and training have proven to be helpful. Moreover, this empowers employees to explore and propose new ideas to improve manufacturing systems, as suggested by previous studies [7]. In this regard, it can be noted that HC factors have the greatest impact on business success [40]. This observation is in line with previous studies that emphasize the importance of the social subsystem [13], [14], [15] from a socio-technical perspective [30].

Finally, the suggested conceptual framework in Fig. 1 illustrates how these intangible assets should be nurtured to achieve greater Industry 4.0 maturity levels. It has been suggested that companies should focus on their leadership training as a key mechanism [13], [15], [43]. Engaged leaders are crucial to establishing adequate grounds for the implementation of Industry 4.0. Democratic leadership is a fundamental aspect of companies that have successfully adopted Industry 4.0 [14]. These observations are in line with prior research, highlighting that leaders are important for the conversion of HC into SC, an essential element for the development of a company's IC [21].

VI. CONCLUSION

This study distilled eight aggregate dimensions as intangible resources of manufacturing companies at higher Industry 4.0 maturity levels, showing how they evolve from lower to higher maturity levels and how they influence each other. Based on these findings, a conceptual framework was suggested to present these factors and their dynamics. A major theoretical contribution of this study is, therefore, the identification of how intangible resources evolve and influence each other toward higher industry 4.0 maturity levels.

Among the observed dynamics, from the IC perspective, it was observed that HC plays a central role, mainly through the engaged leaders aggregate dimension, as they are responsible for developing adequate organizational structures to empower employees, for instance, by promoting systematic training and a collaborative and open-minded culture. Leaders also play a key role in fostering knowledge-sharing within companies, converting HC into SC, which is the backbone of companies at higher Industry 4.0 maturity levels. Moreover, it was observed that RC factors play a key role in accelerating the adoption of Industry 4.0.

From the sociotechnical perspective, the observed dynamics suggested that the social subsystem plays a key role in developing the work organization subsystem dimension, accelerated by environmental subsystem factors. Finally, technical subsystem factors, such as lean manufacturing, were found to be an important groundwork for the Industry 4.0 adoption process.

Overall, this research suggests that, by nurturing the IC factors related to the aggregate dimensions, a company may achieve greater Industry 4.0 maturity levels and thus become a learning, agile company capable of continuous and dynamic adaptation to a changing environment.

A. IMPLICATIONS

The results of this study have several implications. First, in terms of public policies for small companies, SMEs correspond to 82.6% of the companies at the lowest maturity level within the scope of this research. Therefore, public policies should be developed to encourage the training of SME leaders in IC management methods.

Second, for managers and practitioners, this study's findings shed light on the importance of IC management in preparing companies to adopt Industry 4.0. Companies should first focus on the development of their HC, starting with their leaders and developing a flat hierarchical organization, providing systematic training for employees, and encouraging the exchange of ideas and learning. Moreover, the findings of this study indicate that enhanced Industry 4.0 adoption results can be achieved by developing pilots, exploring the use of new technologies with partners, sharing lessons learned, and creating a virtuous circle of positive reinforcement for IC growth.

B. LIMITATIONS AND FUTURE RESEARCH

As only eight of the 353 companies in our initial scope were analyzed in-depth, this research presents limited empirical evidence. In addition, the data analyzed are related to one industry sector only. An additional limitation is the fact that only one executive from each company was interviewed. To broaden this view, future research could analyze data from a larger number of manufacturing companies in different industrial segments. Besides, future studies should consider interviewing more experts from the same company in order to achieve a more thorough picture of the dynamics of sociotechnical factors. Additionally, this study is focused on Brazilian companies. Since Industry 4.0 and IC management also play an important role in many other economies, an international perspective could add interesting perspectives to this stream of work.

Another aspect to be explored is that some aggregate dimensions revealed by this study could present different dynamics in SMEs as compared to large companies [44].

So, it is suggested that future studies could seek to identify and compare potential differences in relations between sociotechnical factors and Industry 4.0 adoption in manufacturing companies of different sizes.

Considering that the findings of this research are based on semi-structured interviews, it is also suggested that future studies should focus on the implementation and management of IC factors on manufacturing companies to verify their feasibility and impact towards achieving higher Industry 4.0 maturity levels. The participatory approach proposed in InCaS would be suitable for this purpose [21].

From a conceptual point of view, it would be interesting to deepen the analysis of the interaction between Industry 4.0 and the IC factors identified herein. Sensitivity analysis or system dynamics approaches, such as those used in the InCaS approach, are suitable for a detailed analysis of such interrelationships.

ACKNOWLEDGMENT

The authors are grateful for the data provided by SENAI in partnership with the Brazilian Ministry of Economy through the Industry Policy ''Route 2030.'' This research did not receive any specific grants from funding agencies in the public, commercial, or not-for-profit sectors.

They confirm that the paper titled ''Identifying the Dynamics of Intellectual Capital Factors for Industry 4.0 Adoption Process'' is an original work and is not currently under consideration by another journal.

REFERENCES

[1] K. Schwab, *The Fourth Industrial Revolution*, 1st ed. Geneva, Switzerland: World Economic Forum, 2017, pp. 11–12.

[2] D. Horváth and R. Z. Szabó, ''Driving forces and barriers of industry 4.0: Do multinational and small and medium-sized companies have equal opportunities?'' *Technol. Forecasting Social Change*, vol. 146, pp. 119–132, Sep. 2019, doi: 10.1016/j.techfore.2019.05.021.

[3] H. Kagermann, W. Wahlster, and J. Helbig. (Apr. 8, 2013). *Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0. Final Report of the Industrie 4.0 WG*. [Online]. Available: https://en.acatech.de/publication/recommendations-for-implementing-the-strategic-initiative-industrie-4-0-final-report-of-the-industrie-4-0-working-group/

[4] M. Ghobakhloo, ''The future of manufacturing industry: A strategic roadmap toward industry 4.0,'' *J. Manuf. Technol. Manag.*, vol. 29, no. 6, pp. 910–936, Jun. 2018, doi: 10.1108/JMTM-02-2018-0057.

[5] A. G. Frank, L. S. Dalenogare, and N. F. Ayala, ''Industry 4.0 technologies: Implementation patterns in manufacturing companies,'' *Int. J. Prod. Econ.*, vol. 210, pp. 15–26, Apr. 2019, doi: 10.1016/j.ijpe.2019.01.004.

[6] J. M. Müller, O. Buliga, and K.-I. Voigt, ''Fortune favors the prepared: How SMEs approach business model innovations in industry 4.0,'' *Technol. Forecasting Social Change*, vol. 132, pp. 2–17, Jul. 2018, doi: 10.1016/j.techfore.2017.12.019.

[7] T. Mahmood and M. S. Mubarik, ''Balancing innovation and exploitation in the fourth industrial revolution: Role of intellectual capital and technology absorptive capacity,'' *Technol. Forecasting Social Change*, vol. 160, Nov. 2020, Art. no. 120248, doi: 10.1016/j.techfore.2020.120248.

[8] G. Schuh, R. Anderl, J. Gausemeier, M. T. Hompel, and W. Wahlster. (Apr. 25, 2017). *Industrie 4.0 Maturity Index. Managing the Digital Transformation of Companies (Acatech STUDY)*. [Online]. Available: https://www.acatech.de/wp-content/uploads/2018/03/acatech_STUDIE_Maturity_Index_eng_WEB-1.pdf

[9] R. Morrar and H. Arman, ''The fourth industrial revolution (industry 4.0): A social innovation perspective,'' *Technol. Innov. Manag. Rev.*, vol. 7, no. 11, pp. 12–20, Nov. 2017, doi: 10.22215/timreview/1117.

[10] L. S. Dalenogare, G. B. Benitez, N. F. Ayala, and A. G. Frank, ''The expected contribution of industry 4.0 technologies for industrial performance,'' *Int. J. Prod. Econ.*, vol. 204, pp. 383–394, Oct. 2018, doi: 10.1016/j.ijpe.2018.08.019.

[11] S. S. Ahmed, J. Guozhu, S. Mubarik, M. Khan, and E. Khan, ''Intellectual capital and business performance: The role of dimensions of absorptive capacity,'' *J. Intellectual Capital*, vol. 21, no. 1, pp. 23–39, Nov. 2019, doi: 10.1108/JIC-11-2018-0199.

[12] L. Edvinsson and M. Malone, *Intellectual Capital: Realizing Your Company's True Value by Finding Its Hidden Brainpower*, 1st ed. New York, NY, USA: HarperCollins, 1997, p. 240.

[13] É. Marcon, M. Soliman, W. Gerstlberger, and A. G. Frank, ''Sociotechnical factors and industry 4.0: An integrative perspective for the adoption of smart manufacturing technologies,'' *J. Manuf. Technol. Manag.*, vol. 33, no. 2, pp. 259–286, Sep. 2021, doi: 10.1108/JMTM-01-2021-0017.

[14] J. W. Veile, D. Kiel, J. M. Müller, and K.-I. Voigt, ''Lessons learned from industry 4.0 implementation in the German manufacturing industry,'' *J. Manuf. Technol. Manag.*, vol. 31, no. 5, pp. 977–997, Aug. 2019, doi: 10.1108/JMTM-08-2018-0270.

[15] V. M. Tabim, N. F. Ayala, and A. G. Frank, ''Implementing vertical integration in the industry 4.0 journey: Which factors influence the process of information systems adoption?'' *Inf. Syst. Frontiers*, pp. 1–18, Nov. 2021, doi: 10.1007/s10796-021-10220-x.

[16] M. Sony and S. Naik, ''Industry 4.0 integration with socio-technical systems theory: A systematic review and proposed theoretical model,'' *Technol. Soc.*, vol. 61, May 2020, Art. no. 101248, doi: 10.1016/j.techsoc.2020.101248.

[17] B. Meindl, N. F. Ayala, J. Mendonça, and A. G. Frank, ''The four smarts of industry 4.0: Evolution of ten years of research and future perspectives,'' *Technol. Forecasting Social Change*, vol. 168, Jul. 2021, Art. no. 120784, doi: 10.1016/j.techfore.2021.120784.

[18] P. M. Bednar and C. Welch, ''Socio-technical perspectives on smart working: Creating meaningful and sustainable systems,'' *Inf. Syst. Frontiers*, vol. 22, no. 2, pp. 281–298, May 2019, doi: 10.1007/s10796-019-09921-1.

[19] M. A. Hitt, B. W. Keats, and S. M. DeMarie, ''Navigating in the new competitive landscape: Building strategic flexibility and competitive advantage in the 21st century,'' *Acad. Manag. Perspect.*, vol. 12, no. 4, pp. 22–42, Nov. 1998, doi: 10.5465/ame.1998.1333922.

[20] M. A. Hitt, L. Bierman, K. Shimizu, and R. Kochhar, ''Direct and moderating effects of human capital on strategy and performance in professional service firms: A resource-based perspective,'' *Acad. Manag. J.*, vol. 44, no. 1, pp. 13–28, Feb. 2001. [Online]. Available: https://www.jstor.org/stable/3069334

[21] L. Edvinsson, ''Developing intellectual capital at Skandia,'' *Long Range Plan.*, vol. 30, no. 3, pp. 366–373, Jun. 1997, doi: 10.1016/S0024-6301(97)90248-X.

[22] *InCaS: Intellectual Capital Statement—Made in Europe*, European Commission, Brussels, Belgium, 2010. [Online]. Available: http://wissenskapital.info/wp-content/uploads/2014/10/european_ics_guideline.pdf

[23] K. Mertins and M. Will, ''Strategic relevance of intellectual capital in European SMEs and sectoral differences. InCaS: Intellectual capital statement—Made in Europe,'' in *Proc. 8th ECKM*, Barcelona, Spain, 2008, pp. 1–12.

[24] K. Mertins, W.-H. Wang, and M. Will, ''InCaS: Intellectual capital management in European SME—Its strategic relevance and the importance of its certification,'' *Electron. J. Knowl. Manag*, vol. 7, no. 1, pp. 111–122, Jan. 2009. [Online]. Available: https://www.researchgate.net/publication/46257336

[25] K. Mertins, M. Will, and C. Meyer, ''InCaS: Intellectual capital statement. Measuring intellectual capital in European small- and medium sized enterprises,'' in *Proc. 9th ECKM*, 2009, pp. 353–362.

[26] M. Bornemann and K. Alwert, ''The German guideline for intellectual capital reporting: Method and experiences,'' *J. Intellectual Capital*, vol. 8, no. 4, pp. 563–576, Oct. 2007, doi: 10.1108/14691930710830756.

[27] M. Bornemann, K. Alwert, and M. Will, ''Lessons learned in intellectual capital management in Germany between 2000 and 2020—History, applications, outlook,'' *J. Intellectual Capital*, vol. 22, no. 3, pp. 560–586, Feb. 2021, doi: 10.1108/JIC-03-2020-0085.

[28] M. F. Prim, J. O. Gomes, G. B. Vargas, and C. F. Costa, ''The relevance of intellectual capital statement as a groundwork for industry 4.0,'' Presented at the 26th COBEM, 2021, doi: 10.26678/ABCM.COBEM2021.COB2021-1441.

[29] J. Avis, "Socio-technical imaginary of the fourth industrial revolution and its implications for vocational education and training: A literature review," *J. Vocational Educ. Training*, vol. 70, no. 3, pp. 337–363, Apr. 2018, doi: 10.1080/13636820.2018.1498907.
[30] B. M. Kleiner, "Macroergonomics: Work system analysis and design," *Hum. Factors, J. Hum. Factors Ergonom. Soc.*, vol. 50, no. 3, pp. 461–467, Jun. 2008, doi: 10.1518/001872008X288501.
[31] R. K. Yin, *Case Study Research: Design and Methods*, 5th ed. Los Angeles, CA, USA: Sage, 2009, p. 352.
[32] A. C. Edmondson and S. E. McManus, "Methodological fit in management field research," *Acad. Manag. Rev.*, vol. 32, pp. 1155–1179, Oct. 2007, doi: 10.5465/AMR.2007.26586086.
[33] C. Voss, N. Tsikriktsis, and M. Frohlich, "Case research in operations management," *Int. J. Oper. Prod. Manag.*, vol. 22, no. 2, pp. 195–219, Feb. 2002, doi: 10.1108/01443570210414329.
[34] *Avaliação de Maturidade: Indústria 4.0*, Instituto Tecnológico de Aeronáutica, Brasília, Brazil, 2020. [Online]. Available: https://maturidade.senai40.com.br/
[35] G. P. Huber and D. J. Power, "Retrospective reports of strategic-level managers: Guidelines for increasing their accuracy," *Strategic Manag. J.*, vol. 6, no. 2, pp. 171–180, Apr. 1985, doi: 10.1002/smj.4250060206.
[36] K. M. Eisenhardt and M. E. Graebner, "Theory building from cases: Opportunities and challenges," *Acad. Manag. J.*, vol. 50, no. 1, pp. 25–32, Feb. 2007, doi: 10.5465/amj.2007.24160888.
[37] D. A. Gioia, K. G. Corley, and A. L. Hamilton, "Seeking qualitative rigor in inductive research: Notes on the Gioia methodology," *Org. Res. Methods*, vol. 16, no. 1, pp. 15–31, Jul. 2012, doi: 10.1177/1094428112452151.
[38] C. Weston, T. Gandell, J. Beauchamp, L. McAlpine, C. Wiseman, and C. Beauchamp, "Analyzing interview data: The development and evolution of a coding system," *Qual. Sociol.*, vol. 24, no. 3, pp. 381–400, Sep. 2001, doi: 10.1023/A:1010690908200.
[39] S. Wuscher, M. Will, K. Alwert, and M. Bornemann, "Wissensbilanz—Made in Germany—Projektstudie über weiche faktoren als teil der unternehmenseinschätzung durch kapitalgeber," Fraunhofer IPK, Berlin, Germany, Tech. Rep., 2006. [Online]. Available: https://www.ipk.fraunhofer.de/content/dam/ipk/IPK_Hauptseite/dokumente/marktstudien/um-weiche-faktoren.pdf
[40] R. Orth, S. Wuscher, E. Steinhöfel, C. Meyer, M. Will, K. Alwert, and M. Bornemann, "Studie wissensstandort deutschland—Deutsche unternehmen auf dem weg in die wissensbasierte wirtschaft—Ergebnisse 2014," Fraunhofer IPK, Berlin, Germany, Tech. Rep., 2014. [Online]. Available: https://www.ipk.fraunhofer.de/content/dam/ipk/IPK_Hauptseite/dokumente/marktstudien/um-wissensstandort-de.pdf
[41] H. Kohl, K. Mertins, and H. Seidel, *Wissensmanagement im Mittelstand: Grundlagen—Lösungen—Praxisbeispiele*, 2nd ed. Berlin, Germany: Springer, 2016, p. 373.
[42] K. Mertins, K. Alwert, and M. Will, "Measuring intellectual capital in European SME," in *Proc. 6th I-KNOW*, Graz, Austria, 2006, pp. 21–25.
[43] E. Princes, "Integrating ambidexterity into the modern manufacturing era of industry 4.0," *Int. J. Supply Chain Manag.*, vol. 9, pp. 58–64, Aug. 2020. [Online]. Available: https://www.researchgate.net/publication/343961990
[44] J. M. Müller, O. Buliga, and K.-I. Voigt, "The role of absorptive capacity and innovation strategy in the design of industry 4.0 business models—A comparison between SMEs and large enterprises," *Eur. Manag. J.*, vol. 39, no. 3, pp. 333–343, Jun. 2021, doi: 10.1016/j.emj.2020.01.002.

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