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Industry 4.0 Implementation Strategies to Enhance Environmental Sustainability in Modern Enterprises.

Theses of the doctoral (PhD) dissertation

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I. INTRODUCTION

Industry 4.0 remarks the new era of industrial production, the roots of Industry 4.0 are driven by the time when the manufacturing process was dependant totally on human and animal physical force, the transition from this situation into machinery, new chemical factories, and iron manufacturing processes, development of waterpower, maximizing the use of steam power, and finally, the development of machine tools is considered as the first industrial revolution. The iron and textile sectors also played crucial roles in the first industrial revolution (Mohajan, 2019). The second revolution was moulded by the introduction of numerous technologies, including internal combustion engines, electricity, chemical industries, alloys, petroleum, as well as advancements in electrical communication and chemical technologies (such as the telegraph, radio, and telephone), alongside the implementation of running water and indoor plumbing (Gordon, n.d.). The third revolution, marked by the integration of digital manufacturing and personal manufacturing, includes the industrialization of the Maker Movement. The term "third industrial revolution" signifies a profound transformation, previously characterized by other authors as an "efficiency revolution," "green capitalism," and a fundamental shift towards a "green industrial revolution" (Bauer et al., 2016). The pivotal question arising is why, despite the third industrial revolution being a promising initiative aimed at assisting organizations in embracing green practices and mitigating environmental impact, the outcomes appear contrary. Over the past few decades, industrial activities have inflicted unprecedented harm on the environment (Hallegraeff, 2010). As per (Parmesan et al., 2022), human activities have emerged as the primary driver behind hundreds of extinctions in the last two centuries, in stark contrast to the natural extinction processes occurring over millions of years. As we navigate the 21st century, human activities continue to reshape the world in unprecedented ways.

Industry 4.0 is no longer a fictional hype that presents repackaged concepts. It is rather a new revolution in manufacturing that is acknowledged by researchers, governments, and industrialists. In May 2022, more than 24.000 papers were available in the SCOPUS database that contained the word Industry 4.0 either in the title, abstract, and/or indexed key words. Since the first industrial revolution in the 18th century, the globe has faced the difficulty of creating more products from limited and decreasing natural resources to fulfil the ever-increasing demand for consumption while minimizing negative environmental and social implications (Müller et al., 2018). The significance of Industry 4.0 is broad, ranging from mass production to satisfying customers through product customization. The adoption rate of Industry 4.0 in the last couple of years has been extremely high (Dev et al., 2020). Given the significant advantages afforded by adopting Industry 4.0 technologies, particularly in an increasingly competitive global environment, it is of great interest to both researchers and practitioners that so many companies are still reluctant to adopt these technologies more broadly (Chiarini et al., 2020; Koh et al., 2019; Tortorella et al., 2019). This resistance is largely justified in the literature; the adoption of industry 4.0 is not trivial, it is rather associated with a chain of challenges and obstacles that needs to be addressed. Even though the integration of Industry 4.0 technologies provide numerous advantages, much work remains (Dalenogare et al., 2018). In 19 different countries, only 14% of CEOs have complete assurance in their companies' ability to adapt to the changes ushered in by Industry 4.0 (Raj et al., 2020) and only four out of ten firms, on average, have made significant headway in the adoption of industry 4.0 (Bauer et al., 2016).

Several researchers have highlighted the possibility and necessity of forging a new trajectory for environmental development (Parajuly & Wenzel, 2017; Sousa-Zomer & Cauchick Miguel, 2018). Even if there is a disconnect between environmental sustainability and I4.0 (Baccarelli et al., 2017), numerous articles underscore its potential to bolster green practices. Notably, it can enhance operational efficiency, streamline data control operations, optimize energy utilization, and reduce waste in processes and machines (Ivanov et al., 2019; Thoben et al., 2017). Taking a closer look at this gap, we've crafted the following scope and research objectives.

II. Scope and research objective

This study centers on a comprehensive exploration of Industry 4.0 implementation, aiming to grasp the various variables shaping this revolution, including challenges, technologies employed, the current state of adoption, companies' investment inclinations, hurdles faced during implementation, perceived obstacles, and desired outcomes. The specific emphasis is on the pivotal aspect of environmental sustainability.

As an integral part of this expansive exploration, our research methodology involves a mixed-methods approach. A quantitative study casts a wide net over SMEs and large companies, providing a numerical overview of Industry 4.0 trends. Concurrently, a qualitative investigation delves deeply into a singular case study, offering nuanced insights into successful implementation and environmental objectives achieved.

The primary aim is to extract valuable insights from this comprehensive approach, providing decision-makers with a strong understanding of Industry 4.0 adoption.

The main objective is to ultimately provide a practical roadmap to navigate decision-makers through the complexities of Industry 4.0 implementation, providing strategic guidance to address challenges identified in the literature and validated through quantitative study. Subsequently, these challenges will be applied to a case study to assess how the studied company effectively tackled them. The qualitative study will delve into the specifics of how the company overcame these challenges, examining achieved objectives, employed strategies, and utilized technologies, all while aligning its approaches with the imperatives of environmental sustainability.

The study's objective can be delineated into eight sub-objectives that will guide the research.

2.1 Research sub-objectives

To achieve our research's main objective and provide decision-makers a coherent and well-structured study as a reference for the industry 4.0 implementation and the use of the technological facilities to mitigate environmental sustainability issues, the following sub-objectives need to be fulfilled relying on the exploration of the literature, quantitative and qualitative studies.

O.1 Examine the current extent of Industry 4.0 adoption among companies.

O.2 Identify desired outcomes from Industry 4.0 investments and assess the proportion dedicated to environmental sustainability.

O.3 Investigate the prevalent technologies used in Industry 4.0 investments.

O.4 Explore challenges and obstacles preventing companies from investing in Industry 4.0.

O.5 Differentiate desired objectives from Industry 4.0 between large companies and SMEs. Assess the emphasis on achieving environmental sustainability objectives in each category.

O.6 Analyze a leading company's successful implementation of Industry 4.0.

O.7 Investigate strategies used to overcome common challenges in Industry 4.0 implementation.

O.8 Document the environmental objectives successfully achieved by a company through Industry 4.0 investment.

2.2 Research hypothesis

The quantitative part of the study will examine the general state of the industry 4.0 implementation for both SMEs and large companies. This part of the study will focus mainly on the percentages of companies that implement industry 4.0, the challenges encountered during the implementation process, the obstacle that hold the entities that do not invest in industry 4.0, technologies used, the underlying objectives and key differences between large and SMEs in the context of industry 4.0. To achieve that, the following hypothesis emerged:

H01: There is no association between the intention to invest in Industry 4.0 in the future and the type of company (SMEs and large enterprises) at the 0.05 significance level.

H02: There is no significant difference in the overall distribution of technologies used by companies (both current adopters and future investors) between SMEs and large companies at the 0.05 significance level.

H03: There is no significant difference in the overall distribution of challenges faced by companies that do not currently invest in Industry 4.0, whether they wish to invest in the future or not, between SMEs and large companies at the 0.05 significance level.

H04: There is no significant difference in the underlying reasons for investment in Industry 4.0 for environmental sustainability between large companies and SMEs at the 0.05 significance level.

III. METHODOLOGY

This study is organized around eight sub-objectives, each integral to achieving the main goal of providing decision-makers with a well-structured guide for implementing industry 4.0 and utilizing I4.0 technologies to tackle environmental sustainability challenges. We have applied the Mixed-Methods approach to answer our research objectives.

3.1 Mixed-Methods Research Design

Our study adopts a Mixed Methods Research design to comprehensively investigate the utilization of Industry 4.0, with a particular focus on how it contributes to environmental sustainability. Initially, a quantitative study is employed to explore the general landscape, identifying primary challenges, objectives, and technologies associated with Industry 4.0. Subsequently, these quantitative findings inform our qualitative research, enabling a deeper examination of specific challenges and technologies aligned with each objective.

This methodological choice aligns with established practices in the literature, as articulated by (Migiro & Magangi, 2011). The mixed methods involves the analysis of numerical data to test correlations and validate hypotheses (Charles, 1998), with qualitative investigation adopting a constructivist approach (Denzin et al., 2006).

3.2 Quantitative phase: Survey-based Exploration

The quantitative methodology employed in this study aims to address five sub-objectives outlined by eight research questions. Following the framework proposed by (Aliaga & Gunderson, 1999), quantitative research methods are used to understand and explain issues or phenomena by systematically collecting numerical data and subjecting it to mathematical analysis. At the core of this approach is the goal of comprehensively grasping and clarifying the main issue.

Based on this reasoning, our research primarily focuses on unraveling the details of Industry 4.0 from a business perspective. This involves exploring essential aspects such as the extent of investment in Industry 4.0, prevalent technologies, and the objectives and challenges associated with such investments. The overarching goal is to gain a holistic understanding of the current state of Industry 4.0.

3.3 Qualitative study: in-Depth Case study of a large company

Case study research has gained prominence among qualitative academics, especially when the aim is to comprehend a complex phenomenon within its real-life context (Thomas, 2011; Yin, 2018). In the context of our research, the complex phenomenon under investigation is the successful implementation of Industry 4.0 and its effects on environmental sustainability within the information technology industry.

Given the scarcity of existing case study research discussing the impacts of Industry 4.0 on environmental sustainability, our study aims to fill this gap by exploring how the selected firm navigated challenges during the digital transformation phase. The focus is on understanding the potential utilization of Industry 4.0 technologies to enhance the efficacy and efficiency of the organization's strategy for environmental sustainability.

IV. RESULTS

4.1 Quantitative study

The landscape of industry 4.0 adoption

This section will be guided by O1: Examine the current extent of Industry 4.0 adoption among companies.

To address the question of the level of Industry 4.0 adoption, the inquiry posed to participants was straightforward: 'Do you consider yourself an Industry 4.0 user?' The rationale behind this lies in determining whether a company falls under the category of Industry 4.0 adopters, a complex and somewhat ambiguous task (Aromaa et al., 2019). several authors assert that a company can be deemed an Industry 4.0 user if its main strategy involves a transition from traditional methods to Industry 4.0 (Toni et al., 2021). Following this line of reasoning, the results of the first two questions are as follows:

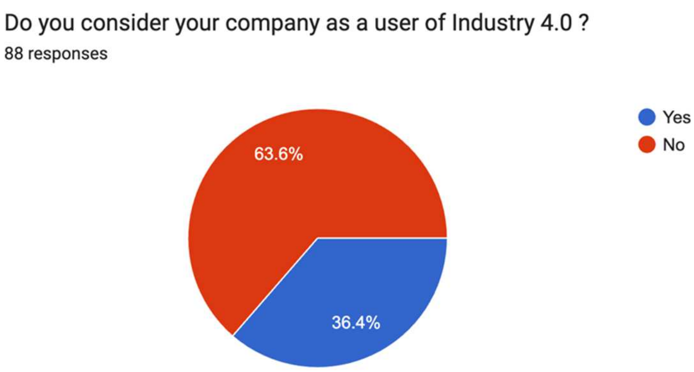

Figure 1*: industry 4.0 users for SMEs*

Source: Own research

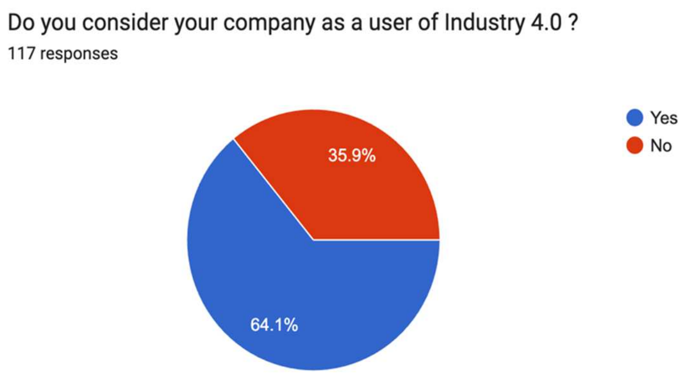

Figure 2*: industry 4.0 users for large companies*

Source: Own research

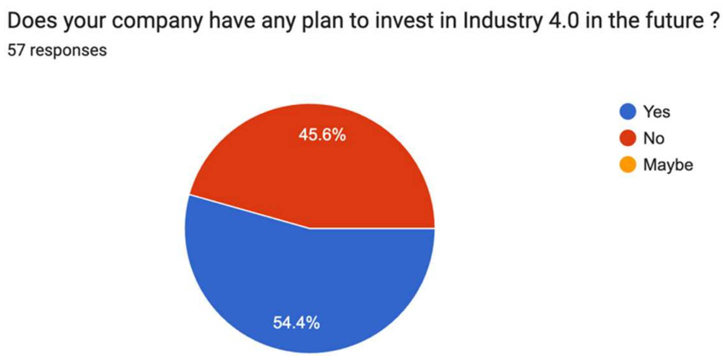

Figure 3*: Industry 4.0 Interest Among Non-User SMEs*

Source: Own research

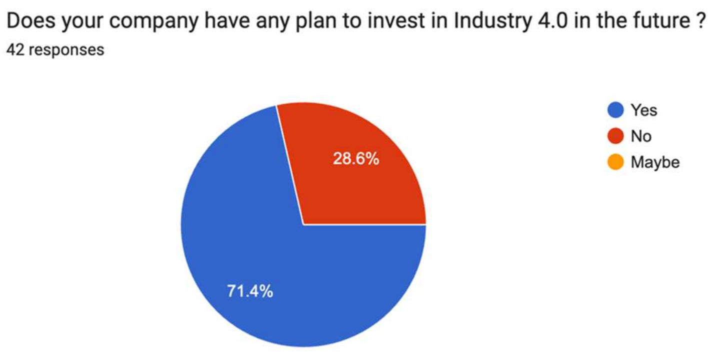

Figure 4*: Industry 4.0 Interest Among Large Non-User Companies*

Source: Own research

Comprehensive Look at Industry 4.0 Ambitions and Objectives

The formula used to answer O2 and O5 for the mean calculation is as follows:

$$\text{Mean} = \frac{\sum(Score\ of\ each\ response)}{Total\ number\ of\ participants\ engaged\ in\ the\ specific\ question}$$

Scores were assigned to responses, ranging from 5 for "Very High" to 1 for "Very Low," excluding responses marked as "Not Included at All" (assigned a score of 0). The mean was then calculated by summing these scores and dividing by the total number of participants who engaged in the specific question. We focused our analysis on participants who either confirmed current usage of Industry 4.0 or expressed plans to invest in it in the future. This targeted approach excluded those not considering Industry 4.0 integration in their strategic plans.

Table 1: Mean Ratings of Objectives by Participant Type (part 1)

Objectives	Company's image	Waste management	Enhance activities efficiency	Enhance resources efficiency (raw materials and energy)	Meet the customer needs	Improve R&D	Increase the company's revenue
Large companies	2.8	0.9	2.4	1.9	2.7	2.6	3.4
SMEs	1.8	0.3	1.7	1.03	4.1	0.9	4.1

Source: Own research

Table 2 Mean Ratings of Objectives by Participant Type (part 2)

Objectives	Communication improvement	Reverse Logistics improvement	Environment harm reduction	Carbon emission reduction	Lead time reduction	Delivery time reduction
Large companies	3.2	0.9	1.06	1.1	5.1	4.2
SMEs	1.7	1.1	1.3	0.2	2.3	1.7

Source: Own research

Table 1/2 shows differing priorities in Industry 4.0 investments between large enterprises and SMEs. Large companies prioritize reducing lead and delivery times, while SMEs focus on revenue growth and customer satisfaction. In terms of environmental goals, large companies exhibit a balanced commitment, while SMEs show lower prioritization, particularly in overall environmental impact reduction and reverse logistics. Overall, both large and small enterprises prioritize efficiency, growth, and customer satisfaction over environmental aspects in their Industry 4.0 investment strategies.

Industry 4.0 Challenges and the Dominant Technologies

This section will be guide by the third and the fourth sub-objectives which are investigating the prevalent technologies used in Industry 4.0 investments and analyzing the challenges and obstacles faced by Industry 4.0 adopters.

To analyze our results, we will compute the mean for each technology and challenge, separately for both large companies and SMEs. This involves employing the following formula:

$$\text{Mean} = \frac{\sum(Score\ of\ each\ response)}{Total\ number\ of\ participants\ engaged\ in\ the\ specific\ question}$$

For challenges, scores were assigned on a scale of 5 for "Very High" to 1 for "Very Low," and for technologies, the scale ranged from 3 for "Highly Interested" to 1 for "Not That Interested," excluding responses marked as "Not Included at All" (assigned a score of 0). The mean was then computed by summing these scores and dividing by the total number of participants who engaged in the specific question. The results are shown in Table 3:

Table 3: mean score of the technologies used and most common challenges

Technologies	**Internet of things**	**Smart factories**	**Big data**	**3D printers**	**Autonomous vehicles**	**Cyber Physical production system**	**Block chain**	**Artificial intelligent**	**The cloud**	**Simulation**
Large companies	2.1	1.9	2	0.9	1.7	1.6	0.4	2.2	1.8	0.5
SMEs	1.9	2.4	2	0.7	1.7	1.8	0.2	1.9	2	0.2
Challenges	**Lack of well skilled employees in the field**		**Low return on investment**	**Lack of financial resources**	**Difficulties to find the suitable partners (ex. Suppliers outsourcers…)**		**Risk of losing data**	**Non-support of top managers/ decision makers**	**It's irrelevant for my company**	
Large companies	3.5		3.7	3.6	3.2		2.6	2.4	1.4	
SMEs	3.8		3.5	3.1	2.1		1.3	3.2	2.5	

Source: Own research

Analyzing the results in Table 3, we observe that Internet of Things (IoT) and Artificial Intelligence (AI) emerge as the predominant technologies among large companies, closely followed by Smart Factories, Big Data, and the Cloud. SMEs, on the other hand, exhibit a similar trend with Smart Factories leading, followed by IoT, AI, and the Cloud.

Hypothesis check:

Table 4; Hypothesis overview

Hypothesis	Test type	Decision
H01: There is no association between the intention to invest in Industry 4.0 in the future and the type of company (SMEs and large enterprises) at the 0.05 significance level.	Chi-square test	Accepted
H02: There is no significant difference in the overall distribution of technologies used by companies (both current adopters and future investors) between SMEs and large companies at the 0.05 significance level.	Mann-Whitney U Test	Rejected
H03: There is no significant difference in the overall distribution of challenges faced by companies that do not currently invest in Industry 4.0, whether they wish to invest in the future or not, between SMEs and large companies at the 0.05 significance level.		Rejected
H04: There is no significant difference in the underlying reasons for investment in Industry 4.0 for environmental sustainability between large companies and SMEs at the 0.05 significance level.		Accepted

Source: Own research

4.2 Qualitative study

As previously outlined, this section will focus on O6, O7, and O8:

- **Constraints in Decision-Making**

In the midst of transitioning from a hardware-centric to a software and services-focused model, the company encountered challenges in decision-making for Industry 4.0 adoption. Despite being a pioneer in digital transformation, decision-makers faced uncertainty during this radical shift. The establishment of an IoT department in Switzerland proved pivotal, demonstrating success before significant commitment.

Organizational culture, supportive of innovation and agility, facilitated a smoother transition. Overcoming decision-making hurdles required showcasing real-world impacts.

The company compiled endorsements and experiences from other firms, offering decision-makers transparent insights into Industry 4.0's potential.

Ultimately, the convergence of transformative pressure, IoT success, and strategic informational support led decision-makers to embrace Industry 4.0, transcending initial challenges and ensuring a successful digital transformation.

- **Data abundant, untapped value**

In the landscape of Industry 4.0, manufacturing data often suffers from biases, inaccuracies, and outdated information due to challenging data gathering conditions, incompatible proprietary systems, and dispersed operational data across multiple databases. Despite generating vast amounts of data, companies typically underutilize these resources, with only 10% of collected manufacturing data being effectively employed.

Strategic Data-Driven Initiatives: The firm under study has established a robust data-driven structure focusing on five key areas:

1. **Unlocking the Latent Power of Data:**
    - Implementation of advanced data management capabilities.
    - Utilization of standardized data architecture and centralized storage facilities.
    - Introduction of a semantic model for improved data organization.
2. **Attaining Cyber Resilience:**
    - Adoption of a "zero trust" cybersecurity methodology.
    - Thorough authentication and authorization processes for all communication.
    - Continual security validation to ensure secure data access.
3. **Establishing an Integrated Enterprise Architecture:**
    - Implementation of a hybrid multicloud IT infrastructure for seamless connectivity and workload optimization.
    - Standardized hybrid cloud architecture at the shop floor for effective IT workload management.
    - Consolidation and regulation of data from different plants for cross-factory insights.
4. **Elevating Manufacturing Excellence:**
    - Upgrades in raw material management, warehouse management, and maintenance applications.
    - Integration of AI into various processes for data-driven efficiency.

- Competitive edge achieved through high-value extraction from technological facilities.

5. **Synergizing Digital Innovations:**
    - Integration of digital strategy with manufacturing plans.
    - Leveraging data and digital technology to fuel innovations and transformation in production.
    - Strategic alignment enabling seamless connections between data, applications, and processes for operational efficiency.

- **Lack of qualified skills**

Inadequate employee proficiency with new technologies can hinder a company's progress and future investmentsn (Breunig et al., 2017). To address this, the company established an educational facility offering free courses in IoT, cloud computing, coding, AI, and Big data across its five main plants. Simultaneously, it prioritizes employee well-being, emphasizing diversity, inclusion, and equity, and supporting work-life balance through recreational activities. Real-time analysis of resignations ensures continuous improvement. This dual strategy positions the company for success in Industry 4.0.

- **Integrating Information Technology (IT) with Operational Technology (OT)**

Industry 4.0 evolution brings IT and OT integration challenges, exposing OT networks and connecting with IT. A manufacturing firm's structure involves five levels, with OT (physical processes and intelligent devices) and IT (control systems, manufacturing operations, and logistics). Efficient operations demand a strategic integration layer at the plant level, fostering seamless connectivity and application deployment. "OT Infrastructure as Code," bolstered by cloud models, enhances manufacturing KPIs like OEE. Direct OT oversight enables intelligent operations, maximizing OEE through predictive maintenance and optimized schedules with machine learning.

- **Industry 4.0 Investment Intensity**

A prominent challenge in Industry 4.0 adoption is the substantial investment required, with companies needing to increase annual capital investments by 50% over five years (Geissbauer et al., 2014).
Acknowledging this financial commitment, our company strategically invested in Industry 4.0, leveraging its IT background to gain expertise and emerge as a leader in implementation. This approach not only ensured market success but also positioned the company as an industry leader, attracting clients seeking its services.

- **Lack of awareness about I4.0**

The company under study identifies a lack of awareness about Industry 4.0 among their customers as a significant challenge. They emphasize that many potential clients, prior to embarking on digital transformation, lacked a clear understanding of Industry 4.0.
To address this, the company prioritizes raising awareness through robust marketing campaigns and dedicated initiatives. A dedicated institution regularly publishes articles on trending subjects, showcasing the company's projects and accomplishments. Despite the integration of certain Industry 4.0 technologies by various companies, the pervasive lack of awareness often hinders them from fully grasping the extensive capabilities and possibilities offered by these technologies.

V. New scientific results

The scientific contributions of our work are multifaceted and substantiate significant advancements in the literature. More concretely, key scientific results include:

- Industry 4.0 Investments: Our study provides valuable insights into Industry 4.0 investments, revealing a pronounced inclination toward adoption by large enterprises, with over 63% considering themselves adopters compared to 35% for SMEs.
- Similarities in Intentions: Statistical analyses, including Chi-square and Mann-Whitney U tests, underscored similarities between SMEs and large companies in their future investment intentions and willingness to invest in Industry 4.0 for environmental sustainability.
- Divergent Patterns of Investment: Noteworthy distinctions between SMEs and large companies surfaced in terms of the most relevant Industry 4.0 technologies and the challenges impeding their investment, as highlighted by the Mann-Whitney U tests
- Implementation Strategies: By examining the company's journey, we addressed and surmounted six critical challenges that often impede Industry 4.0 adoption: navigating constraints in decision-making, leveraging the abundance of data for untapped value, addressing the lack of qualified skills, seamlessly integrating Information Technology (IT) with Operational Technology (OT), managing the intensity of Industry 4.0 investments, and tackling the pervasive lack of awareness about Industry 4.0. By providing a comprehensive guide, our research contributes significantly to the scientific community's understanding of actionable strategies for overcoming these common obstacles.
- Environmental Sustainability Outcomes: Through collaborative efforts with the company's customers, our study highlights tangible environmental sustainability outcomes resulting from Industry 4.0 investments. Specifically, we showcase the positive impact on waste management, the reduction of CO2 emissions, and improved energy management. This aspect of our research is pivotal in reshaping the discourse around Industry 4.0, emphasizing the need to redirect attention towards its environmental implications.

In summary, our research fills a void in the existing literature, offering nuanced insights into Industry 4.0 implementation, investment patterns, and environmental sustainability outcomes. These findings contribute substantively to both academic discourse and practical applications in the field.

VI. SUMMARY

In summary, our research represents a comprehensive exploration of Industry 4.0 implementation, addressing various dimensions such as challenges, technologies, adoption trends, investment inclinations, implementation hurdles, perceived obstacles, and desired outcomes, with a crucial emphasis on environmental sustainability.

Employing a mixed-methodology approach, our quantitative study provides a broad overview of Industry 4.0 trends across SMEs and large companies, offering a numerical perspective on the current state of adoption. Simultaneously, our qualitative investigation delves deeply into a singular case study, extracting detailed perspectives into successful implementation strategies and the achievement of environmental objectives.

The overarching goal of this extensive exploration is to extract valuable insights for decision-makers, offering a comprehensive comprehension of Industry 4.0 adoption. As a primary objective, our study aims to provide a practical roadmap, guiding decision-makers through the complexities of Industry 4.0 implementation. This roadmap serves as a strategic guide, assisting decision-makers in overcoming existing challenges and aligning their efforts with the necessities of environmental sustainability.

With eight sub-objectives outlined, our study has fulfilled the overarching objective, offering decision-makers a coherent and well-structured reference for Industry 4.0 implementation. This research not only contributes to academic discourse but also holds practical significance, empowering decision-makers to navigate the complex landscape of Industry 4.0 while addressing crucial environmental sustainability concerns. As we conclude this thesis, we emphasize the lasting need for ongoing research and strategic approaches to ensure the continued success and positive impact of Industry 4.0 in the realm of environmental sustainability.

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