International Journal of Science and Research (IJSR)
ISSN: 2319-7064
Impact Factor 2024: 7.101

Integration of Industry 4.0 Technologies for Enhanced Quality Control in Manufacturing

Jesus Gerardo Cruz Alvarez[1], Jesús Santoyo Ortega[2], Osiris Noel Pérez Moreno[3]

[1]Nuevo Leon State University, School of Business Management, Ciudad Universitaria, San Nicolas de los Garza, 66455, Mexico
Email: *jesus.cruzlv[at]uanl.edu.mx*

[2]Nuevo Leon State University, School of Business Management, Ciudad Universitaria, San Nicolas de los Garza, 66455, Mexico
Email: *jesus.santoyoo[at]uanl.edu.mx*

[3]University of the Valley of Puebla, School of Operation Management, Calle 3 sur, Puebla, 72440, Mexico, Mexico
Email: *da01920[at]uvp.edu.mx*

Abstract: ***Industry 4.0 has revolutionized manufacturing processes by incorporating advanced technologies that enable smarter, more flexible, and more efficient production systems. This study aims to analyze the impact of integrating emerging technologies-such as the Internet of Things (IoT), cyber-physical systems (CPS), big data analytics, artificial intelligence (AI), and blockchain-on the improvement of quality control in industrial environments. A systematic literature review based on the PRISMA methodology and an empirical study using the Delphi technique were conducted to collect and analyze the opinions of 22 experts with relevant experience in quality and digital transformation. A measurement instrument was developed with questions distributed across five thematic sections, and the responses were evaluated through non-parametric statistical analysis (Wilcoxon signed-rank test). The findings indicate that the effective implementation of CPS and Quality 4.0 has a statistically significant impact on quality control, while the level of investment in technologies such as AI, big data, or blockchain alone does not guarantee quality improvement. The study concludes that digital transformation strategies should focus more on the competencies and strategic alignment of personnel than on isolated technological investment, thus emphasizing the human-technical synergy required for sustainable quality innovation.***

Keywords: Industry 4.0; quality control; artificial intelligence; big data; blockchain; Quality 4.0.

1. Introduction

Industry 4.0 represents a paradigm shift in manufacturing, leveraging advanced technologies to create smarter, more interconnected production systems. At its core, Industry 4.0 integrates cyber-physical systems (CPS), the Internet of Things (IoT), cloud computing (CC), Blockchain technologies and artificial intelligence (AI) to optimize processes, enhance productivity, and drive innovation. CPS enable machines and devices to communicate and collaborate with each other autonomously, while IoT sensors collect vast amounts of data from various points in the manufacturing process. This data is then analyzed in real-time using AI algorithms to identify patterns, predict maintenance needs, and optimize workflows. Cloud computing provides the infrastructure for storing and processing this data, facilitating seamless connectivity and accessibility across the manufacturing ecosystem, Finally, Blockchain technologies guarantee the integrity of records while adding a cryptographic ledger of bits and bytes to products. Overall, Industry 4.0 transforms traditional manufacturing into a highly flexible, efficient, and responsive ecosystem, empowering businesses to adapt to changing market demands and gain a competitive edge in the global marketplace.

2. Literature Review

Industry 4.0, characterized by the integration of advanced digital technologies into manufacturing processes, has revolutionized the landscape of quality control within industrial settings. This review synthesizes existing research to elucidate the impact Industry 4.0 on quality control practices and outcomes.

To ensure methodological rigor in the literature review, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework was adopted. A structured and systematic search was carried out across Scopus, Web of Science, IEEE Xplore, and ScienceDirect, focusing on studies published between 2017 and 2023. Inclusion criteria targeted peer-reviewed articles that addressed Industry 4.0 technologies—such as cyber-physical systems (CPS), artificial intelligence, big data, blockchain, and smart quality systems—in relation to quality control and Quality 4.0. Articles were excluded if they were not available in full text, duplicated, or lacked conceptual or empirical relevance.

The PRISMA process was conducted in four key phases: identification, screening, eligibility, and inclusion. The search initially yielded over 120 records, which were filtered down based on relevance and quality, resulting in a final selection of 28 high-quality sources. Among the selected works are studies focused on blockchain in traceability systems [1], quality inspection via robotics [2], data-driven frameworks [3], and Quality 4.0 strategies [4] [5]; These references formed the foundation for the theoretical and empirical development of the present study and directly supported the design of the Delphi instrument.

2.1 Integration of Cyber-Physical Systems (CPS)

Industry 4.0 emphasizes the convergence of physical and digital systems. The actual Manufacturing Execution Systems (MES) soon designed, tested, and built under an approach supported by cyber-physical systems (CPS) must evolve to achieve optimized reconfiguration or adaptability -as defined by ISO 25010 standard [5], fulfilling requirements such as agility, efficiency, and scalability. With this vision in consideration, CPS, and the Internet-of-Things (IoT) become more economically sound to manufacturing. This union allows industrial robots to work collaboratively in real-time with measuring and vision systems [2] creating a dynamic learning closed loop that improves quality, cost, and delivery.

2.2 Utilization of Big Data Analytics

Also, the proliferation of IoT and CPS in industrial environments generate vast amounts of data. Big data analytics (BDA) enable the extraction of valuable insights from this data everywhere, everytime, to optimize manufacturing processes through data-driven discovery offering unprecedented opportunities for quality control improvement [6]. By leveraging machine learning algorithms, manufacturers can identify patterns indicative of potential defects, thus enhancing product quality and reliability.

2.3 Implementation of Advanced Quality Control Techniques

Industry 4.0 fosters quality manufacturing: simulations predict that by 2030 at least 70% of the companies will adopt at least one type of AI solution [7], needed to boost quality control using an evolved problem-solving approach of seven steps, namely, Identify, Acsensorize, Discover, Learn, Predict, Redesign, Relearn. This means that statistical quality control upon inspection and sampling of fabricated goods is replaced by monitoring products for defects and collecting data in real time [8] to be processed through combined cloud computing (CC) applications and CPS infrastructure enabling unseen decision making. Control and traceability of products go hand in hand in a world craving for a myriad of possibilities as seen on social media. This condition gets support using Blockchain technology [9] that assures integrity of serialization records and process and product data by adding cryptographic ledgers available on the cloud regardless of product volumes or configurations.

2.4 Implications for Quality Management Systems (QMS)

Managerial thinking must now ride on the wave of quality management systems (QMS) needing for an accelerated digitalization [10]. Augmenting the way data-driven and innovation knowledge is kept, leveraging on BDA capabilities and skills, playing lean on industrial processes by means of automation and autonomation, and constructing networked firms and ecosystems will have a differentiating competitive advantage [11]. A QMS under Industry 4.0 must empower the leadership groups to maintain quality control [12] by monitoring key performance indicators in real time through real-time statistics and dashboards. Hence, integration of Industry 4.0 to the management of quality manufacturing forces for a reevaluation of traditional QMS, more and more aligned to the demands of digital manufacturing as part of a holistic supply chain structure to manage remotely by individuals located around the globe.

2.5 Translation into Quality 4.0

Introducing Industry 4.0 to the quality assurance and control fields, turned them a powerful pair of approaches by integrating state-of-the-art sensors and actuators, improved networking protocols, as well as the utilization of the latest AI-powered algorithms over massive amounts of data [4]. This higher idea comes as a conceptual framework naturally called Quality 4.0, defined as the empirical way to do quality by learning and discovering knowledge through the data generation, collection, and analysis, real-time, enabling smart decision [7]. Technology aligns QMS practices to an exponential reach under Quality 4.0 [13]: manufacturing parameters and schedule goals learn and adjust instantly, production lines reach zero-defect rates decided by smart inspection machinery, and quality gets embedded to the products and the processes from the design stages.

Research question
What is the impact of Industry 4.0 on Quality control in the manufacturing environment?

3. Methods

To uncover the truth behind the impact of Industry 4.0 on Quality control in the manufacturing environment this study will target to explore and analyze a set of data by means of gathering data using a panel of Subject Matter Experts (SME), leveraging on the Delphi technique. Individuals conforming the subject group will suffice a specific profile with the aim of collecting an objective and comprehensive response to a series of questions within an instrument designed to assure the quality of scientific knowledge available from the manufacturing realm, as well as from some other professional fields to have a sense to reinforce, contrast or debate the concepts behind the research question. Once data gets collected, these will go through a non-parametric statistical algorithm to reveal trends and variations, which in turn will allow the study to offer an educated set of results of statistical significance to interpret and discuss, and to encourage for future research.

3.1 Procedure

Defined the expert profile which included four criteria: education level (Master or Doctor degree); industry experience (10+ years of exposure to quality improvement in the automotive, consumer goods, information technology, and education); function (Quality, Operations, Information Systems, Engineering, and Research); technological savviness (familiarity, use or development of CPS, Big-Data, AI, Blockchain and Quality 4.0). See Table 1.

Table 1: Profile of Subject Matter Experts for research panel

Item	Criteria	Profile
1	Education level	Graduate: Master; Doctor
2	Industry experience (10+ years)	Automotive; Consumer goods; IT; Education
3	Function	Quality; Operations; IS; Engineering; Research
4	Tech savviness	CPS; Big-Data; AI; Blockchain; Quality 4.0

Source: Author's own work based defining the subject matter expert´s profile

Designed a measuring instrument made of up to five sections with four questions each, and covering 5 main topics: CPS, Big-Data (BDA), AI, Blockchain (BLK), and Quality 4.0

(Q4O), respectively, as described in Table 2. Each question will be subject to a score following a 5-value Likert scale, where '1' means the least and '5' means the most, allowing the collection of data with less sensitivity to undesired bias during the analysis.

Table 2: Set of four questions by section; five sections; one per topic

Item	Factor	Key	Question
1	CPS	1.1	Q1. Do you think the successful implementation of topic* is necessary to enhance quality control in manufacturing?
		1.2	Q2. Do you believe the amount of investment in topic* significatively enhances quality control in manufacturing?
		1.3	Q3. What value do you assign to the impact of topic* on quality control in manufacturing, regardless of implementation or investment?
		1.4	Q4. What impact do you think topic* has over quality control in industry in general?
2	Big-Data	2.1	Q1. Do you think the successful implementation of topic* is necessary to enhance quality control in manufacturing?
		2.2	Q2. Do you believe the amount of investment in topic* significatively enhances quality control in manufacturing?
		2.3	Q3. What value do you assign to the impact of topic* on quality control in manufacturing, regardless of implementation or investment?
		2.4	Q4. What impact do you think topic* has over quality control in industry in general?
3	AI	3.1	Q1. Do you think the successful implementation of topic* is necessary to enhance quality control in manufacturing?
		3.2	Q2. Do you believe the amount of investment in topic* significatively enhances quality control in manufacturing?
		3.3	Q3. What value do you assign to the impact of topic* on quality control in manufacturing, regardless of implementation or investment?
		3.4	Q4. What impact do you think topic* has over quality control in industry in general?
4	Blockchain	4.1	Q1. Do you think the successful implementation of topic* is necessary to enhance quality control in manufacturing?
		4.2	Q2. Do you believe the amount of investment in topic* significatively enhances quality control in manufacturing?
		4.3	Q3. What value do you assign to the impact of topic* on quality control in manufacturing, regardless of implementation or investment?
		4.4	Q4. What impact do you think topic* has over quality control in industry in general?
5	Quality 4.0	5.1	Q1. Do you think the successful implementation of topic* is necessary to enhance quality control in manufacturing?
		5.2	Q2. Do you believe the amount of investment in topic* significatively enhances quality control in manufacturing?
		5.3	Q3. What value do you assign to the impact of topic* on quality control in manufacturing, regardless of implementation or investment?
		5.4	Q4. What impact do you think topic* has over quality control in industry in general?

Source: Author's own work structuring the field survey instrument.

Analyzed the resulting data set to cleanse it for the appropriate features needed to apply a non-parametric statistical technique, like the Wilcoxon Signed-Rank test. Confirmed values to the tests assisted on qualifying the hypothesis and on providing enough indication of the impact of Industry 4.0 components to enhance quality control in a manufacturing environment. The study took advantage of these results, opening a discussion, comparing, and contrasting findings to what scientific literature has revealed as well as providing a few essential conclusions.

4. Results

The measurement instrument was applied to a group of 38 individuals who in gross terms fulfilled the desired profile: selected people among industries where years of exposure to topics about manufacturing, operations, quality and technology might drive their career development throughout the years, either as practitioners or as scholars and researchers, and would point them to acquire post-secondary studies as Master or Doctor graduates, qualifying them as an ideal SME panel to be capable and to be comprehensive responding the instrument.

The present study took advantage of the Google Forms application given its simple features allowing the researchers to build the set of four questions by section; five sections; one per topic, as shown in Figure 1. Just after discussing the ideal and limited package of questions, sufficient to cover the five topics of interest and appealing enough to invite and to engage the participant's attention to gather key data. An initial analysis discriminated the population to a sample of 22 experts that complied with the expected characteristics delineated by a typical Delphi technique.

Source: Author's own work using google forms

Figure 1. Measuring instrument built and applied using Google Forms

4.1. Demographics

The 22-expert sample comprised 16 Master and 6 Doctor graduates, that is 72.7% and 27.3%, respectively. Around 41% possess above 25 years of experience in their industry, which is something to mention; while the following two categories make up 45%; finally, 13.6% have over 10 years of experience. Manufacturing is the predominant industry with almost 82% of the sample, followed by the Academy and Research realm with 9.1% and followed by Consumer Goods and Other for the remainder 9.1%. There are 12 Quality and CI practitioners, 4 individuals in Engineering, and 3 IT professionals and 3 under Other, follow suit respectively.

Overall, the compound of characteristics among the selected group of experts qualifies it ideally as an exploratory study considering the seniority level and the competence and the technological savviness needed to respond appropriately the instrument designed. Figure 2 synthetizes graphically its demographics.

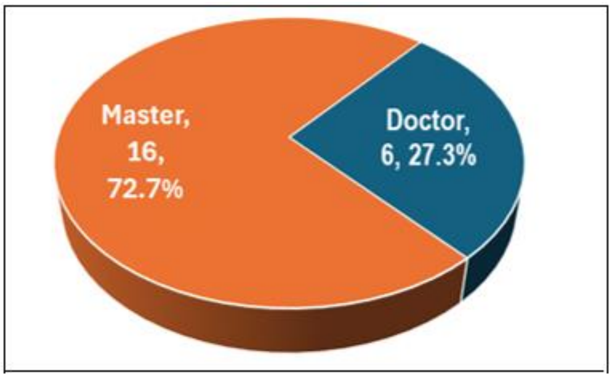

Figure 2: Expert´s education level

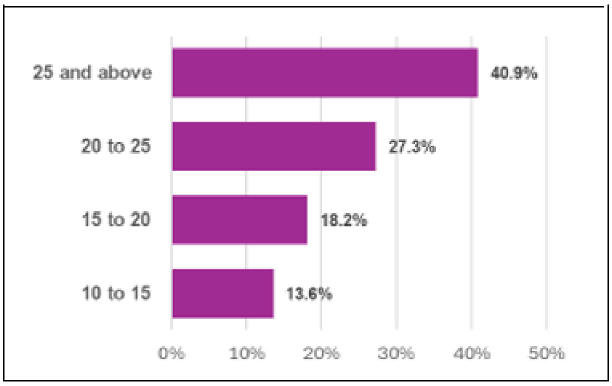

Figure 3: Expert´s years of experience

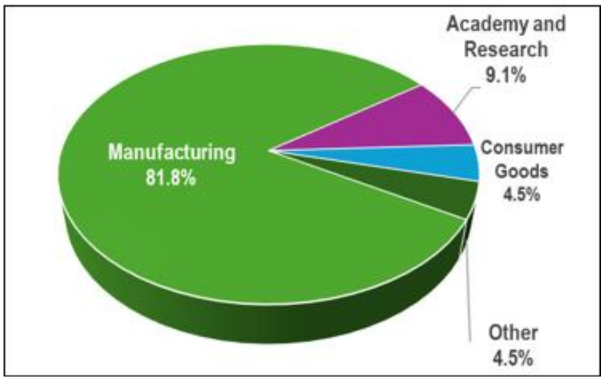

Figure 4: Expert´s by field

Source: Author's own work based on descriptive statistics analyzed using Minitab

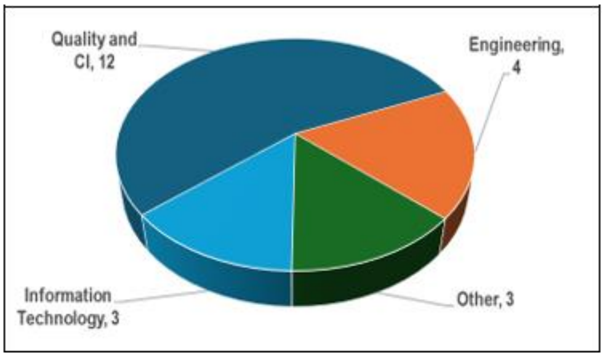

Figure 5: Expert´s by function

Source: Author's own work based on descriptive statistics analyzed using Minitab

4.2. Hypothesis testing

After cleanse the initial data set, typical descriptive statistics were calculated using Minitab due to its immediate availability at the time of the study. See Table 3. Due to its size of 22 the researchers decided to use medians over modes and means to analyze the sample with the Wilcoxon Signed-Rank test, as they could increase accuracy while determining the values needed to decide from hypothesis testing.

Recall the declared research question 'What is the impact of Industry 4.0 on Quality control in the manufacturing environment?' invited the experts to relate the proposed topics, and hence, hypothesis forming based in the possibility of each one of the components to effectively impact quality control in the manufacturing environment, that is, CPS, BDA, AI, BLK, and Q4O, to separately impact on quality control in the manufacturing environment by assessing key factors such as its successful implementation (DEPL), the level of investment (INVS), its impact in manufacturing (IMPM), and even its impact to the industry in general (IMPI).

Using Minitab, the Wilcoxon Signed-Rank test was calculated utilizing the medians for each one of the proposed questions for a 95% of significance. See Table 4.

Table 5: Descriptive statistics to each one of the proposed questions in the study

Topic	Question	Variable	N	N*	Mean	StDev	Min	Q1	Median	Q3	Max	IQR	Mode	Mode
CPS	DEPL	1.1	22	0	4.545	0.739	2	4	**5**	5	5	1	5	**14**
	INVS	1.2	22	0	3.955	0.999	2	3.75	**4**	5	5	1.25	4	**10**
	IMPB	1.3	22	0	4.364	0.581	3	4	**4**	5	5	1	4	**12**
	IMPI	1.4	22	0	4.318	0.646	3	4	**4**	5	5	1	4	**11**
BDA	DEPL	2.1	22	0	4.364	0.902	2	4	**5**	5	5	1	5	**13**
	INVS	2.2	22	0	3.955	0.950	2	3	**4**	5	5	2	4	**9**
	IMPB	2.3	22	0	4.318	0.716	3	4	**4**	5	5	1	5	**10**
	IMPI	2.4	22	0	4.409	0.666	3	4	**4.5**	5	5	1	5	**11**
AI	DEPL	3.1	22	0	3.955	0.999	1	3	**4**	5	5	2	4	**9**
	INVS	3.2	22	0	4.000	0.690	3	3.75	**4**	4.25	5	0.5	4	**12**
	IMPB	3.3	22	0	4.318	0.716	3	4	**4**	5	5	1	5	**10**
	IMPI	3.4	22	0	4.318	0.780	3	4	**4.5**	5	5	1	5	**11**
BLK	DEPL	4.1	22	0	3.545	1.224	1	3	**3.5**	5	5	2	3	**8**
	INVS	4.2	22	0	3.318	0.995	1	3	**3**	4	5	1	3, 4	**8**
	IMPB	4.3	22	0	3.545	1.057	1	3	**4**	4	5	1	4	**8**
	IMPI	4.4	22	0	3.455	1.184	1	3	**4**	4	5	1	4	**8**
Q40	DEPL	5.1	22	0	4.273	0.703	3	4	**4**	5	5	1	4	**10**
	INVS	5.2	22	0	4.000	0.816	3	3	**4**	5	5	2	4	**8**
	IMPB	5.3	22	0	4.364	0.658	3	4	**4**	5	5	1	4, 5	**10**
	IMPI	5.4	22	0	4.364	0.727	3	4	**4.5**	5	5	1	5	**11**

Source: Author's own work based on descriptive statistics analyzed using Minitab

Table 6: Results of hypothesis testing using Wilcoxon Signed-Rank test

Topic	Question		Median	Null hypothesis	Alternative hypothesis	N for Test	Wilcoxon Statistic	P-Value
CPS	DEPL	1.1	**5**	$H_0: \eta = 5$	$H_1: \eta \neq 5$	8	0.0	**0.014**
	INVS	1.2	**4**	$H_0: \eta = 4$	$H_1: \eta \neq 4$	12	35.0	**0.784**
	IMPM	1.3	**4**	$H_0: \eta = 4$	$H_1: \eta \neq 4$	10	49.5	**0.028**
	IMPI	1.4	**4**	$H_0: \eta = 4$	$H_1: \eta \neq 4$	11	54.0	**0.068**
BDA	DEPL	2.1	**5**	$H_0: \eta = 5$	$H_1: \eta \neq 5$	9	0.0	**0.009**
	INVS	2.2	**4**	$H_0: \eta = 4$	$H_1: \eta \neq 4$	13	42.0	**0.834**
	IMPM	2.3	**4**	$H_0: \eta = 4$	$H_1: \eta \neq 4$	13	70.0	**0.093**
	IMPI	2.4	**4.5**	$H_0: \eta = 4.5$	$H_1: \eta \neq 4.5$	22	115.5	**0.733**
AI	DEPL	3.1	**4**	$H_0: \eta = 4$	$H_1: \eta \neq 4$	13	45.5	**1.000**
	INVS	3.2	**4**	$H_0: \eta = 4$	$H_1: \eta \neq 4$	10	27.5	**1.000**
	IMPM	3.3	**4**	$H_0: \eta = 4$	$H_1: \eta \neq 4$	13	70.0	**0.093**
	IMPI	3.4	**4.5**	$H_0: \eta = 4.5$	$H_1: \eta \neq 4.5$	22	104.5	**0.485**
BLK	DEPL	4.1	**3.5**	$H_0: \eta = 3.5$	$H_1: \eta \neq 3.5$	22	137.0	**0.745**
	INVS	4.2	**3**	$H_0: \eta = 3$	$H_1: \eta \neq 3$	14	74.0	**0.187**
	IMPM	4.3	**4**	$H_0: \eta = 4$	$H_1: \eta \neq 4$	14	24.0	**0.079**
	IMPI	4.4	**4**	$H_0: \eta = 4$	$H_1: \eta \neq 4$	14	22.0	**0.060**
Q40	DEPL	5.1	**4**	$H_0: \eta = 4$	$H_1: \eta \neq 4$	12	58.5	**0.136**
	INVS	5.2	**4**	$H_0: \eta = 4$	$H_1: \eta \neq 4$	14	52.5	**1.000**
	IMPM	5.3	**4**	$H_0: \eta = 4$	$H_1: \eta \neq 4$	12	65	**0.045**
	IMPI	5.4	**4.5**	$H_0: \eta = 4.5$	$H_1: \eta \neq 4.5$	22	110	**0.603**

Source: Author's own work based on descriptive statistics analyzed using Minitab

4.3. Findings

Notice the IMPM questions (Q1.3 and Q5.3) associated with CPS and Q40, respectively, show the null hypothesis cannot be rejected as values sustain below 5% confirming there is a statistically significant difference. However, this statement does not occur for BDA, AI and BLK (Q2.3, Q3.3, and Q4.3). Hence, the voice of the experts tells there is indeed an impact on quality control in a manufacturing environment when Industry 4.0 topics such as CPS and Q4O; and their opinion seemed to be divided for the remaining three components including BDA, AI, and BLK, when included in the organization's manufacturing strategy.

It is also interesting to note that according to the SME panel insights, a successful implementation DEPL of CPS and BDA also make a difference on quality control (Q1.1 and Q2.1) as confirmed by their own hypothesis testing; this finding is contrasting to results over AI, BLK, and Q4O, respectively (Q3.1, Q4.1, and Q5.1). Nonetheless, the latter may be perceived by the panel to impact quality control to some extent in a manufacturing environment.

It is even farther surprising to find that the level of investment INVS seemed to have poor or no impact on the enhancement of quality control in the manufacturing environment as in all cases (Q1.2, Q2.2, Q3.2, Q4.2, and Q5.2) the null hypothesis testing confirmed they were not significantly different. Not trying to move forward with early conclusions at this point, the researchers need to point out that the unexperienced practitioner may have a questionable vision believing the larger the investment in Industry 4.0, the better the quality control gets in manufacturing.

Finally, the study pointed out that the questions about the impact of Industry 4.0 components to enhance quality control in the industry in general (Q1.4, Q2.4, Q3.4, Q4.4, and Q5.4) do not have a uniform perception as testing rejects their null hypothesis. However, something to note needing further discussion is the opinion the SME have over the possible impact CPS and BLK have on quality control in industry in general. The researchers will take these and the above findings to enrich discussion on the theme at hand and to develop a few essential conclusions.

5. Discussion and Conclusions

Clearly, Industry 4.0 revolutionizes quality control practices in manufacturing through the integration of CPS, BDA, advanced data-driven quality control techniques leveraging on BLK and adaptive quality management systems under Q4O and AI [14]. By taking advantage of digital technologies combining CPS and BDA to cite on example -think of the Internet-of-Things (IoT) and digital twins, manufacturers can enhance their manufacturing systems in real time (Friedrich et. al, 2022) enhancing their competitive advantage while modeling product and processes using data, automation, and human interaction. The need for scrupulous control over product and process throughout the supply chain makes BLK technology an ideal candidate for keeping traceability and granularity at different levels and industries [14]. Plenty of research is available in scientific literature covering for all these specific topics separately. However, very few of them have comprehensively grouped the findings from each one of the interest themes within Industry 4.0 over the enhancement of quality in manufacturing [9] and the automation of quality [2].

The present study attempts to close the still present gap between the impact of Industry 4.0 technologies and the enhancement of quality in manufacturing. Using the Delphi technique a measurement instrument was applied to a selected group of 22 SMEs complying with a demographic and a competence profile assuring reliability and validity in the responses. After gathering data with the 20-question instrument in Google Forms and analyzing them with Minitab by applying a Wilcoxon Signed-Rank test the study got several findings that need to be assessed, compared, and contrasted with the existing research found in the literature.
Regarding CPS and its successful implementation, it really makes an impact to quality control in a manufacturing environment. The present study coincides with conclusions found by [2] who identified a strong influence when implementing Industry 4.0 technologies in manufacturing strategies such as CPS and BDA as pivotal components needed to evolve the traditional role of quality control into Q4O. Moreover, in their study about robotics as the base to enhance the control of quality based on a Zero-Defect Mindset (ZDM), [2] conclude automated cells fall under CPS capable of detecting, predicting, preventing, and even repairing non-conforming parts in manufacturing.

Nevertheless, the study also assisted to identify several interesting aspects of Industry 4.0 technologies. One of these aspects deals with the fact that there is no convincing evidence that technologies such as BDA, AI and BLK, really mark an impact to quality control in manufacturing. When looking for evidence of Industry 4.0 applied to a ZDM strategy in manufacturing, Wan & Leirmo (2023) concluded a common pitfall is to implement sophisticated systems with the aim of cutting down the quantity of defects in production lines while removing the role of humans as part of the manufacturing system.

The other aspect to highlight deals with the fact a larger amount of investment INVS on Industry 4.0 technologies is not necessarily perceived as a game changer for quality control in manufacturing. In that regard, since the investments needed to implement CPS, BDA, AI or BLK are significant, as many other solutions for manufacturing and industry in general, there are studies that better point out for the need of developing a highly specialized taskforce, as concluded by [14], whose competences make them capable of designing, reconfiguring and repairing manufacturing systems under Industry 4.0 to keep up with the more stringent customer requirements the modern quality control demands.

In conclusion, there is plenty of evidence confirming the integration of Industry 4.0 truly impacts quality control in a manufacturing environment. And at the same time there is space for filling the breaches of theory around Industry 4.0 and it's the enhancement of quality. For future research, this study also coincides with the ideas presented by Liu et. al (2023): e.g. the introduction of Blockchain technology to modernize Quality Management Systems, the digitalization of current audit processes under norms and standards to be sustainable in a Quality 4.0 environment, the traditional problem-solving methodologies such as Six-Sigma, PDCA or 8D while incorporating AI and BDA and the impact Industry 4.0 may have on reducing non-conforming product as a way to reduce the Cost of Quality.

References

[1] W. A. Ahmed and B. L. MacCarthy,"Blockchain-enabled supply chain traceability: How wide? How deep?," *International Journal of Production Economics*, vol. 263, p. 108963, 2023. https://doi.org/10.1016/j.ijpe.2023.108963
[2] V. Azamfirei, A. Granlund, and Y. Lagrosen, "Lessons from adopting robotic in-line quality inspection in the Swedish manufacturing industry," *Procedia Computer Science*, vol. 217, pp. 386–394, 2023. https://doi.org/10.1016/j.procs.2022.12.186
[3] A. Cassoli, L. D. Cassoli, A. C. S. Santos, and L. C. Oliveira, "Industry 4.0 and Quality 4.0: A data-driven framework for quality management systems," *Journal of Manufacturing Systems*, 2022.
[4] M. Javaid, A. Haleem, R. P. Singh, R. Suman, S. Rab, and R. Vaishya, "Quality 4.0 in healthcare: Exploring the key dimensions and roadmap," *Sustainable Operations and Computers*, vol. 2, no. 1, pp. 1–9, 2021. https://doi.org/10.1016/j.susoc.2020.12.001
[5] P. O. Antonino, R. Capilla, P. Pelliccione, F. Schnicke, D. Espen, T. Kuhn, and K. Schmid, "A Quality 4.0 model for architecting Industry 4.0 systems," *Advanced Engineering Informatics*, vol. 54, p. 101801, 2022. https://doi.org/10.1016/j.aei.2022.101801
[6] P. V. Thayyib et al., "State-of-the-art of Artificial Intelligence and Big Data Analytics: Reviews in five different domains – A bibliometric summary," *Preprint*, 2023.
[7] R. Verner, M. Tkáč, and M. Tkáč, "Improving quality of long-term bond price prediction using artificial neural networks," *Quality Innovation Prosperity*, vol. 25, no. 1, pp. 103–123, 2021. https://doi.org/10.12776/qip.v25i1.1532
[8] M. Sony, "Quality 4.0: A systematic literature review and research agenda," *Computers & Industrial*

Engineering, vol. 150, p. 106874, 2020. https://doi.org/10.1016/j.cie.2020.106874

[9] E. Baran and T. K. Polat, "Classification of Industry 4.0 for total quality management: A review," *Sustainability*, vol. 14, no. 6, p. 3329, 2022. https://doi.org/10.3390/su14063329

[10] O. J. De Oliveira, C. R. Silva, J. J. Angelis, and M. A. P. Pimenta, "Quality management and digital transformation: The path to Industry 4.0," *The TQM Journal*, vol. 31, no. 4, pp. 491–509, 2019. https://doi.org/10.1108/TQM-12-2018-0201

[11] M. Asif, "Are QM models aligned with Industry 4.0? A perspective on current practices," *Journal of Cleaner Production*, vol. 258, p. 120820, 2020. https://doi.org/10.1016/j.jclepro.2020.120820

[12] S. J. Miranda, M. A. Zilber, and C. Faiad, "Impact of Industry 4.0 on organizational culture and quality," *International Journal of Quality & Reliability Management*, vol. 38, no. 2, pp. 458–476, 2021. https://doi.org/10.1108/IJQRM-03-2020-0091

[13] P. Sanghvi, J. Thakkar, and A. Nair, "Enabling quality 4.0 through digital transformation: A resource-based view," *Technological Forecasting and Social Change*, vol. 191, p. 122507, 2023. https://doi.org/10.1016/j.techfore.2023.122507

[14] M. Sony and S. Naik, "Critical factors for the successful implementation of Industry 4.0: A review and future research direction," *Production Planning & Control*, vol. 31, no. 10, pp. 799–815, 2020. https://doi.org/10.1080/09537287.2019.1631469

Author Profile

Dr. Jesús Gerardo Cruz Álvarez is a Full-Time Professor and Researcher at the School of Accounting and Business Administration at the Universidad Autónoma de Nuevo León (UANL), Mexico. He holds a Ph.D. in Management from UANL, and his research focuses on business models, productivity, competitiveness, business ethics, lean manufacturing, Industry 5.0, operations strategy, and sustainability. He has published in peer-reviewed national and international academic journals and actively participates in research networks focused on the financial performance of organizations from an operations management perspective. His work aims to strengthen the link between empirical evidence and strategic decision-making in Latin American business contexts. Dr. Cruz Álvarez serves as a thesis advisor at the undergraduate, master's, and doctoral levels and has been recognized as a distinguished professor by both UANL and SEP-PRODEP. In the corporate sector, he has held positions as operations director in plants and business units, with full profit and loss (P&L) responsibility acro ss various enterprises in the Americas.

Dr. Jesús Santoyo Ortega holds a Ph.D. in Philosophy with a specialization in Management from the Autonomous University of Nuevo León (UANL), Mexico, an MBA in Quality and Operations from Purdue University's Daniels School of Business, and a Master's in Quality Systems from the Autonomous University of Aguascalientes. He is currently Central Manufacturing Quality Manager at Cummins Inc., with over 15 years of experience in quality management, operational leadership, and continuous improvement. He holds international certifications as an IATF 16949 Supplier Auditor and ISO 9001 Lead Auditor (Plexus International). His interests focus on operational excellence, process innovation, and organizational leadership in manufacturing and automotive sectors.

Dr. Osiris Noel Pérez Moreno holds a Ph.D. in Business Management from the University of the Valley of Puebla (UVP), Mexico. He has over 20 years of professional experience as a leader, manager, and director in the ceramics industry, both in Mexico and abroad. His career bridges operational management and organizational strategy, focusing on process optimization, industrial competitiveness, and innovation in business models. His academic interests include applied business leadership, change management, and continuous improvement within the Latin American manufacturing context.