International Journal of Industrial Engineering and Operational Research (IJIEOR)

Contents lists available at IJIEOR
International Journal of Industrial Engineering and Operational Research
journal homepage: http://ijieor.ir
Volume 6, No. 1, 2024

Enhancing Operational Performance in Industry 4.0: The Mediating Role of Total Quality Management and Total Productive Maintenance at Zarharan Industrial Complex

Mehdi Khosroniya [a], Reza Hosnavi [a*], Mohammad Reza Zahedi [a]

[a] *Faculty of Management and Industrial Engineering, Malek Ashtar University of Technology, Tehran, Iran.*

ARTICLE INFO

Received: 2024/02/20

Revised: 2024/04/22

Accept: 2024/04/22

Keywords:

Total Quality Management, Total Productive Maintenance, Industry 4.0.

ABSTRACT

Industry 4.0 represents the integration of cyber-physical systems, enabling real-time data exchange and automation, enhancing efficiency and productivity while fostering innovation in manufacturing processes. Its significance lies in optimizing production, minimizing errors, and facilitating adaptive manufacturing, crucial for competitive edge and sustainable growth in modern industries. The objective of this research is to explore the effects of implementing Industry 4.0 on enhancing operational performance through the implementation of Total Quality Management (TQM) and Total Productive Maintenance and Repairs (TPM). The study focuses on Zarharan Industrial Parts Renovation-Optimization Complex employees, employing a simple random sampling method for data collection. The research employed field methods to gather information, utilizing a Likert scale questionnaire as the primary data collection tool. Content validity was used to establish questionnaire consistency, while Cronbach's alpha coefficient and composite reliability index were utilized for reliability assessment. Additionally, construct validity was verified. With regards to investigating the mediating role of comprehensive quality management and TPM and repairs between Industry 4.0 and operational performance, seven hypotheses were formulated.

1. Introduction

In the realm of modern manufacturing, the advent of Industry 4.0 has marked a transformative era characterized by the seamless integration of cyber-physical systems. This integration facilitates a symbiotic relationship between the digital and physical components of production, enabling real-time data exchange and automation. The core of Industry 4.0 lies in its ability to enhance efficiency and productivity, while simultaneously fostering innovation in manufacturing processes [1, 2].

* Corresponding author email address: r.hosnavi.mut@gmail.com (Reza Hosnavi).
Available online 04/23/2024
2676-3311/BGSA Ltd.

At the heart of this revolution are two pivotal methodologies: TQM and TPM. TQM is a comprehensive approach focused on long-term success through customer satisfaction, involving all members of an organization in improving processes, products, services, and the culture in which they work. TPM, on the other hand, is a system of maintaining and improving the integrity of production and quality systems through the machines, equipment, processes, and employees that add business value to an organization.

The convergence of TQM and TPM within the Industry 4.0 framework aims to optimize production, minimize errors, and enable adaptive manufacturing—key factors for gaining a competitive edge and ensuring sustainable growth in contemporary industries. This research delves into the effects of implementing Industry 4.0, particularly examining how TQM and TPM can mediate and enhance operational performance within the industrial setting of the Zarharan Industrial Parts Renovation-Optimization Complex [3].

To scrutinize the data and validate the hypotheses, we employed the structural equation modeling technique utilizing partial least squares (PLS) in conjunction with Smart-PLS software. The outcomes reveal that both TQM and TPM methodologies possess the potential to function as intermediaries for bridging the gap between Industry 4.0 implementation and enhanced operational performance. Moreover, a noteworthy positive linkage has been established between these entities [4, 5].

Furthermore, with the intricate intricacy of the worldwide business milieu steadily escalating and the advent of cutting-edge digital innovations, distinct imperative surfaces for novel systems centered on quality management and maintenance management. In this intense climate of fierce rivalry, enterprises must embody agility, adaptability, and an inherent capacity to continuously evolve [6, 7]. It is important to recognize that companies are able to foster innovation through the utilization of advanced digital technologies. By implementing cutting-edge technological tools like smart sensors, machine learning, big data analysis, and artificial intelligence within a dynamic ecosystem, businesses can effectively employ these advancements as integral components of their operational strategy for future-oriented smart factories concerning quality management and maintenance. The integration of intelligent machinery, sophisticated factory systems, and skilled operators allows for the identification and elimination of underlying issues causing production defects while enabling prompt actions aimed at preventing such defects and failures. These efforts culminate in an intelligent approach towards maintaining optimal quality standards through intelligent maintenance and repair processes [8].

The attainment of quality management's advantages remains elusive unless one ensures the unrelenting perseverance in upholding equipment maintenance and repairs. These twin methodologies are regarded as all-encompassing schemes for adeptly managing operations, stemming from shared bedrock of perpetual enhancement and active involvement at the organizational level.
The primary objective of this article is to address a void in existing research by delving into the consequences of implementing Industry 4.0 through the incorporation of TQM and TPM and Repairs (TPM). Additionally, it aims to establish the interconnections between these two components while showcasing their potential influence on business performance.

2. Theoretical Literature and Research Background

2.1. Industry 4.0

The concept of Industry 4.0 encompasses the recent advancements in technological innovations within industrial production systems. This transformative system has emerged from the seamless integration of various cutting-edge technologies such as the Internet of Things, cyber-physical systems, big data analytics, artificial intelligence, cloud computing, and others into industrial operations [9]. The emergence of this fourth-era industry signifies a profound understanding and utilization of interconnected machinery, intelligent products, and systems, along with their associated solutions [10]. This integration can support newly acquired abilities in attaining a heightened level of business superiority, efficacy, and proficiency [9]. The ultimate ambition of Industry 4.0 is to attain an automated and adaptable alignment of the value chain, coupled with the capability to personalize products and uphold mass production. Additionally, it aims to promote seamless communication among all constituents involved in production, including machines, individuals, resources, and the products themselves [11]. The advent of Industry 4.0 in our present time extends beyond its economic advantages, encompassing the response to novel technological advancements resultant from the swift proliferation of data quantities, cloud computing, and artificial intelligence systems, enhanced communication channels, and the capacity to process vast volumes of operational data at an advanced level instantaneously—something previously deemed unattainable. Industry 4.0 intensifies the imperative for highly sophisticated analysis on products, markets, and clientele. As analytical capabilities become more profound, product quality surges correspondingly. Examination of customer requirements coupled with delivering responsive input becomes crucial for upholding customer contentment. Consequently, robust, uninterrupted, and trustworthy analyses assume utmost importance in this context. The standards set forth in ISO 9000 regulations stipulate that the attainment of effective and efficient business processes arises from managing activities in a manner that is consistent and logical. The achievement of peak performance within the system can be attained by delineating the desired outcomes and determining the methods to achieve them. In line with this notion, Industry 4.0 will contribute to enhancing visibility in business and production processes, aiding their optimization, bolstering efficiency, as well as facilitating resource allocation [12].

2.2. TQM

TQM holds significant stature as a management approach that is widely acknowledged for its relentless commitment to enhancing the caliber of products, services, and processes. This resolute focus revolves around understanding and fulfilling the needs and expectations of customers, thereby augmenting their level of satisfaction while concurrently bolstering the performance of the enterprise [13, 14]. Quality management encapsulates the process of appraising and effectively controlling an organization's activities in order to achieve optimal quality objectives. In essence, it encompasses a range of endeavors targeting product creation, service administration, as well as procedural refinement through preventive measures and assessments [15]. The paramount aim underlying quality management lies in attaining heightened competitiveness by surpassing benchmarks with regards to quality accomplishments [16, 17 & 18]. Indeed, it is evident that quality management stands as an indispensable facet facilitating strategic advantage attainment within various competitive landscapes [4]. Comprehensive quality management encompasses various fundamental principles. One such principle is management, which comprises two interconnected aspects. Without effective management and leadership, attaining the desired level of quality is likely unattainable [19]. Similar to the overarching concept, TQM's understanding of management extends beyond traditional notions. In TQM, every individual assumes responsibility for their tasks; as such, everyone becomes a manager in their own right [20]. Contrary to mere supervision, TQM emphasizes the importance of leadership over focusing solely on outcomes (such as numerical targets or performance evaluations). Effective leadership plays a vital role in guiding and inspiring individuals towards achieving exceptional results [21]. Another critical aspect of comprehensive quality management lies within the notion of quality itself. Within this approach, quality can be defined as meeting customers' expectations and demands at an optimal economic level while maintaining suitability [22]. A dynamic state characterizes quality in TQM – a constant striving to meet or surpass customer needs and desires [23] while taking into account external factors that influence these requirements [24]. The improvement journey towards better quality begins with understanding and catering to customers' concerns – they are both the starting point and final destination for any progress made in this regard within TQM principles [25]. Comprehensive: This term pertains to the incorporation or involvement of every employee who partakes in manufacturing or service procedures [19]. In the realm of TQM, totality accentuates the action of perpetual advancement, encompassing all individuals and facets within an establishment [26, 20]. TQM is a multidimensional framework that is appraised as a strategic instrument surpassing mere restructuring of quality criteria, methods, and implements [14]. It may also be perceived as a systematic approach toward cultivating anticipated organizational conduct with an emphasis on people-oriented management. This approach fosters employee engagement and cultivates a collaborative ethos in order to continuously enhance performance and create additional value for customers [27]. TQM methodologies underscore perpetual improvement in all company operations with the objective of producing and delivering top-notch merchandise and services that consistently cater to evolving customer preferences [28].

2.3. TPM

TPM is a significant worldwide manufacturing initiative that emerged amidst the transformative tide of the quality revolution [29]. The purpose of TPM lies in its ability to enhance the efficiency of equipment. This is achieved through an extensive system of preventive maintenance and repairs, which span throughout the entire lifespan of the equipment across all departments and levels within an organization.

Not only does TPM extend to equipment, but it also extends to personnel, encompassing senior managers down to factory floor operators. One way in which TPM improves production processes and ensures high-quality standards is by encouraging small-scale and voluntary group activities. These activities aim to motivate employees and boost their morale and job satisfaction. By doing so, TPM becomes a valuable tool in bolstering both physical assets as well as human resources [30]. By combining continuous improvement with maintenance and repair strategies, productive comprehensive maintenance aims at improving the overall efficiency of equipment. The ultimate goal here is to facilitate a process that enables the most effective and efficient utilization of existing production structures. In this way, TPM contributes towards maximizing productivity while minimizing resource waste [31]. The implementation of TPM yields numerous advantages. These benefits encompass enhancements in productivity, timely delivery, workplace safety, employee morale, diminished maintenance and repair expenses for equipment and processes, decreased idle time and interruptions, fewer defects, decreased disorderly circumstances, improved financial performance and profitability as well as heightened sales and market share [31, 32]. One cannot disregard the definite advantage that TPM brings forth – an augmentation in the efficiency and profitability of companies [33]. The introduction of TPM not only diminishes equipment failures but also amplifies machine dependability, process quality, and product output [34]. Through the implementation of TPM, there arises an opportunity for enhanced performance in maintenance and repairs, an essential facet within the realm of business operations. The comprehensive approach maintained by TPM cultivates a harmonious relationship between the production and maintenance departments, effectively negating any potential conflicts of interest. Central to this philosophy is an unwavering commitment towards bolstering equipment efficiency, optimizing productivity levels, ensuring workplace safety, addressing environmental concerns, and ultimately eradicating instances of production losses. It therefore becomes imperative that all members of the organization - from top-tier management to operators on the ground - actively engage with TPM in order to achieve sustainable success [35].

2.4. Relationship between TQM and TPM

In order to maintain their competitive edge, factories must uphold robust practices of TPM and TQM. These two approaches are closely intertwined, as effective maintenance and quality control greatly influence one another. TPM places emphasis on operator involvement, aiming to enhance their skills, knowledge, and technical training in order for companies to gain a competitive advantage [36]. Similarly, TQM also plays a crucial role in achieving both competitive advantage and operational excellence. Both TPM and TQM share common objectives such as continuous improvement, focusing on processes, and securing commitment from senior management, empowering employees, as well as collecting and analyzing information [37]. Both are characterized by extensive involvement and dedication from all members of the organization, emphasizing the importance of teams that can handle multiple tasks simultaneously. They both adhere to a philosophy of continuous improvement [38]. Furthermore, other scholars have recognized numerous shared aspects between TPM and TQM, such as human resource practices focused on employee development and committed leadership. They emphasize the need for responsible employees who actively participate in multiple task development and skill enhancement while striving for continuous improvement [38, 39 & 40]. Additionally, explained that TPM shares similarities with TQM in its maintenance philosophy. Both require top management's overall commitment to their respective programs and empower employees to take corrective actions or bring innovative ideas forward. Finally, they both maintain that a long-term strategy is essential for sustained success [41]. TPM serves as one of the methodologies that elevate and enhance quality, while also functioning as a supplementary approach to augment other techniques aimed at ensuring high levels of quality [42]. The realm of TPM primarily concerns itself with the maintenance and efficiency of equipment management, an essential factor determining the overall performance in modern manufacturing enterprises [43]. Additionally, it is contended that TQM alone has only a limited impact on machine performance. However, through the support and emphasis of TPM, this discrepancy is resolved by placing greater focus on optimizing equipment conditions [44]. In a study conducted, it was revealed that four intangible methods encompassed within TQM—namely senior management leadership, training programs, effective workforce management practices, and customer-centric approaches—effectively contribute to enhancing the implementation level of TPM. Furthermore, three tangible elements associated with TQM—continuous improvement initiatives, valuable information feedback mechanisms, and efficient process management strategies—significantly influence and facilitate successful adoption of TPM practices [45]. Similarly, corroborate these findings by acknowledging and confirming that having an orientation towards quality management plays a positive role in streamlining maintenance procedures as well as repair processes [46]. In practice, the implementation of TPM holds a significant role in attaining excellence within processes, consequently influencing product quality and the ability to meet customer demands. The continual monitoring of TPM operations allows organizations to effectively carry out daily functions while also addressing maintenance requirements and necessary repairs for each device within specified intervals. Beyond human resources, the condition of machinery and equipment serves as an indicator of an organization's strength. These devices necessitate regular maintenance and repair in order to produce products that adhere to desired specifications and maintain high quality. Through TPM operations, factories can enhance their operational performance by prioritizing process quality.

By properly maintaining equipment, companies are capable of delivering superior products that meet societal expectations. In this regard, TPM methods play a critical role in sustaining and enhancing overall product quality through waste reduction initiatives and minimizing defective items produced. Effective integration of maintenance and quality operations helps companies to save time, money, and other resources [5]. TPM has a complementary relationship with TQM, as the zero-defect concept of TQM is utilized in TPM to maintain control over equipment. It is imperative that the equipment does not produce any defective products. While TQM concentrates on strategic aspects, TPM focuses primarily on operational matters. The main objective of TQM is to minimize deviations in processes and consequently decrease errors. On the other hand, TPM centers on equipment maintenance, enhancing reliability, and reducing changes within equipment processes. In order to achieve optimal operational performance, it is necessary for TPM to influence TQM activities. More precisely, this means that TPM indirectly enhances an organization's production performance by supporting TQM initiatives. Essentially, TPM combines maintenance engineering principles with those of TQM [48]. Despite the fact that the two concepts (TQM and TPM) have common features, the mutual effect of these two concepts has been largely ignored by many manufacturing companies. Such a situation adversely affects the dimensions of competitive performance in manufacturing companies such as inventory level, product quality, and delivery performance, in addition to lowering the reliability of factories and reducing the availability of machinery due to equipment failure [49].

2.5. Organizational Culture and the Role of TPM and TQM

Any scholarly investigation concerning organizational culture must take into account the numerous dimensions inherent to such a complex concept (50). While productivity is deemed important, it should not overshadow the equally crucial aspect of maintaining high standards. Achieving both production and quality can only be accomplished through the seamless operation of machinery, equipment, and skilled personnel [5]. This intricate matter, however, can be remedied by fostering a comprehensive organizational culture within the factory. A plausible rationale argues that organizations must cultivate a supportive culture centered on excellence to effectively execute maintenance endeavors [51]. This involves instilling a collective commitment among management and employees towards implementing robust maintenance and repair programs. The indispensable role of cultural support becomes evident as it consistently emerges as an integral component for attaining success in quality management and maintenance initiatives [52, 53]. The development of a robust quality management and real-time maintenance system should arise from an organizational culture that fosters collaboration among all stakeholders, promotes shared information, and establishes common goals [10]. The manufacturing industry has come to realize that the successful execution of TQM and TPM hinges upon the organization's cultural fabric [35]. Numerous studies have surmised that if the predominant organizational culture aligns with the core values and assumptions put forth by TQM principles, there is a higher probability of achieving success in implementing TQM programs [54]. Crucially, attaining triumph with TQM necessitates a substantial metamorphosis in an organization's values, attitudes, and overall culture. The success or failure of TQM as an agent for organizational change rests heavily on this cultural transformation. In fact, posits that fostering a collaborative team-oriented ethos within the organization is pivotal to maximizing outcomes derived from TPM implementation [53].

2.6. The Relationship between Business Performance and TPM and TQM

During this era of rapid industrial expansion mentioned earlier, it becomes imperative for the organization to generate a product of unparalleled excellence at competitive prices through the reduction of production costs. This objective can be attained by enhancing business performance. Various scholars have delved into the ramifications brought forth by the correlation between TQM and TPM on business performance. In general, most studies indicate a synergistic relationship between these two approaches that positively influence operational performance, especially when implemented concurrently. The outcomes derived from Singh and Ahuja's investigations in 2012 revealed that amalgamating TQM and TPM results in heightened quality standards and better maintenance practices within manufacturing facilities, thereby facilitating an improvement in overall business performance [29]. Furthermore, conducted an analysis on the consequences of implementing TQM and TPM in 410 pharmaceutical factories in India. Through their study, they demonstrated that when TQM and TPM are simultaneously implemented, TQM significantly supports TPM, thus exerting a substantial influence on operational performance [5]. Moreover, after examining a sample of 1500 companies in Malaysia concluded that TPM can act as a mediator between TQM and business performance [55]. In particular, TQM plays an instrumental role in supporting TPM to enhance business performance [56]. This alignment of TQM supported by TPM is often referred to as a hybrid strategy—a combination where both methodologies complement each other—and it is widely adopted by various businesses for achieving synergy [35]. Maintenance operations play a crucial role in influencing the efficiency, effectiveness, overall quality of operations, and product quality.

Consequently, this leads to increased productivity and ultimately contributes to exceptional business outcomes [57]. In addition, TQM offers valuable assistance to corporations in the reduction of subpar quality, warranty issues, and the need for multiple deliveries [58]. Consequently, quality management practices have been recognized as a viable means to not only augment market share and productivity but also enhance overall organizational performance. Scholars such as contend that TQM serves as a managerial philosophy aimed at refining processes, products, and ultimately the health of businesses [59]. Further support can be found, which emphasizes the requirement for commitment, resources, training opportunities, and inter-organizational integration among employees when implementing methodologies like TQM. This collective effort tangibly aids organizations in achieving enhanced performance levels [60]. Contrarily, TPM pursues limited incidence rates of failures or downtime by incentivizing effective maintenance activities and equipment repairs capable of yielding higher performance outcomes.

As a result of this approach that prioritizes comprehensive integrity checks on machinery alongside timely interventions, if necessary, proves successful in advancing overall efficiency levels within an organization. Therefore, through combining both TQM and TPM within their operations, enterprises can ultimately elevate equipment quality standards along with product reliability while simultaneously boosting productivity measures [61]. The implementation of TQM and TPM can significantly impact the operational performance of a factory. These two methodologies, when applied to factory-level operations and activities, serve as an accurate representation of an organization's overall efficiency [5]. Moreover, TQM and TPM bring about positive outcomes in terms of enhancing an organization's competitive advantage. By adopting these practices, organizations are able to elevate themselves to a world-class level [62].

2.7. The Relationship of Industry 4.0 with TQM and TPM

An alive ecosystem, enriched with cutting-edge digital advancements like smart sensors, machine learning capabilities, big data analysis, and artificial intelligence, holds immense potential to serve as an indispensable strategic approach for future smart factory enterprises seeking quality management and maintenance. This convergence of intelligent machines, advanced factories, and skilled operators will realize the ability to identify and eradicate the underlying sources of production flaws swiftly while proactively averting defects and failures. Consequently, this seamless amalgamation shall culminate in an astute assurance of quality driven by intelligent maintenance and repair processes.

2.7.1. Process Management and Continuous Improvement

Continuous improvement is of utmost importance for the growth and advancement of an organization. It enables the organization to maintain its edge in terms of innovation amidst competition, continually enhance the performance of its processes, reinforce its organizational capacity, and ensure customer satisfaction. With the advent of Industry 4.0, organizations will have a solid foundation upon which they can achieve ongoing improvements at various levels such as product development, process optimization, and overall business operations. One crucial objective pursued by quality management and maintenance teams is to establish a strong commitment within the organization towards the continuous enhancement of processes as well as production cycles for products and services. This commitment serves two vital purposes: firstly, it boosts customer satisfaction by minimizing defective products during delivery or repair; secondly, it fosters a culture that constantly seeks ways to better serve customers. Moreover, it is imperative that all activities and processes within an organization are fully understood and aligned with one another in coherence with the entire system. By ensuring this compatibility across different aspects of operations—from individual tasks to overarching strategies—organizations can maximize their effectiveness in achieving their goals. Therefore, identifying these goals becomes fundamental in comprehending what procedures are necessary to attain them efficiently and effectively. The effective management of processes necessitates the establishment of authorities, the delineation of responsibilities, and the implementation of accountability policies in order to discern these objectives and strategies. Furthermore, it is imperative that due attention be given to the interdependencies among processes and their mutual relationships as a means to realize the organizational goals. In contemporary times, intelligent quality control systems have gained widespread usage and have supplanted conventional methods such as statistical quality control and statistical sampling. Leveraging sensors and inspection technologies, these advanced systems are capable of addressing not only a mere sample size but all productions by removing defective products from the equation. Additionally, they operate at every stage throughout production, resulting in minimized costs associated with maintaining high product quality since early defects can be detected promptly while thorough analysis allows for the timely resolution of underlying causes. By integrating production into a unified system, overall performance within the value chain is enhanced while ensuring heightened sensitivity across the entirety of said system. Furthermore, numerous industries have embraced the integration of intelligent devices capable of transmitting unprocessed data from vehicles to performance data centers. This allows for the prompt reporting of any issues that arise during operational and production processes [63]. Moreover, Industry 4.0 incorporates cutting-edge technologies such as artificial intelligence and machine learning, empowering industrial systems to identify or even anticipate machine breakdowns or faulty products at an early stage. Consequently, immediate root cause analysis can be conducted along with recommendations for necessary corrective measures. These programs play a pivotal role in facilitating continuous improvement and effective process management while also paving the way for further innovation. Within Industry 4.0, internal communication assumes a crucial role by fostering connectivity among various devices throughout an interconnected network known as the smart digital value chain. Herein lies the ability to hold information in a machine-readable format using RFID technology, enabling machines to autonomously regulate and repair themselves whenever necessary towards achieving desired outcomes in the production process [9].

Through empirical investigations, it has been demonstrated that the implementation of fourth-age industrial strategies enables more expeditious prognostications regarding the well-being and efficiency of machinery, subsequently minimizing instances of interruption and facilitating timely maintenance and repairs [64]. The supervision and acquisition of contemporary technological advancements are integral components of TQM procedures. An influential factor in this regard is the Trusted Platform Module (TPM), which fosters effective technology management by ensuring the comprehensive safeguarding of equipment and machinery [46]. Within the realm of fourth-age industries lies a fundamental necessity for quality digitalization, encompassing cutting-edge technologies as well as proficient personnel who possess considerable influence over this digital transformation [6, 65 & 66]. Such a revolutionary industry of the fourth era, harnessing its advanced technologies, tools, and capabilities, possesses the potential to serve as a foundation for executing maintenance and repair strategies whilst optimizing current methodologies. The fusion of this fourth-age industry with management practices pertaining to maintenance and repair brings about a transformative shift from periodic approaches towards predictive policies in the realm of maintenance and repairs, thereby unveiling both economic prosperity and technical advantages [67]. In an exploration conducted, proposed a conceptual framework aimed at devising predictive methods for maintenance and repair by employing big data mining techniques and intelligent algorithms within the realm of Industry 4.0 [63]. Within their investigation, expounded upon several pragmatic concepts encompassing the design and practical implementation of predictive quality management systems through Industry 4.0. Additionally, they elucidated that future quality management endeavors would be anchored upon features centered on predictive maintenance and repair derived from digital technologies [1]. The enhancement of environmental, health, and safety aspects in relation to TQM and TPM practices can effectively be achieved through a concentrated emphasis on the Generation 4.0 industry. These advanced technologies are designed to comprehend and disseminate data throughout an entire organization. For instance, Industry 4.0 has the capability to monitor carbon and greenhouse gas emissions by means of data classification and analysis, thereby enabling effective control over environmental pollution as well as energy and resource consumption. Moreover, it leverages its distinct attributes to optimize the recycling process for waste products and refuse [68].

2.7.2. Focus on the Customer

The advent of Industry 4.0 holds the promise of enhancing customer satisfaction for businesses, as it allows them to improve the quality of their products and services through rigorous quality control and assurance processes. It is widely acknowledged that the successful execution of these processes is contingent upon utilizing proper equipment, which can only be achieved by ensuring regular maintenance and repairs are conducted in accordance with established protocols. Scholars have identified a profound correlation between prioritizing customer-centric approaches to quality management and optimizing maintenance and repair performance [9]. Stressed the significance of integrating a customer focus within the TPM paradigm, as this leads to improved productivity levels, waste reduction, meticulous data collection and analysis practices, timely delivery schedules, and effective activity planning [69]. Moreover, principles delineated within ISO 9000 Principles and Vocabulary further support this argument [70]. To illustrate, the advent of the fourth-era industry has granted companies the ability to tailor their offerings to customers in a bespoke and personalized manner. This means that products and services can be provided in a timely manner, free from the complexities associated with mass production. Consequently, individualized services are made available to customers, resulting in heightened satisfaction levels as their quality expectations are met. Simultaneously, this approach entails actively involving customers throughout the entire production process by equipping them with communication tools prior to, during, and after production. By doing so, they become an integral part of the manufacturing journey rather than mere recipients of end products [9]. Thus, successfully attaining organizational goals such as profitability and productivity is achievable through ensuring customer satisfaction—a vital aspect shared between both TQM and TPM.

2.7.3. Leadership and Relationship Management

The presence of effective leadership plays a crucial role in establishing and maintaining a shared sense of purpose across all levels of command with regard to the organization's objectives. This implies that those in positions of leadership bear the responsibility of effectively conveying the overarching vision, mission, strategies, and policies of the organization throughout every level of management. Additionally, fostering a collective commitment to fundamental principles within the entire organizational framework is essential; this necessitates ensuring uniform beliefs and practices among both leaders and individuals at all echelons [64]. At its core, leadership serves as an instrument for forging solidarity among participants within an establishment, thereby bolstering their joint efforts towards accomplishing the qualitative aspirations set by the organization. Moreover, senior management involvement is paramount when it comes to executing successful maintenance and repair initiatives [9]. Through the active involvement of upper-level executives in the execution of efficient maintenance and reliability management, the organizational culture as a whole places special emphasis on recognizing the necessity and significance of supporting an effective maintenance and reliability management program [71]. Conversely, it is imperative for senior management to assume a crucial role in introducing and facilitating the implementation of TQM strategies by establishing an environment that encourages learning and collaboration, ultimately resulting in customer satisfaction, continuous improvement, and employee engagement [72]. To effectively achieve this objective, senior management must delegate maintenance and repair responsibilities to their fullest extent. This specifically entails expanding decision-making authority to include machine operators as well as workers within the maintenance and repair unit. It is only through such measures that an intelligent quality management system can be attained—one which continuously improves itself via independent decisions made at all levels [73]. By aligning strategies, policies, processes, and resources towards the attainment of specific objectives, businesses can effectively fortify their operations. Furthermore, leaders and managers can enhance operational efficiency by identifying harmonious relationships and intervening in potential issues to deter imprudent decision-making and wasteful investments. Crucial to achieving and sustaining success in any organization are its stakeholders. These stakeholders encompass a range of interests that include both opportunities and constraints. The management of partnerships serves as an instrumental approach in realizing TQM and TPM, aiming to optimize the production supply chain while ensuring seamless delivery of goods and services to customers. Recognizing these stakeholders within the organization along with their respective connections fosters an expanded network for production. A collaborative effort is necessary when managing suppliers, partners, customers, investors, and employees—all must work collectively to align with the goals set forth by the organization. Complete integration and effective communication between all stakeholders of an organization in its supply chain, from suppliers to customers, has become one of the main advantages of the 4.0 generation industry using the tools and features of this industry [9].

2.7.4. Participation and Increasing the Ability of People

The involvement of individuals within an organization is crucial in attaining collective goals. Empowering, acknowledging, enhancing skills, supporting personal growth, and encouraging initiatives are all factors that contribute to organizational excellence. They not only enhance business activities but also foster a creative environment while increasing motivation and trust among members. Consequently, this results in elevated employee satisfaction and bolstered support for and adherence to organizational values across the board. Furthermore, ensuring that individuals receive proper training and facilitating their acquisition of authority and responsibilities necessitate an appropriate training program coupled with a clear accountability policy. One of the primary tenets of TPM involves imparting necessary skills to personnel while involving them in the decision-making process [60]. To establish a successful quality management system, it is imperative that individuals at all levels within the organization actively engage themselves in augmenting its capabilities to generate value for customers [70]. In this research, it has been consistently asserted that both TQM and TPM strive to establish an organizational culture that fosters the empowerment and active involvement of individuals across all levels, from laborers to senior executives. Employing cutting-edge industrial tools characteristic of the fourth industrial revolution, such as comprehensive data analysis, Enterprise Resource Planning (ERP) systems, artificial intelligence, and real-time data interpretation capabilities, is crucial for equipping individuals in their respective roles. This empowers them to identify potential risks and propose fully-developed and tested solutions. As a result, these advancements contribute significantly to effective quality management as well as efficient maintenance and repairs. Undoubtedly, Industry 4.0 heralds a transformation in the role played by workers within industrial settings; they are no longer mere machine operators but instead assume higher positions involving work supervision. In this context, workers must possess enhanced decision-making abilities coupled with adept problem-solving skills—particularly when confronted with unforeseen challenges [9]. In this given context, the concept of Industry 4.0 encompasses a support system that facilitates effective communication and collaboration among all individuals within the organization. This implies the provision of various tools aimed at facilitating interaction and efficient human resource management through the utilization of communication features as well as social networks. Furthermore, Industry 4.0, in its essence, promotes innovation by encouraging individual participation in organizational development. Gaining a profound understanding of how Industry

4.0, TQM, and TPM collectively contribute expectations throughout their operational processes. The distinguishing characteristics observed within the fourth-age industry include vertical, horizontal, and end-to-end integration alongside enterprise resource planning systems (ERP), big data analysis capabilities, as well as advanced communication technologies; these new dimensions have significantly augmented leadership responsibilities, fostering increased levels of collaboration across varying hierarchical levels within organizations. They facilitate leadership that collectively improves the company's ability to deliver results. In Table 1, the measures of the four indicators of TQM and TPM that were explained and introduced in the previous section can be seen, as well as the positive results that can be expected through the features of Industry 4.0 according to them.

Table 1. Industry 4.0 support for TQM and TPM characteristics

Industry4.0 partnerships	**Actions**
• Improved responsiveness , awareness and customer engagement from production to consumption • Customer/product customization • Smart market demand forecast Smart planning of activities to increase customer service and satisfaction	• Improv stomer ction ithful • growth in their customer base • Improve the reputation of the organization Timely delivery and customer support through product service and warranty
• Intelligent allocation of resources • coordination een all levels Organization • Evaluation of effective water for the results of c • Expanding the range of decision-making through clear access and data analysis • Using the right tools and methods • Identification tools and easy communication • The ability to divide shareholders based on priorities Stronger collaboration with suppliers and partners to encourage continuous improvements	• Strategies , systems , processes and resources should be aligned • Effective communication between all executive levels and creating a collaborative environment • Implementation and management of strategies • Identifying stakeholders and appropriate communication tools for top management • Stakeholder satisfaction considering their feedback • Management of suppliers and distributors The complete chain is sustainable and does not fail due to lack of resources
• Improve communication and colleague • Facilitate the innovation and sharing of dozens • Proposing developed solutions • Raising the authority and status of employees Increasing information, learning technology and knowledge management	• Increasing stigma , trust _ and strengthening abilities • Personal development and encouragement of initiatives • Creating an organizational culture and aligning employees with the organization's goals • Staff training Self-evaluation of water and self construction of culture
• Transparent processes and integrity distribution system • , Self - learning of equipment and machines independent maintenance and repairs, first preview Errors • less damage , repair forecast and first reactions • Active dynamic interaction with market needs • Immediate follow - up of proTo respond to requests Maintenance • Analysis and quality assurance • Use of intelligent systems • Reducing pollution and recycling waste • A signal for environmental change	• Identification of processes and key points of improvements • Continuous performance and management Effective processes • Management of processes and interrelationships as well as dependenciesSystems responsive to customer needs • Increasing the ability to respond to the development of processes , products and market needs • Support for innovative stimuli Increasing safety and attention to the environment

Industry4.0 partnerships	Actions
Removal of defective products and failure to deliver and repair again	

2.7.5. Hypotheses

Upon careful examination of the presented arguments and supporting documents, coupled with the absence of empirical substantiation, it is evident that two pivotal research inquiries emerge from this discourse. Firstly, one must inquire about the repercussions imposed by Industry 4.0 on the execution of both TQM and TPM. Furthermore, an equally pressing question arises: how can these disparate methodologies harmoniously coexist within an ever-evolving domain to enhance operational efficiency?

With a fervent desire to address these dexterous inquiries, this comprehensive investigation strives to shed light upon the influence exerted by Industry 4.0 when employed in conjunction with renowned management approaches such as TQM and TPM; its prime objective being to bolster operational performance. For this purpose, 7 hypotheses were considered, which can be seen in Table 2.

Table 2. Research hypotheses

Row	Description of hypotheses
1	Generation industry 4.0 sitive effect on comprehensive quality management
2	Generation industry 4.0 Effective comprehensive maintenance and repairs have a positive effect
3	Generation industry 4.0 has a positive impact on operational performance
4	Total quality management has a positive effect on operational performance
5	Effective comprehensive maintenance and repairs have a positive effect on operational performance
6	The implementation of total quality management can play a positive mediating role between the adoption of Industry4.0 operational performance
7	Implementation of effective comprehensive maintenance and repairs can play a positive mediating role between the adoption of Industry4.0and the improvement of operational performance .

Also, for a better understanding of the research topic, Figure 1 shows the conceptual model of the research:

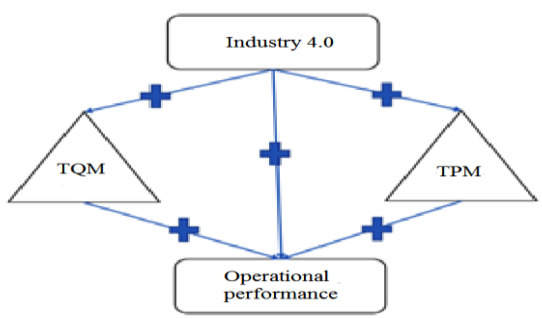

Figure 1. Research conceptual model

3. Research methodology

In terms of the classification of research according to the method of data collection, or in other words, the research design, the present research is considered descriptive research that describes the characteristics of the sample and then generalizes these characteristics to the statistical community. Self-descriptive researches are of several categories, and in this research, the correlation type is used, in which the relationship between variables is analyzed based on the purpose of the research, and it is specifically based on structural equations that this research is based on partial least squares (PLS). Also, from the point of view of the goal, it is considered applied research. Field method was used to collect data. The data collection tool is also a questionnaire. The main part of the questionnaire used in this research includes specialized questions. In this questionnaire, with the design of 24 questions, an attempt has been made to collect and analyze the views of the members of the statistical community on the variables of the problem. To measure the variables of comprehensive quality management and comprehensive maintenance and repairs, the indicators (leadership and relationship management, process management and progress continuous, focus on the customer, participation and increasing the ability of people) in which these two approaches are aligned according to the literature review. According to these indicators, 5 items from the questionnaire were prepared for comprehensive quality management approach and 4 items were prepared for efficient comprehensive maintenance and repairs. Also, to measure the 4.0 generation industry, considering that in this research, the intention was to examine the acceptance of this industry on TQM and TPM, the axes (big data, integration and internal connections, machine learning, Internet of Things, sensors and remote control and monitoring) were considered and 10 questions were presented according to them, in the last part of the questionnaire, 5 questions were also asked according to 5 indicators (general effectiveness of equipment, production service level, quality (waste and rework), productivity and cost, safety) Injuries and work accidents)) were included.

The spectrum used in this research is a five-choice Likert scale. 24 items of the Likert scale questionnaire were used in the form of 5 options from 1 (worsened) to 5 (significant improvement). The method of distribution of the questionnaire and access to the sample members was done through e-mail, virtual spaces and face-to-face.

The sampling process in this research is a simple random sampling method. The statistical population of this research is related to the renovation-optimization and manufacturing of Zerharn industrial parts. The statistical population was 230 personnel of the complex, including senior and middle managers, engineers and analysts, employees of administrative departments. In determining the statistical sample, an attempt was made to select a sample that was in line with the objectives of the research and was the study population. The sample size was determined using Cochran's formula and 144 people were selected.

In this article, library methods for theoretical foundations and field methods, i.e., a questionnaire for information on hypotheses and objectives, were used to collect information, and information was used through the combination of four questionnaires presented in the table, as well as through sources such as books, publications, internet and magazines. Are collected Questionnaire questions are categorized in Table 3.

Table 3. Questions related to research variables

Row	Variables	Number of questions	Number of questions
1	TQM	1--5	5
2	TPM	6--9	4
3	Generation 4.0 industry	10--19	10
4	operational performance	20--24	5

To show the normality or non-normality of the research variables, given that the questionnaire is in the form of a Likert scale, the skewness-kurtosis test was used, the results of this test can be seen in Table 4. The results indicate that the ratio of skewness and kurtosis of all research variables is in the range of (-2, 2), which indicates the normality of the problem variables.

Table 4. Skewness - kurtosis test

Variables	Elongation		crookedness	
	error	statistics	error	statistics
TQM	0.468	0.752	0.236	0.311
TPM	0.468	0.802	0.236	0.328
Generation industry4.0	0.468	0.545	0.236	0.107
operational performance	0.468	0.321	0.236	0.179

3.1. Validity and reliability of the questionnaire

In this research, in order to determine that the questions of the questionnaire collect the data needed to test the research hypotheses, the opinions of professors, management experts and research methods were used. After attracting opinions and making corrections, the final questionnaire has been distributed in the statistical community. To ensure the reliability of the questionnaires distributed among the employees, Cronbach's alpha coefficient and composite reliability index have been calculated for each of the questionnaires separately. For this purpose, before the final distribution of the questionnaire, a preliminary study was conducted by distributing the questionnaire among 10 managers of the collection, and then the Cronbach's alpha coefficient and composite reliability index were calculated. They showed a high value of 0.8 for both criteria, which indicates the good adequacy of the measurement model. Also, factor loading coefficients were obtained, Table 6 shows that no factor loading is smaller than 0.5, which means that all the observed variables are can be considered in the analysis. The validity of the structure was also confirmed based on the AVE coefficients of the structures, the AVE value for all variables is greater than 0.5, and therefore suitable convergence validity has been achieved for all variables. Table 5 shows the results of the measurement model fit tests.

Table 5. Measurement model fit

Row	Variables	Composite reliability	Cronbach's alpha	AVE
1	TQM	0.879	0.832	0.596
2	TPM	0.837	0.81	0.565

Row	Variables	Composite reliability	Cronbach's alpha	AVE
3	Generation4.0 industry	0.906	0.855	0.503
4	operational performance	0.848	0.823	0.529

Table 6. Coefficients of factor loadings

Objects	TQM	Objects	TPM	Objects	Generation 4.0 industry	Objects	O perational performance
1	0.769	6	0.777	10	0.833	20	0.819
2	0.635	7	0.736	11	0.65	21	0.751
3	0.841	8	0.826	12	0.597	22	0.73
4	0.742	9	0.658	13	0.684	23	0.683
5	0.854			14	0.727	24	0.644
				15	0.744		
				16	0.616		
				17	0.582		
				18	0.799		
				19	0.756		

3.2. Descriptive statistics of research demographic variables

To select the respondents, two criteria were used: the respondents must be aware of Industry 4.0 technology; the units selected in the collection must have experience in implementing TPM and TQM in their industrial sectors. Also, based on the collected information, it showed that most of the respondents, 47.2% were engineers or analysts working at the factory level, 25.7% were personnel of the administrative departments related to the net and quality assurance and control unit, 18% were assistants and middle managers, and finally 9% were senior managers in the organization. The frequency distribution of the education level also indicated that among the 144 respondents, only 13 people had a doctorate degree, 35 people had a master's degree, and the rest of the personnel had a bachelor's degree. The frequency distribution of the respondents according to work experience is as follows. 17% have 1-5 years of work experience, 28% have 10-6 years of experience, 42% have 15-11 years of experience, and 13% have more than 16 years of experience in this field. It should also be noted that in the Zerharan industrial complex, all personnel are male.

3.3. Divergent validity

In the present investigation, the method employed by Fornell and Larcker was utilized to gauge divergent validity. The criterion established by Fornell and Larcker pertains to the observation that the square root of explained variance (AVE) for each construct ought to surpass its correlation values with other constructs. A valid discrepancy is deemed acceptable if the numeric values incorporated within a principal diameter exceed their respective underlying values. Indeed, we examined whether or not the square root of AVE for each construct surpassed its correlations with any additional construct. Table 7 visually illustrates that all AVE square roots exceeded estimated correlations between latent variables.

Table 7. Divergent validity results by Fornell and Larcker method

Description	O perational performance	Generation industry4.0	TPM	TQM
TQM				0.772
TPM			0.751	0.682
Generation industry4.0		0.709	0.627	0.635
operational performance	0.727	0.616	0.641	0.743

3.4. Evaluating structural model

Within the scope of ongoing research, appropriateness indicators were employed to assess the research model. The findings from this evaluation are duly provided in Table 8. By utilizing partial least squares, we determined how well the formulated theoretical model adhered to the experimental model implemented by our diligent researcher. Model fit indices serve the purpose of measuring concordance between experimental and theoretical curves. In relation to structural equation modeling, these indices help evaluate the structural elements, specifically focusing on discerning connections among latent variables that constitute significant dimensions within this issue.

Table 8. Structural model fitting results

R^2	Q2 –	Subscription amount	Variable
0.33	0.49	0.60	TQM
0.40	0.34	0.54	TPM
0.42	0.31	0.53	operational performance

In Table 8, we can observe the examination of two specific criteria. The coefficient of determination (R2) serves as a significant gauge in connecting the measurement aspect and structural aspect within structural equation modeling. It indicates the degree to which an exogenous variable influences an endogenous variable. This coefficient ranges from zero to one, with higher values being more preferable. Weak, medium, and strong R2 values are designated by 0.19, 0.33, and 0.67, respectively [74].

Furthermore, the Q2 criterion plays a pivotal role in evaluating the predictive capabilities of a model. Models that exhibit satisfactory structural alignment must possess the ability to accurately predict endogenous variables within said model. In other words, if these variables are appropriately defined and possess substantial influence over one another—thus confirming any underlying hypotheses—an effective fit will be established. The positivity of the Q2 index signifies both favorable model fitment and impressive predictive power for future outcomes ahead [75].

Also, in order to check the overall fit of the model, the criterion (GOF) is used, where three values of 0.01, 0.25 and 0.36 are introduced as weak, medium and strong values [76].

$$\text{GOF} = \sqrt{AVE\ (Communality) * AVE\ (Rsquare)} \quad (1)$$

The share value is determined from the average share values of the hidden variables of the research. According to (1), the GOF was calculated to be 0.461 and it shows a good fit for the model.

3.5. Testing the research hypotheses

In this section, we shall delve into an examination of the research hypotheses through the utilization of PLS software. The magnitude of the correlation between the factor (a concealed variable) and the observable variable is unveiled by means of factor loading. This term refers to a numerical value ranging from zero to one. Figure 2 demonstrates that all variables possess factor loading coefficients surpassing 0.3, thereby indicating a favorable relationship between them. Furthermore, in order to assess whether these relationships hold significance, we employ a statistical measure known as the test statistic (t-value). By evaluating this value against a predetermined significance level error margin of 0.05, we can determine if there exists statistical significance. If these coefficients fall within the range (-1.96, +1.96), then it signifies an absence of significant relationship; however, if they extend beyond those limits, then it suggests a noteworthy association. Conversely put, should t exceed +1.96, it portrays a positive effect; whereas falling beneath -1.96 indicates an adverse effect instead. The findings obtained are elucidated in Figure 3 for observation and further analysis.

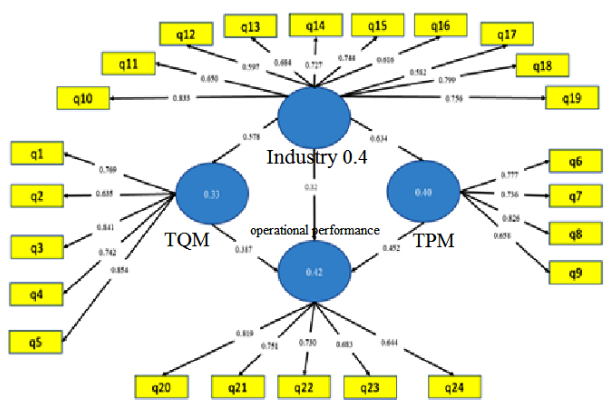

Figure 2. Research model with factor loadings

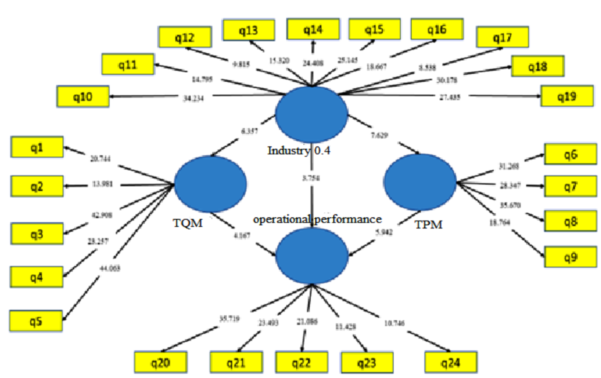

Figure 3. Research model with significant coefficients

In the subsequent passage, we shall expound upon the findings acquired from our structural equation model, predicated on our research hypotheses. Table 9 elucidates that the embracement of Industry 4.0 technology bestows a favorable and noteworthy correlation with both TQM and TPM implementation levels. Moreover, the results demonstrate that the integration of TQM and TPM approaches conveys beneficial and substantial associations in regard to augmenting operational performance. These revelations evince that incorporating both methodologies play an instrumental role in ameliorating the overall operating proficiency within Zerharan Industrial Complex.

Table 9. Results of research hypotheses (direct relationships)

The result of the hypothesis	The significance level	Standard error	statistics t	Path coefficient	Direction
proving a theory	p <0.01	0.207	6.357	0.578	4.0 Industry← TQM
proving a theory	p <0.01	0.212	7.629	0.634	4.0 Industry← TPM
proving a theory	p <0.01	0.119	3.754	0.320	4.0Industry ← operational performance
proving a theory	p <0.01	0.101	4.167	0.387	TQM ← operational performance
proving a theory	p <0.01	0.108	5.942	0.452	TPM ← operational performance

Table 10 displays the indirect ramifications of embracing Industry 4.0 on amplifying operational performance. The findings disclose that the implementation of TQM and TPM practices effectively moderate the correlation between Industry 4.0 and elevating operational performance. Consequently, amalgamated with its direct influence, adopting Industry 4.0 ultimately produces a positive outcome in enhancing operational performance. While the indirect results outweigh the direct ones, this elucidates the profound impact of TQM and TPM management strategies as well as their mediation function concerning attaining improved levels of operational performance through implementing Industry 4.0 techniques.

Table 10. Results of research hypotheses (indirect relationships)

The result of the hypothesis	The significance level	Standard error	Path coefficient	Direction
proving a theory	p <0.01	0.105	0.223	4.0 Industry ← TQM ← operational performance
proving a theory	p <0.01	0.133	0.286	4.0 Industry ← TPM ← operational performance
-	-	-	0.830	Total direct and indirect impact for 4.0Industry

When considered from a different perspective, it becomes apparent that both methodologies possess an affirmative and notable correlation with the advancement of operational performance. This indicates that their collaborative execution possesses the potential to yield remarkable levels of improvement in comparison to their individual application. Moreover, the encouraging relationship between Industry 4.0 and TQM as well as TPM elucidates that they can augment preexisting management approaches while harmoniously coexisting with established practices and fundamental principles.

In addition to this article, it also has management findings which are as follows:

- The intersection of Industry 4.0 and management heralds a paradigm shift in how businesses operate and compete. Industry 4.0, often referred to as the Fourth Industrial Revolution, is not merely about technological advancements; it's a new era where technology becomes intertwined with every aspect of business operation. This integration leads to the creation of cyber-physical systems that enable real-time data exchange and automation. For management, this means a transition from traditional practices to a more dynamic, data-driven approach that emphasizes predictive analytics, adaptability, and strategic decision-making based on real-time information.
- From a management perspective, the principles of TQM and TPM are being redefined in the context of Industry 4.0. TQM evolves to encompass not just the quality of the end product but also the quality of data and processes that drive automated systems. Similarly, TPM extends beyond routine maintenance to include predictive maintenance powered by data analytics and machine learning, ensuring minimal downtime and optimal performance of the cyber-physical systems.
- The relationship between Industry 4.0 and management also manifests in the form of enhanced operational performance. The real-time data provided by interconnected systems allows managers to make informed decisions that can lead to improvements in efficiency, productivity, and innovation. This data-driven management approach enables a more responsive and flexible production process, which is essential for maintaining a competitive edge in today's fast-paced market.
- The role of management in Industry 4.0 is crucial for driving sustainable growth. Managers must navigate the challenges of integrating new technologies while ensuring that the

workforce is equipped with the necessary skills. They are also responsible for fostering a culture of continuous improvement and innovation, which is vital for leveraging the full potential of Industry 4.0 technologies. In essence, effective management in the era of Industry 4.0 is about harmonizing technology, people, and processes to achieve long-term sustainability and success.

- In the context of the articles [77,78,79,80,81 & 82], the proposed multi-objective mixed-integer linear programming (MILP) model aligns with Industry 4.0 by optimizing key sustainability objectives and enhancing resilience against disruptions. Industry 4.0 technologies facilitate the gathering and analysis of large volumes of data, which can improve the accuracy of the MILP model in predicting demand fluctuations, return rates, and disruption probabilities. This data-driven approach allows for more informed decision-making and scenario planning, which is crucial for managing the complexities of CLSCNs. Furthermore, the scenario-based stochastic programming approach mentioned in the abstract is a method that can leverage Industry 4.0's computational power and connectivity. By simulating various scenarios, the approach can identify robust solutions that can withstand different types of disruptions and uncertainties. This is particularly relevant in Industry 4.0, where supply chains are expected to be resilient and capable of rapid recovery from unexpected events.

  Lastly, the insights provided by the model for optimizing network configuration, resource allocation, and risk mitigation strategies are essential components of smart supply chain management in Industry 4.0. The ability to design sustainable and resilient CLSCNs is enhanced by Industry 4.0's emphasis on integration, automation, and real-time data exchange, leading to improved overall supply chain performance. In summary, the abstract's focus on sustainable and resilient supply chain design is intrinsically connected to the digital transformation and innovation goals of Industry 4.0.

4. Conclusion

In this article, we explored the intricate connections between comprehensive quality management and TPM and repairs. We also delved into how Industry 4.0 can be utilized to implement principles of TQM and TPM while examining their impact. The utilization of TPM methods holds great significance in preserving and advancing product quality by effectively reducing defective parts and products. Undoubtedly, the quality of a product is pivotal as it directly affects customer satisfaction. This achievement is realized through well-maintained machinery coupled with proper production operations. When machinery and equipment are duly maintained, the production process flourishes accordingly, ultimately delivering high-quality products to society at large. Consequently, we can infer that the overall health of an economy indirectly hinges on the wellness of its machinery and industrial equipment.

Industry 4.0 embodies a multitude of advancements, such as the integration of the Internet of Things (IoT), wireless sensors, big data analytics, artificial intelligence capabilities, enterprise resource planning (ERP) systems, remote monitoring and control functionalities, as well as machine learning techniques. These innovative features align with the tenets of TQM and TPM, offering an opportunity to enhance organizational efficiency.

The implications brought forth by Industry 4.0 on production systems are anticipated to revolutionize quality management methodologies and maintenance procedures. Such transformations will unlock novel approaches for refining and bolstering these cornerstone principles. Figure 4 aptly delineates Industry 4.0's potential contributions to TQM and TPM principles while showcasing the resulting enhancements in organizational performance that stem from synergizing these advanced features with established management practices.

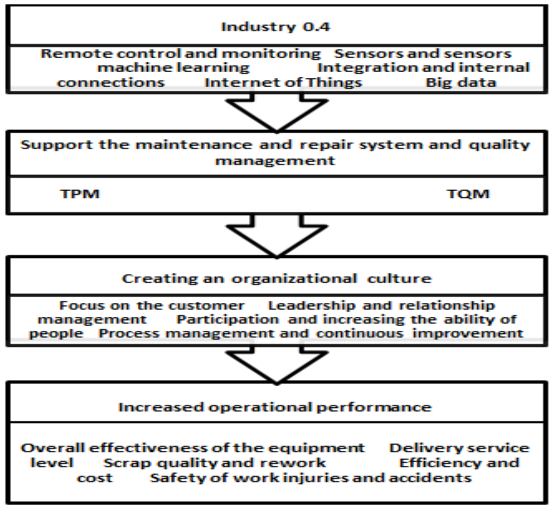

Figure 4. Industry 4.0 adoption impact perspective

Furthermore, the research findings revealed that the influence of Industry 4.0 on operational performance has the potential to be amplified if manufacturing companies effectively implement measures related to TQM and TPM. Consequently, not only do these methods directly contribute to improving operational performance, but they also act as positive mediators in enhancing the linkage between such improvements and Industry 4.0 technology. This outcome serves to emphasize an inherent characteristic of Industry 4.0—its advantages are only discernible when its technologies are integrated within the specific context of companies and aimed at supporting existing management practices like TQM and TPM.

- The article discusses the importance of TPM in preserving and advancing product quality by reducing defective parts and products.
- The quality of a product directly affects customer satisfaction, highlighting the significance of well-maintained machinery and production operations.
- Industry 4.0 advancements, such as the Internet of Things and artificial intelligence, can be utilized to implement TPM principles and enhance organizational efficiency.
- Industry 4.0 is expected to revolutionize quality management methodologies and maintenance procedures, offering new approaches to improve organizational performance by synergizing advanced features with established management practices.
- Implementing measures related to TQM and TPM can amplify the influence of Industry 4.0 on operational performance.
- TQM and TPM not only directly contribute to improving operational performance but also enhance the linkage between these improvements and Industry 4.0 technology.
- Future research should explore the associations between quality management, maintenance, and repair tasks, as well as employ structural equation modeling to validate the impact of a multidimensional management approach with Industry 4.0 integration.

- Utilizing statistical communities with expertise in TQM, TPM, and Industry 4.0 technologies can aid in conducting more precise analyses and further research in this area.

For future investigations, it may be advantageous to delineate various aspects of quality management along with maintenance and repair tasks, enabling a thorough exploration of the associations between these facets and different strategies employed for maintenance and repairs.

To gain a more expansive understanding, future investigations should encompass additional elements and variables within the framework of structural equation modeling. This will aid in validating the true impact of a multidimensional management approach when paired with the integration of Industry 4.0 technology. Moreover, utilizing statistical communities that possess extensive expertise in TQM and TPM methodologies, as well as fourth-generation industrial technologies, would contribute to a more precise analysis through implementing this model elsewhere. In this article, several factors and attributes pertaining to Industry 4.0 were considered alongside the principles of TQM and TPM for examination purposes, while also recognizing that delving into further facets of this vast industry concerning various dimensions associated with TQM and TPM principles presents an opportunity for future research endeavors.

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