

A Machine Learning–Assisted Evaluation of Industry 4.0 Maturity and Sustainability in Manufacturing Enterprises

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Abstract: The increasing digitalization of manufacturing systems through Industry 4.0 (I4.0) technologies has transformed global industrial operations by integrating cyber-physical systems (CPSs), the Internet of Things (IoT), robotics, additive manufacturing, and big data analytics. Despite widespread recognition of their potential, the sustainability and practical implementation of these technologies remain challenging, particularly within developing economies such as India. This study aims to evaluate the sustainability and maturity of Industry 4.0 enabling technologies in Indian manufacturing industries. A comprehensive mixed-method approach was adopted, combining literature review, expert interviews, and a structured questionnaire survey conducted across 16 manufacturing industries, including heavy engineering, metallurgical, textile, food processing, and chemical sectors. Findings reveal that smart sensors and robotic systems exhibit the highest adoption rates, while big data analytics and CPSs remain at the early implementation stage. The maturity–importance matrix indicates that sustainability in Industry 4.0 enhances both economic performance and social stability. Results demonstrate a positive correlation between sustainability and business profitability, supported by a rise in job creation and workforce skill levels as industries advance toward higher digital maturity. The research establishes that sustainable Industry 4.0 integration contributes to technological advancement, economic growth, and workforce transformation, offering an evidence-based roadmap for smart manufacturing implementation in developing economies.

Keywords: Industry 4.0; Sustainability; Smart Manufacturing; Cyber-Physical Systems, (CPSs); Big Data Analytics; Indian Manufacturing

1. Introduction

The global manufacturing landscape is rapidly transitioning toward smart manufacturing, a concept that integrates digital technologies such as the Internet of Things (IoT), cyber-physical systems (CPS), cloud computing, and Big Data analytics. These technologies enable real-time data acquisition and analysis across production lines, logistics, and supply chains, leading to improved efficiency, reduced downtime, and enhanced decision-making [1]–[3].

Smart manufacturing emphasizes connectivity and intelligence through the seamless interaction of sensors, machines, and control systems. This interconnected infrastructure transforms traditional factories into self-optimizing systems capable of predicting failures, scheduling maintenance, and dynamically adjusting operations [4]. The result is greater flexibility, productivity, and sustainability

throughout the product life cycle [5].

This technological revolution is widely recognized as Industry 4.0, representing the fourth industrial revolution after mechanization, electrification, and automation [6]. Industry 4.0 introduces intelligent integration between humans and machines using advanced communication technologies, digital twins, and analytics platforms [7].

Sustainability forms a central pillar of Industry 4.0. The combination of smart technologies and sustainable manufacturing practices allows industries to minimize waste, optimize energy consumption, and achieve environmental stewardship [8], [9]. Through autonomous control and predictive algorithms, Industry 4.0 promotes long-term economic and social benefits while reducing the ecological footprint [10].

Historically, the First Industrial Revolution relied on water and steam power, the Second on electricity and mass production, and the Third on computers and automation. The Fourth Revolution now merges these achievements with data-driven intelligence and connectivity [11], [12]. Despite its

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potential, challenges such as cybersecurity risks, high implementation costs, lack of skilled workforce, and cultural resistance continue to restrict widespread adoption [13]. In developing nations like India, the movement toward digital manufacturing is still in its formative stage. Government initiatives such as “Make in India,” “Smart City Mission,” and “Digital India” seek to promote industrial modernization and job creation by leveraging Industry 4.0 technologies [14]. However, issues related to infrastructure, awareness, and funding have slowed progress. India’s ranking of 91 in the Network Readiness Index (2016) illustrates the gap between potential and implementation compared with countries such as China and Malaysia [15].

Hence, this study aims to evaluate the sustainability of Industry 4.0-enabling technologies in Indian manufacturing industries and to propose an implementation roadmap validated through empirical analysis. The objective is to bridge the gap between theoretical frameworks and practical adoption to achieve sustainable industrial transformation [16].

2. Literature Review

2.1 Industry 4.0 and Enabling Technologies

The term Industry 4.0 was first introduced at the Hanover Messe 2011, referring to the digital integration of manufacturing systems through advanced automation and communication technologies [17]. It connects machines, materials, and humans within a cyber-physical production environment, enabling decentralized control and intelligent decision-making.

The evolution of industrial revolutions shows a continuous trend toward higher efficiency and intelligence. The first three revolutions successively introduced mechanization, electrification, and computerization, while the fourth builds upon these through networked systems and real-time analytics [18]. Industry 4.0 enables seamless information flow between design, production, and logistics, improving responsiveness and customization capabilities [19]. Modern manufacturing enterprises are increasingly adopting IoT-based sensors, CPSs, robotics, and data analytics to establish smart factories. These technologies support predictive maintenance, production planning, and quality assurance through real-time monitoring [20]. By integrating lean

principles and continuous improvement methodologies such as Six Sigma and Kaizen with digital tools, firms can achieve sustainability while maintaining competitiveness [21].

Industry 4.0 also promotes sustainability by enhancing transparency in material flows, reducing energy use, and supporting life-cycle management [22]. In developing economies, however, challenges such as high capital investment and limited digital skills constrain adoption. Collaborative frameworks among academia, industry, and government are essential for overcoming these barriers.

Consequently, Industry 4.0 is more than a technological upgrade—it is a strategic transformation paradigm combining operational excellence, environmental consciousness, and digital intelligence [23], [24].

3. Methodology

The methodology adopted in this study involves a combination of quantitative and qualitative approaches to assess the sustainability of Industry 4.0 enabling technologies in Indian manufacturing industries. The framework includes questionnaire-based data collection, expert interviews, and the use of a sustainability evaluation matrix. The aim is to analyze how Indian industries implement Industry 4.0 technologies and to measure their maturity and importance within different industrial sectors.

3.1.2 Data Collection Through Questionnaire

Primary data for this research were collected using a structured questionnaire distributed among selected manufacturing industries in India. The questionnaire was designed to evaluate the adoption level, awareness, and sustainability impact of various Industry 4.0 enabling technologies such as cyber-physical systems (CPSs), big data analytics, smart sensors, radio frequency identification (RFID), quick response (QR) codes, robotic arms, additive manufacturing (3D printing), and automated guided vehicles (AGVs).

A total of 48 industries were initially considered for the survey, out of which 32 were excluded after screening for non-compliance with the selection criteria. Only those industries that had been practicing Industry 4.0 technologies for at least three consecutive years were included. Consequently, 16 industries were finalized for the

survey, representing multiple sectors including heavy engineering, metallurgical, textile, food processing, and chemical industries. The

distribution of participating industries based on size, employee strength, and turnover is presented in Table 1.

Table 1 Industries considered for data collection through questionnaires

Industry category	No. of employees	Turnover (in INR million)	Contribution in the questionnaire survey
Big-sized industries	>100	>17	02 (12.5%)
Medium-sized industries	50-100	15-17	06 (37.5%)
Small-sized industries	<50	<15	08 (50%)
	Total		16 (100%)

3.2 Expert Interviews

To supplement the quantitative findings, expert interviews were conducted with professionals from selected industries who had practical experience with Industry 4.0 implementation. These interviews were aimed at understanding how Indian industries interpret Industry 4.0 concepts, what technologies are being utilized, and what barriers and challenges exist in the process of implementation. Experts

were chosen from the automotive, metallurgical, textile, and aircraft subcomponent manufacturing sectors. The interviewees held technical and managerial positions such as R&D Heads, Production Heads, Technical Heads, and HR Heads. Their years of experience ranged from 9 to 34 years, ensuring a diverse and informed viewpoint. Details of the interviewed experts are summarized in Table 2.

Table 2 Expert interviewees' details

Industry type	No. of interviewee	Interviewee designation		Interviewee experience (in years)	
		1 st	2 nd	1 st	2 nd
Automotive manufacturer	01	R & D Head	---	34	---
Metallurgical industry	02	Production Head	HR Head	17.5	12
Textile manufacturer	02	Technical Head	HR Head	24	09
Aircraft subcomponent manufacturer	02	R & D Head	HR Head	21	11

3.3 Spread of Industry 4.0 Enabling Technologies

- The spread and adoption of Industry 4.0 enabling technologies among the surveyed industries were evaluated based on the responses to the questionnaire.
- The analysis revealed that technologies such as smart sensors and robotic arms are widely implemented, while technologies

like big data analytics and cyber-physical systems (CPSs) are still in the early stages of adoption.

- The overall distribution of observed technologies is shown in Table 3, which summarizes the number of industries adopting each technology and the corresponding percentage.

Table 3 Spread of Industry 4.0 enabling technologies

Industry 4.0 enabling technology	No. of observations (out of 16)	Percentage
CPS	8	50
Big Data Analytics	6	37.5
Smart Sensors	14	87.5
RFID	10	62.5
QR Code	11	68.75
Robot Arms	13	81.25
3D Printing	9	56.25
Automated Guided Vehicles (AGV)	10	62.5

4. Results and Discussion

4.1 Job Loss, Job Creation, and Workers’ Qualification vs. Industry 4.0 Sustainability

The relationship between Industry 4.0 sustainability and its social impact in terms of job dynamics and workers’ qualification is presented in Figure 1. The analysis indicates that the sustainability level of Industry 4.0 significantly influences workforce transformation within manufacturing industries.

At the initial stage of Industry 4.0 adoption, the job loss rate exhibits a steep increase. This rise is attributed to the replacement of repetitive and low-skill manual tasks with automation and robotics. As technologies such as robotic arms, automated guided vehicles (AGVs), and smart sensors become integrated into production lines, routine operations

are increasingly performed by machines. However, as sustainability progresses to higher levels, the job loss curve reaches a plateau, indicating that automation saturation has been achieved and new employment opportunities begin to emerge.

Simultaneously, the job creation curve follows a steadily increasing trend with rising Industry 4.0 sustainability. This implies that the introduction of advanced technologies generates new categories of employment, particularly in data analytics, maintenance of cyber-physical systems, additive manufacturing design, and digital process control. The creation of these roles compensates for the earlier losses caused by automation, thereby stabilizing employment levels in mature smart factories.

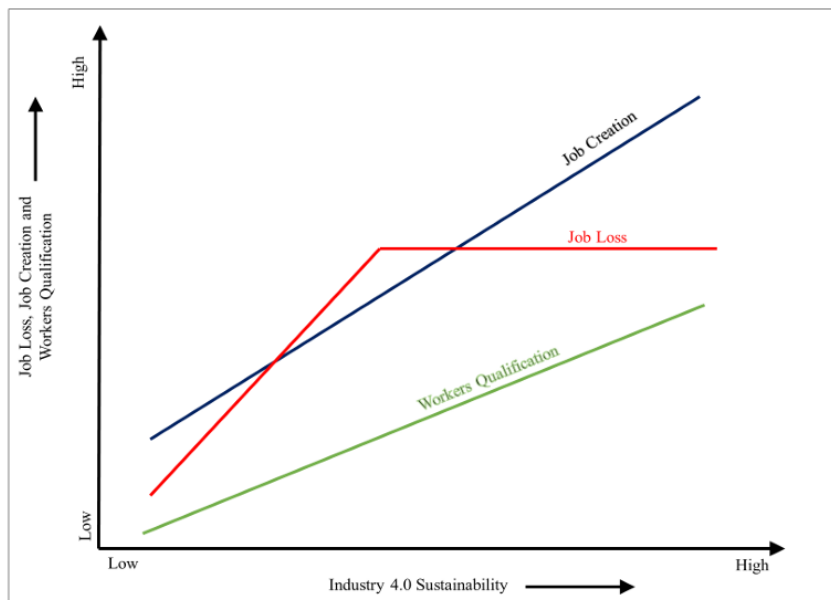


Figure 1. Relationship between job loss, job creation, and workers’ qualification with Industry 4.0 sustainability

The workers’ qualification curve, shown in green, increases linearly with sustainability. This trend highlights the growing need for technically

competent personnel who can operate, monitor, and optimize digitally connected systems. The progressive movement of this curve confirms that

human capital development is a key component of Industry 4.0 sustainability. Industries advancing toward higher maturity levels rely more on skilled engineers, data analysts, and process integrators capable of handling complex digital ecosystems.

The graphical relationships depicted in Figure 1 illustrate that as Industry 4.0 systems become more sustainable, the balance between job loss and job creation improves, shifting the labor demand from manual to cognitive and supervisory roles. The findings emphasize that technological sustainability is not merely an automation milestone but a socio-technical evolution that requires continuous upskilling and adaptation.

4.2 Business Profit vs. Industry 4.0 Sustainability

The economic implications of Industry 4.0 sustainability are represented in Figure 2, which demonstrates a positive linear relationship between business profit and sustainability level. As the adoption of Industry 4.0 technologies increases, manufacturing industries experience gradual improvements in operational efficiency and profitability.

At lower levels of sustainability, industries tend to incur high initial costs associated with infrastructure development, digital integration, and workforce training. However, as implementation

progresses and production systems evolve into data-driven, automated, and predictive environments, these costs are offset by gains in productivity and quality consistency. The improved coordination between big data analytics, real-time monitoring, and resource optimization directly contributes to higher profit margins.

The slope of the graph in Figure 2 indicates that even moderate improvements in Industry 4.0 sustainability yield substantial economic benefits. This is mainly due to reduced downtime, optimized energy usage, and enhanced product traceability achieved through smart technologies. Furthermore, the interconnectivity of supply chains enabled by IoT and cloud-based systems allows for dynamic demand forecasting and lean inventory management, leading to long-term profitability.

The results also reveal that the transition toward sustainable Industry 4.0 practices enhances business resilience. Enterprises adopting advanced automation and digital intelligence are better positioned to respond to market fluctuations, regulatory changes, and customer-specific customization demands. Therefore, the correlation between sustainability and business profit shown in Figure 2 substantiates that economic growth in modern manufacturing is directly proportional to the degree of digital sustainability achieved by Industry 4.0 integration.

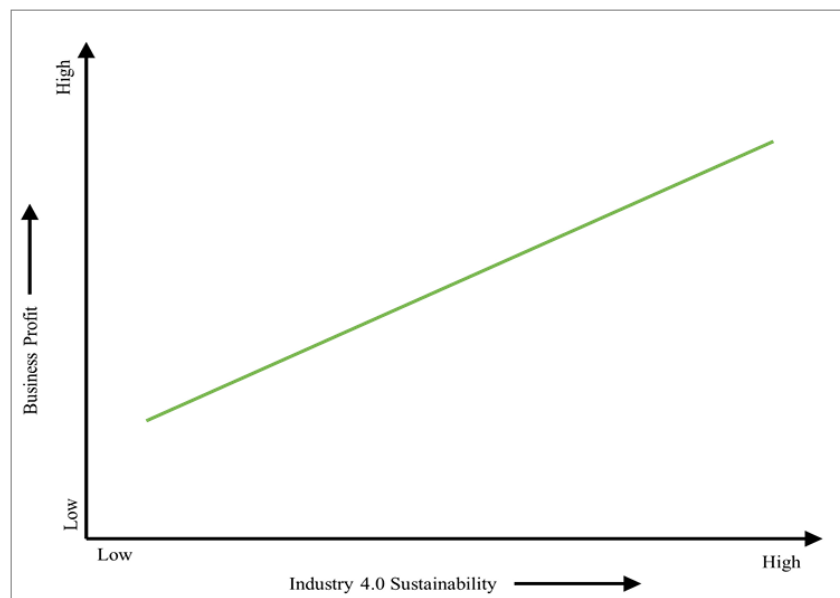


Figure 2. Relationship between business profit and Industry 4.0 sustainability

4.3 Interpreting Sustainability Impacts

The combined analysis of Figures 1 and 2 indicates that Industry 4.0 sustainability simultaneously

affects both social and economic dimensions of industrial growth. While automation initially disrupts employment structures, it gradually

transforms workforce composition toward higher skill levels and cognitive engagement. On the economic side, sustainability-driven adoption of advanced manufacturing technologies translates into increased efficiency, reduced waste, and improved profitability.

These findings collectively demonstrate that as industries evolve along the Industry 4.0 maturity path, both social and economic performance indicators improve through a synergistic relationship between human capability enhancement and technological advancement.

5. Conclusion

This study provides a detailed assessment of the sustainability of Industry 4.0 enabling technologies in Indian manufacturing industries using a structured evaluation framework that combines quantitative and qualitative methods. The analysis shows that the implementation of technologies such as smart sensors, robotic systems, and RFID-based monitoring is already progressing steadily, while advanced tools such as CPSs, additive manufacturing, and big data analytics are emerging with moderate maturity levels.

The evaluation of job loss, job creation, and workers' qualification revealed that while automation initially leads to temporary displacement of low-skilled labor, it ultimately facilitates a net increase in employment opportunities through the creation of high-value technical and managerial roles. The qualification level of workers shows a proportional rise with the sustainability index, indicating that digital transformation demands continuous upskilling and reorientation of the industrial workforce.

The economic analysis further confirms a direct positive relationship between Industry 4.0 sustainability and business profit. As industries adopt data-driven systems, integrate real-time monitoring, and optimize operational efficiency, their profitability improves significantly. Higher sustainability levels correlate with reduced downtime, energy savings, and improved product quality, contributing to long-term competitiveness.

Overall, the study demonstrates that sustainable adoption of Industry 4.0 technologies fosters both economic and social growth in manufacturing ecosystems. It underscores the importance of skilled workforce development, data integration, and policy-driven incentives for ensuring successful implementation. The proposed

methodological framework and empirical findings can serve as a reference model for policymakers, industrial strategists, and academic researchers aiming to accelerate India's transition toward a sustainable and intelligent manufacturing future.

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