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INTERNATIONAL JOURNAL OF RECENT TECHNOLOGY SCIENCE & MANAGEMENT

“IMPLEMENTATION OF INDUSTRY 4.0–ENABLED SMART MANUFACTURING SYSTEMS IN INDIAN MANUFACTURING INDUSTRIES: A ROADMAP AND CASE STUDY APPROACH”

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ABSTRACT

Industry 4.0 offers significant opportunities for transforming conventional manufacturing systems through the integration of the Internet of Things (IoT), cyber-physical systems, automation, data analytics, and intelligent human-machine interaction. However, its practical adoption, particularly in developing economies and small- and medium-scale manufacturing industries, remains constrained by technological, organizational, financial, and implementation-related challenges. The present study develops a systematic roadmap for the implementation of Industry 4.0 and smart manufacturing systems in Indian manufacturing industries. The research methodology combines an extensive literature review, identification of major barriers, drivers, enablers and risk factors, expert consultation, questionnaire-based investigation, and industrial case studies, followed by the development and validation of practical smart manufacturing solutions. The proposed approach was validated through multiple industrial applications. Implementation of a voice-assisted forging system reduced the average rejection count by 90.3%, increased operational productivity by 71.2%, and improved process accuracy from 92.75% to 99.30%, while eliminating reported operational incidents. An IoT-enabled assembly-line framework further reduced rejection rate from 25% to 10%, decreased non-value-added activity from 33.33% to 11.06%, increased resource utilization from 85% to 95%, and eliminated scrap. An automated quality-inspection system increased inspection accuracy to 100% and reduced inspection time from 53 s to 16 s, while a smart printing system provided automated, accurate, safe, and less labour-dependent component identification. The findings demonstrate that gradual, application-oriented adoption of Industry 4.0 technologies can substantially improve productivity, quality, resource utilization, process safety, and operational efficiency in manufacturing industries.

Key Words: Industry 4.0, Smart Manufacturing, Internet of Things, Manufacturing Automation

I. INTRODUCTION

Due to an increase in competition among manufacturing industries, manufacturers need to rethink their manufacturing operations and develop effective factory management i.e. smart manufacturing (Ashton, et al., 2015). In smart manufacturing, the focus is on improving asset utilization by using IoT-driven data analytics (Fleisch, 2012). IoT - driven data analytics combines new and old data which gives a high degree of flexibility and decision-making capability to manufacturing workers (Swan, et al., 2012).

Smart manufacturing deals with capturing and analysis of shop floor data, logistics data and supply chain data in real-time (Lucke, et al., 2016; McFarlane, et al., 2012). Smart manufacturing covers different aspects such as product design and development, factory processes, supply chain, and demand management (J. Gubbi, et al., 2013). Smart

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manufacturing allows enterprises to have full visibility and real-time tracking of investments in assets, advancements in the business/process, capital, and products which optimizes supply and demand (Yam, et al., 2015). The inclusion of proactive and autonomic analytics capabilities in smart manufacturing makes smart manufacturing an intelligent and self-healing environment that can forecast disruptive issues, develop/modify operations and delight customers (J. Lee, et al., 2015).

Now a days, smart manufacturing is also called as fourth industrial revolution i.e. Industry 4.0. Smart manufacturing combines connectivity technologies, the cloud and Big Data analytics (F. Shrouf, et al., 2014). Connectivity technologies allow taking active and precise decisions related to the business by linking factory automation assets to end-user apps as well as mobile devices (Lee, et al., 2015).

Now a days, organizations are looking for sustainability features in their business activities (Hermann, et al., 2016; Liao, et al., 2017). On the other hand, industries are facing problems to fulfil the continuously varying demands of customers along with confirming a sustainable evolvement in business (Tseng, et al., 2018). The industry 4.0-based concept helps industrial managers to integrate environmental protection, control initiatives and process safety (Wang, et al., 2016). Because of Industry 4.0 initiatives, a production system can be transformed into a smart production system. This makes the manufacturing system more flexible, economical, and environmentally friendly (Sarkis, 2012; Schmidt, et al., 2015; Stock and Seliger, 2016; Waibel, et al., 2017).

Out of four industrial revolutions, the First Industrial Revolution deals with the use of water and steam powers to develop mechanical production facilities (Buer, et al., 2018; Dolgui, et al., 2018). During the Second Industry Revolution electrical energy generation was accelerated which helped to achieve mass production. The Third Industrial Revolution introduced electronic and information technologies that furthered production automation (Malte, et al., 2014; Fetterman, et al., 2018; Rane, et al., 2019). Over the last few years, Industry 4.0 has emerged as a promising technology framework used for integrating and extending manufacturing processes at both intra-organizational and inter-organizational levels (Dolgui, et al., 2018). The industry 4.0 concept enables the manufacturer to achieve maximum operational efficiency of manufacturing plants with minimum resource utilization. The concept of Industry 4.0 was developed in Germany which deals with the development of the smart manufacturing system. Industry 4.0 allows manufacturing with information technology (Machado, et al., 2019; Mariyono, 2019). Industry 4.0 integrates cloud computing, the Internet of Things (IoT) and cyber-physical systems (CPS) with an aim to develop a highly efficient production plant (Buer, et al., 2018). Industry 4.0 concept sounds best at first but it has multiple challenges that are to be overcome before implementing Industry 4.0. Structural resistance, cyber security, cultural resistance and training for employees are important issues that need to be addressed on the road to Industry 4.0 (Tortorella, et al., 2017).

Industry 4.0 enabling technologies are still in the infancy stage and firms are far away from enjoying its complete benefits. The perception level of manufacturing firms on smart manufacturing systems is very low. The smart manufacturing concept is largely adopted only by big firms. This includes companies of Indian origin as well as global players who have set up a base in this country. The growth of the fourth industrial revolution depends upon progress in academic research. It has been found that sometimes practical implementation of outcomes of academic research is difficult. The outcomes of many research articles are theoretically based. The unavailability of strong empirical data is the main reason for the less adoption of Industry 4.0 in the manufacturing sector. Due to a lack of implementation details and a large amount of fund requirements many industries are still not sure about the use of these new technologies. Therefore, it is need of time to transform an Industry 4.0 research proposal into an Industry 4.0 implementation.

II. LITERATURE REVIEW

Over the past few years, the Internet of Things (IoT) and cyber-physical network concepts have improved industrial systems. For an in-depth understanding of 'fourth industrial revolution', it is significant to know the previous three industrial revolutions (D. Schaefer, et al., 2015; Theorin, et al., 2017). The first industrial revolution provides the groundwork for industrialization. The second revolution provides the groundwork for Power and emerges the concept of 'hard automation'. The third revolution provides the groundwork for computers and emerges the idea of 'flexible automation' (Huang, et al., 2016; Tortorella, et al., 2017). The fourth revolution provides the groundwork for Industry 4.0 with an application of modern information and communication technology and connected with the integration of industrial automation, data networks, and advanced manufacturing technologies like smart production, human-

computer interaction, 3D printing, remote operations, etc. (Bagheri, et al., 2015; Viryasitavat et al., 2018).

The concept of “Industry 4.0” was presented by Hanover Messe in 2011. Industry 4.0, can be understood as the “smart manufacturing” or “integrated industry” that has the ability to influence the whole business in terms of products designed, manufactured and delivered etc. (Wulfsberg, et al., 2016; Wang, et al., 2017). Industry 4.0 offers a more effective means to control the production system compared to the traditional centralized system. In recent years, Industry 4.0 predominantly enlightening the upcoming revolutions of the manufacturing industry landscape, especially in the developed economy. However, the concept is somewhat novel to developing economies and needs an in-depth understanding and practice in business (Wang, et al., 2016; Xu, et al., 2018).

In recent years, due to high competition in the manufacturing field, manufacturers are forced to accept modern technological development and process innovations (Yin, et al., 2018; Zhong, et al., 2016). The process innovations like six sigmas, lean, kaizen and Just-in- time when coupled with modern information technology-based Industry 4.0 initiatives lead to a sustainable culture in manufacturing (Jagdish, et al., 2015; Zikopoulos, et al., 2012). This will evolve new sustainable trends in the manufacturing environment in developing economies (Dolgui, et al., 2018).

Industry 4.0 allows industrial systems to develop a global cyber-physical network of machines, equipment, sensors, and facilities for better data exchange and control. This worldwide cyber-physical network would be extremely flexible and smarter leads to a smart factory (Li BH, et al., 2010; Yin, et al., 2018). This further improves the total performance of the whole business by extemporizing each business activity like design, material and machine requirements, product lifecycle and supply chain management, etc. Industry 4.0 technologies allow the real-time monitoring and controlling of vital production parameters, such as production status, energy consumption, the flow of materials, customers’ orders, and suppliers’ data. Industry 4.0 and sustainability have become the recent developing threads for manufacturing for improving productivity and evolving a more sustainable culture (Buer, et al., 2018; Zhong, et al., 2016). Industry 4.0 is assumed to be a new business mindset that can help business organizations and society to move toward sustainable development (Karen Rose, et al., 2015).

III. METHODOLOGY

The literature review is done by searching some keywords along with their combinations such as – Challenges and Barriers; Industry 4.0; Manufacturing and Sustainability; Industry 4.0 diffusion and Sustainability and Manufacturing; Industry 4.0 and Manufacturing Industry and Sustainability and Challenges. For searching these keywords, Scopus and Google Scholar are explored.

Next, the collected articles are examined in relation to these keywords. In this way, the literature review is performed in this research. Then, key challenges are finalized by using literature support and expert inputs. These challenges provide the theoretical foundation. A questionnaire-based survey and case study for the manufacturing industry is conducted. Then, smart systems for manufacturing industries are developed. The developed smart systems are validated by adopting them in the industries. The results of the model implementation are verified with the developed theory. The above-said work is carried out in following phases shown in figure 1:

Phase I:

- Introduction of smart manufacturing system / Industry 4.0.
- Detailed literature survey on smart manufacturing system / Industry 4.0.
- Determination of the current research scenario of Industry 4.0.
- Identification of key barriers in implementing smart manufacturing system / Industry 4.0.

Phase II:

- Analyze the enablers and drivers for smart manufacturing system / Industry 4.0.
- Identify the risk factors for the smart manufacturing system / Industry 4.0 enabling technologies.

Phase III:

- Evaluate the sustainability of Industry 4.0 in Indian manufacturing industries.
- Analyze the co-relation between Industry 4.0 enabling technologies' importance and their maturity in Indian manufacturing industries.
- Determination of the limitations of smart manufacturing systems / Industry 4.0.

Phase IV:

- Design and development of a roadmap for implementation of smart manufacturing system / Industry 4.0.
- Development of smart systems in manufacturing industries.
- Develop the difference between traditional manufacturing systems and smart manufacturing systems.

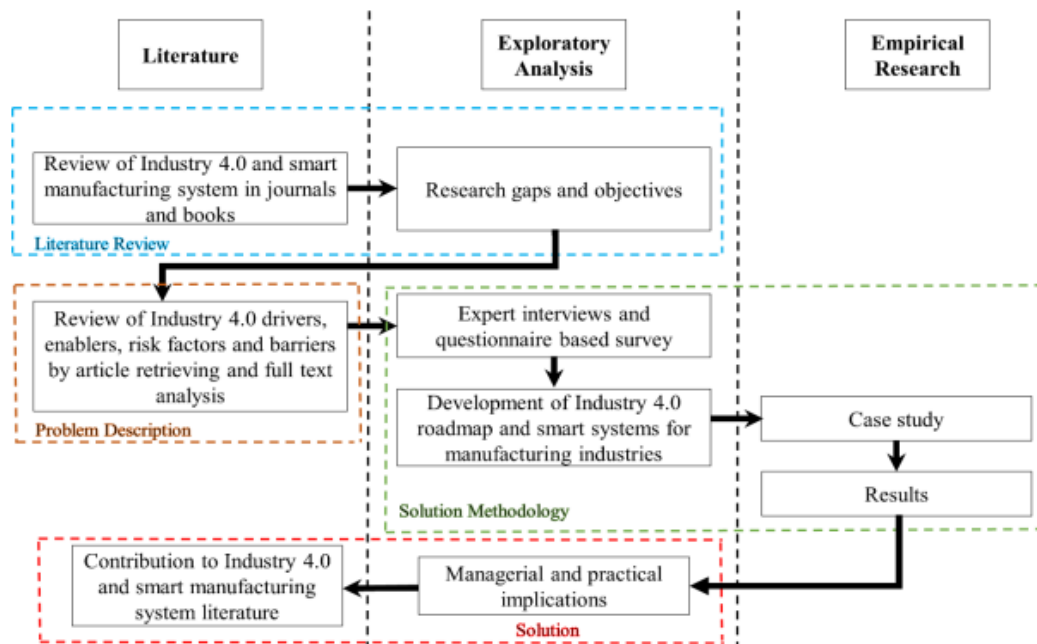


Figure 1: Research methodology flow chart

IV. RESULT AND DISCUSSION

The proposed roadmap is implemented in Indian industries to check its validity. The focus was on small tasks that can bring faith and belief in Industry 4.0 concept. The first case study was successful in lowering the rejection rate, creating high productivity and reducing the number of incidents by converting the traditional forging system into a voice-assisted forging system. It was possible to reduce the average rejection count by 90.3% and increase operational productivity by 71.2%. The process accuracy was elevated from 92.75% to 99.30% and no incidents were reported after the installation of the voice-assisted forging system.

After the success of creating hassle-free human-machine interaction, a solution based on IoT for the small-scale transformer manufacturing industry's assembly line was developed. It was found that IoT based framework for assembly line can optimize various parameters such as rejection rate, resource utilization, productivity, Non-value-added activity time (NVA), etc. Table 1 shows the comparison between before and after IoT.

After two success stories, an Industry 4.0-enabled automatic quality inspection system was developed to overcome the problems (such as higher inspection error, lower inspection accuracy, etc.) faced during the manual sampling inspection process. In this system, the principle of image processing technology and computers aided by some mechanical devices were used. This system has increased the efficiency and accuracy of the quality inspection process shown in Table 2.

Table 1: Before IoT vs. after IoT

Parameters	Before IoT	After IoT
Rejection Rate	25%.	10%
NVA	33.33%.	11.06%.

Production Rate / day	49%.	67%.
Percentage Utilization of Resources	85%	95%.
Scrap	5%.	zero.

Table 2: Manual inspection vs. automatic inspection

Parameters	Before	After
Process accuracy	90.67%	100%
Average time required	53 seconds	16 seconds
Labour productivity	5.69 units/min	18.4 units/min

In today's industry, where production rates are higher and large number of components are produced every day, it is necessary to keep a track of components produced every day. While some industries may do so by giving each component a unit number, it is relatively difficult to give each component a unit number by carving the number of units on the component using a hammer and nail. This method is time-consuming.

Figure 2 shows the smart printing device. The present invention comprises a dual- story frame having a plurality of ground-engaging elements to stabilize or move the frame, wherein the plurality of ground-engaging elements includes one or more of the wheel and/or one or more of a rubber pad; a housing positioned at a certain height from a ground of one of the stories of the dual-story frame with support or at least two vertically support member; a printhead coupled to the housing for securing a laser emitter; a fixture configured to receive an article for desired printing over the article upon manual pushing the fixture at printing point, which is below the printhead; and a sensor engaged with the printhead and disposed towards the fixture to sense the presence of article to activate the laser emitter for printing/engraving a design or literatures over the article through a control unit.

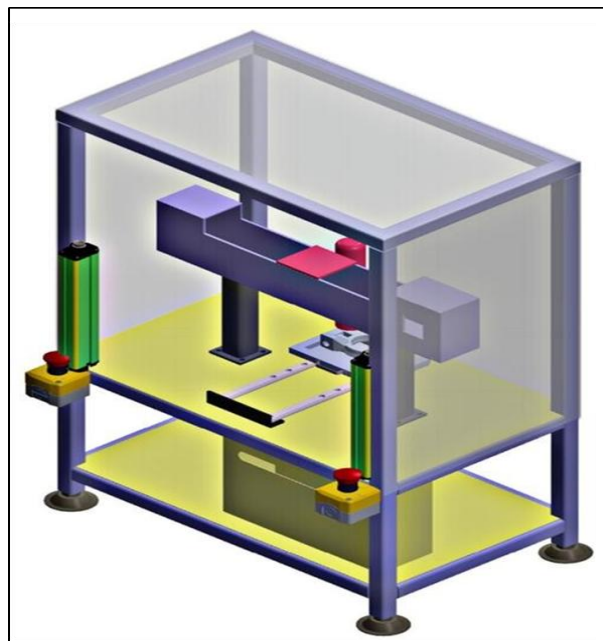


Figure 2: Smart printing device

The smart printing machine is more efficient than the manual printing process (nail and hammer). This machine provides safety to workers working on it. There will be no wastage of material or job due to improper printing. The printing of the barcode on the job will be accurate at the same position and there will no confusion during the marking system. Experience workers are not required to operate this machine.



Figure 3: Operation performed by using hammer and nail



Figure 4: Operation performed by using smart printing device

The advantages of smart printing device shown in figure 3 are as follows: (a) It is time efficient; (b) No human energy is required as the process is automated; (c) Printed numbers are clearly visible; (d) No unnecessary material loss; (e) Worker's safety is improved; (f) No need of experienced workers; and (g) It is extremely easy to operate.

V. CONCLUSION

The present study investigated the practical implementation of Industry 4.0 and smart manufacturing concepts in Indian manufacturing industries. Rather than limiting Industry 4.0 to a theoretical technological framework, the study followed a structured approach involving identification of implementation challenges, analysis of drivers and enablers, assessment of sustainability and technological maturity, and development of a practical roadmap for industrial implementation. The methodology incorporated literature-based investigation, expert inputs, questionnaire-based assessment, development of smart manufacturing systems, and their subsequent validation through industrial case studies. This approach demonstrates that Industry 4.0 adoption can be initiated through focused and relatively small technological interventions before progressing toward complete smart-factory transformation.

The industrial applications demonstrated substantial improvements over conventional manufacturing practices. The voice-assisted forging system reduced the average rejection count by 90.3%, improved operational productivity by 71.2%, and increased process accuracy from 92.75% to 99.30%, with no operational incidents reported after implementation. Similarly, implementation of the IoT-enabled assembly-line framework reduced rejection rate from 25% to 10% and non-value-added activity from 33.33% to 11.06%. Production performance and resource utilization

improved, while scrap was reduced to zero. These results establish that even selective implementation of digital connectivity and real-time monitoring can generate measurable improvements in manufacturing performance. The development of an Industry 4.0-enabled automatic inspection system further demonstrated the potential of digital technologies for improving product quality. The system increased process accuracy from 90.67% to 100%, reduced the average inspection time from 53 s to 16 s, and increased labour productivity from 5.69 to 18.4 units/min. In addition, the proposed smart printing device replaced the conventional hammer-and-nail marking process with an automated laser-based arrangement capable of accurate and repeatable component identification. The developed device offers advantages in terms of operating time, worker safety, material conservation, printing accuracy, ease of operation, and reduced dependence on experienced workers.

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