INDIAN JOURNAL OF SCIENCE AND TECHNOLOGY

ORIGINAL ARTICLE

OPEN ACCESS

Received: 19/12/2025

Accepted: 31/01/2026

Published: 13/02/2026

Citation: Raval MB, Joshi HI, Valaki J, Khatri B, Modi AD, Bhavsar KH (2026) An Investigation into the Impact of Technological Advancements, Advanced Manufacturing Methods and Industry 4.0 Adoption on the Bearing Manufacturing Industry: A Research Framework. Indian Journal of Science and Technology 19(5): 280-297. https://doi.org/10.17485/IJST/v19i5.1994

* **Corresponding author**.

j_hiren@yahoo.com

Funding: None

Competing Interests: None

Published By Indian Society for Education and Environment (iSee)

ISSN
Print: 0974-6846
Electronic: 0974-5645

An Investigation into the Impact of Technological Advancements, Advanced Manufacturing Methods and Industry 4.0 Adoption on the Bearing Manufacturing Industry: A Research Framework

Manan Bhavesh Raval[1,2], Hirenkumar Indravadan Joshi[3]*, Janak Valaki[4], Bharat Khatri[5], Amit D Modi[6], Kaushal H. Bhavsar[7]

1 Mechanical Department, Gujarat Technological University, Ahmedabad, Gujarat 380015, India
2 Mechanical Department, Government Polytechnic, Junagadh, Gujarat 362263, India
3 Mechanical Department, Govt. Engineering College, Rajkot, Gujarat 360005, India
4 Mechanical Department, Govt. Engineering College, Bhavnagar, Gujarat 364002, India
5 Mechanical Department, Govt. Engineering College, Modasa, Gujarat 383315, India
6 Mechanical Department, Government Polytechnic, Junagadh, Gujarat 362263, India
7 Mechanical Department, LDRP Institute of Technology, Gandhinagar, Gujarat 382015, India

Abstract

Objectives : The purpose is to conduct a systematic study on how technological improvements, modern manufacturing methods, and Industry 4.0 implementation affect productivity, the quality of the product, measurement accuracy, and overall performance in the bearing manufacturing industry. The framework also questions the impact of superior manufacturing techniques and process-improvement instruments as well as Industry 4.0 technologies on quality, measurement accuracy, and production efficiency and Overall Equipment Effectiveness in bearing manufacturing. **Method :** A programmed literature search was conducted using Scopus, Web of Science, Science Direct and Google Scholar. It covered the period between 1997 and 2025. Peer-reviewed articles reporting a quantifiable outcome, i.e. defect percentage. The synthesis of findings was done through comparative tabulation, analysing of key performance indicators and categorising the technologies thematically. **Findings :** The data reveal that the use of quality tool, process improvement tools and Industry 4.0 techniques reduces bottlenecks, defects and cycle time. The Study highlights the significant improvements in OEE, quality and productivity. **Novelty :** The present manuscript presents an integrative, holistic research framework that highlights the most recent technological advances, process optimization strategies and the systematic implementation of Industry 4.0 practices and thus provides a methodical answer to the main challenges facing modern bearing production companies.The study provides a comprehensive, evidence-based model of the relationship between issues, technologies, and performance outcomes. It provides an implementation plan of Industry 4.0 Techniques, outlines the bottlenecks, and outlines the future research directions which include AI-driven defect prediction and low-cost Industry 4.0 adoption of micro, small, and medium enterprises.

Keywords: Industry 4.0; Production Quality; Bearing Manufacturing; Process Improvement; Quality Control

1 INTRODUCTION

Bearings are critical machine elements that support rotating components while minimizing friction, vibration, and wear. Owing to their fundamental role in motion transmission and load- carrying, bearings are extensively employed across diverse industrial sectors, including the automobile industry, aerospace and aviation systems, machine tools, electrical machinery, and railway locomotives and wagons. Broadly, bearings are classified into two principal categories: sliding contact bearings and rolling contact bearings. The manufacturing of bearings demands exceptionally high precision and stringent dimensional tolerances to ensure reliability, service life, and operational safety.

Bearing manufacturing involves a sequence of tightly integrated and precision-oriented processes such as forging, heat treatment, turning, grinding, honing, lapping, assembly, and non-destructive testing (NDT). Each stage contributes significantly to the final quality and functional performance of the bearing. The global bearing market was valued at USD 150.63 billion in 2024 and is projected to reach USD 279.83 billion by 2032. Asia currently represents the largest share of this market, while Europe is emerging as the fastest-growing region, underscoring the increasing demand for high-quality and technologically advanced bearing products[(1)].

Recent advancements in bearing manufacturing have been driven by the adoption of simulation-based process planning, fully automated inspection systems, Internet of Things (IoT)-enabled condition monitoring, and Industry 4.0 technologies. These include cyber-physical systems, real-time data analytics, digital quality control, and interconnected manufacturing environments. Collectively, these innovations have triggered a paradigm shift from experience-based and manual manufacturing practices toward data-driven, automated, and intelligent production systems. However, existing research largely addresses these developments in isolation, focusing on individual approaches such as Six Sigma, lean manufacturing, machining optimization, additive manufacturing, or specific Industry 4.0 applications. Consequently, the available literature remains fragmented, limiting a holistic understanding of how these methodologies can be integrated to effectively address persistent manufacturing challenges such as defects, process inefficiencies, inadequate measurement accuracy, material waste, and the pressing need for factory digitalization.

In this context, the present review aims to synthesize and consolidate these diverse advancements into a unified and coherent framework. It establishes a clear linkage between long-standing challenges in bearing manufacturing and contemporary technological solutions, while critically contrasting prior studies and identifying research gaps emerging from recent technological evolution. Furthermore, the study proposes a consistent methodology that harmonizes continuous improvement tools, digital technologies, and performance objectives. This integrated perspective is essential for aligning traditional manufacturing practices with current industrial requirements and for providing an empirically grounded and practically viable roadmap for modernizing the bearing manufacturing sector.

Within bearing manufacturing, certain processes are inherently critical and demand heightened attention due to their direct influence on product quality and performance. With the increasing adoption of advanced machinery, cyber-physical systems, and IoT-based web monitoring platforms, bearing manufacturing plants have significant opportunities to enhance quality assurance, process control, and operational efficiency. At the same time, manufacturers continue to face challenges related to defect reduction, process variability, and productivity improvement. The typical manufacturing sequence for rolling contact bearings includes hacksaw cutting of steel bars, turning, heat treatment, multi-stage grinding, honing, lapping, magnetic particle-based NDT, assembly, final inspection, packaging, and dispatch.

Despite advancements in manufacturing technologies, several defects are commonly observed during bearing production. These include dimensional variations, scratches, chatter marks, profile errors, cracks, grinding marks, scaling, porosity, excessive surface roughness, cage bending, rivet misalignment, and faulty riveting. Additionally, issues related to noise and vibrations are frequently identified during final testing stages. To minimize rework and rejection rates, it is imperative that process parameters are meticulously designed and controlled. Factors such as workforce skill levels, machine capability, technological sophistication, process settings, environmental conditions, management policies, and measurement methodologies collectively influence the accuracy and consistency of bearing manufacturing. The distribution of major defects as a percentage of total defects is illustrated in Figure 1.

The data utilized in this study are obtained from historical production records, expert consultations with industry professionals, and direct observations conducted within bearing manufacturing facilities located in a specific region of India. These multiple data sources ensure practical relevance while capturing real-world manufacturing conditions. To address process variability, uncertainty, and inefficiencies, established improvement methodologies such as Six Sigma (DMAIC framework), lean manufacturing, Just-in-Time (JIT) production, 5S, and Kaizen have been implemented in bearing manufacturing environments. In addition, process capability analysis is employed as a quantitative tool to evaluate and monitor manufacturing performance in terms of product quality, process stability, and overall effectiveness.

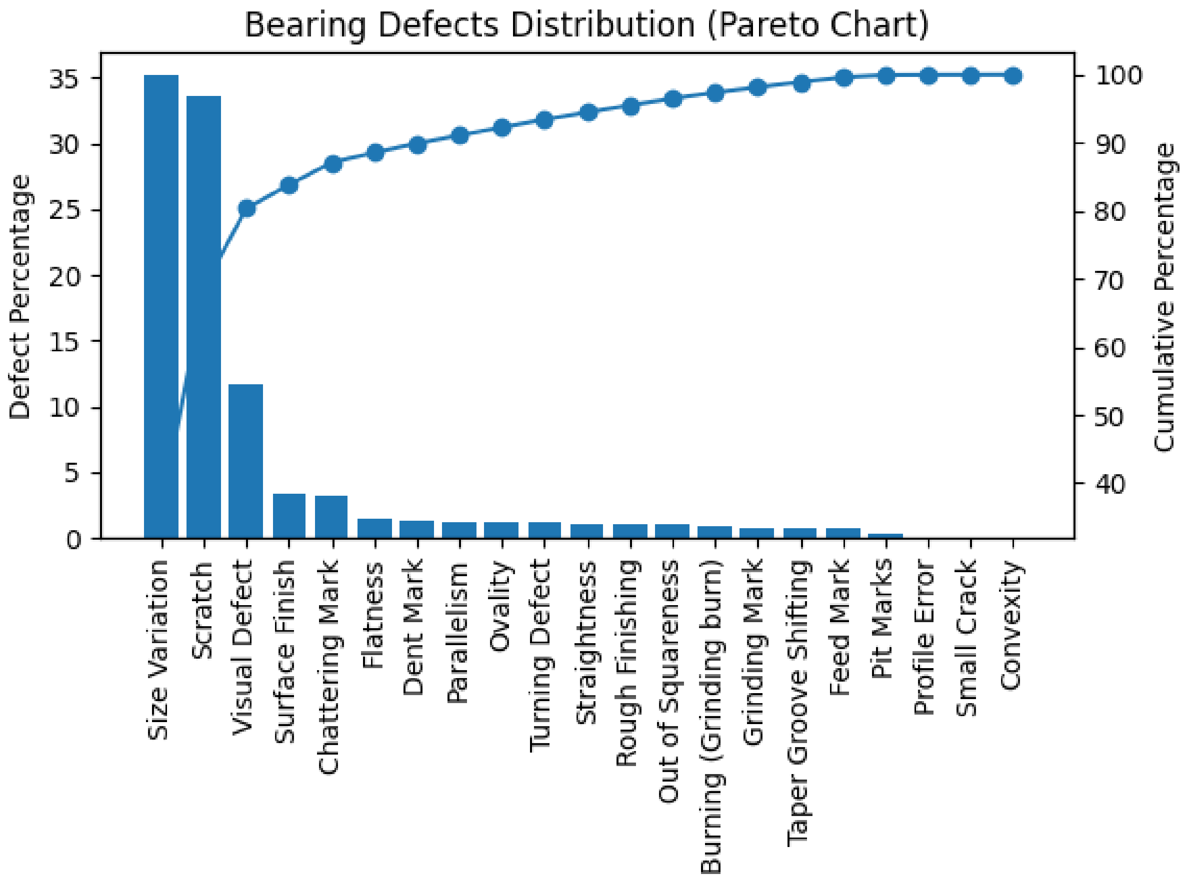

Fig 1. Pareto Chart Bearing manufacturing defects distribution pattern [1–29]

Significant technological advancements have been adopted in contemporary bearing manufacturing, while several emerging technologies remain in developmental stages. Notably, the application of additive manufacturing, including three-dimensional (3D) printed bearings, is an evolving area of research, alongside ongoing advancements in bearing materials. An ideal bearing material must exhibit high toughness, corrosion resistance, wear resistance, thermal stability, and superior fatigue strength to withstand demanding operational conditions. In this paper, globally adopted methods, processes, techniques, and technologies for bearing manufacturing are systematically reviewed with a focus on process improvement, quality enhancement, and productivity optimization. The study presents a comprehensive analysis of manufacturing methods, measurement and inspection techniques, quality and productivity improvement frameworks, simulation and mathematical modeling approaches, statistical analysis tools, and recent technological advancements relevant to bearing manufacturing.

1.1 Limitations of Past Literature

1. The literature reviews discuss bearing manufacturing, but the discourse is limited to single areas (i.e. Six Sigma, machining, or automation).
2. There is a complete lack of a synthesis that represents a combination of technological progress and modern production methods, as well as Industry 4.0 implementation.
3. The relationship between digital tools and productivity, quality improvement, and defect mitigation is still limitedly covered.
4. There is no systematic comparison in terms of impediments of the processes, source of defects, measurement uncertainty, or readiness to digital transformation.
5. Still, the fact remains that although there are technological-based studies but do not form a holistic industrial framework on which to build behavioural improvement.

1.2 Need for the Present Review

It is a review that incorporates the traditional issues and the modern solutions in one coherent framework (Figure 2).

1. It correlates process-improvement tools, automation, and Industry 4.0 practices with measurable results.
2. It outlines a common research agenda to be used in future studies on bearing manufacturing.
3. It highlights real problems of industry and suggests solutions.

1.3 Gap Mitigation

1.3.1. Integrative Scope

1. The framework is a synthesis of bearing manufacturing issues and innovative solutions using technology, which avoids a disjointed review in favour of a unified one.
2. It encompasses Six Sigma, lean tools, simulation, automation, and Industry 4.0 in an integrated analysis paradigm.

1.3.2. Gap to Solution Mapping

1. It also matches the particular industrial points, such as defects, bottlenecks, uncertainty, rework, with customized improvement tools and digital tools.
2. It associates process weaknesses with technologies like IoT monitoring, digital inspection, predictive analytics, and 3D printing.

1.3.3. Practical Industrial Applicability

1. The construct presents a process-technology fit framework which helps firms decide the best locus, rationale, and implementation plan to use interventions.
2. It goes beyond the theoretical expositions to anchor the insights on real manufacturing situations and measurable KPIs.

1.3.4. Research Framework Contribution

1. Coherent structure: proposal provides a structure towards future research, implementation plans, and performance development in bearing manufacturing.
2. It supports the path of modernization through the gradual systematic process of assimilation into Industry 4.0 principles.

The Six Sigma DMAIC methodology has been widely applied as an effective framework for process improvement within the bearing manufacturing industry. A case study reported in [2] investigated the machining of bearing inner and outer races using CNC machines, wherein process capability analysis was conducted using Minitab software. The study employed the DMAIC approach to assess quality performance and simultaneously evaluate cost reduction potential, demonstrating the effectiveness of structured quality improvement methodologies in bearing production.

To analyze the influence of various process parameters on measurement uncertainty, an experimental investigation was carried out in [3]. In this study, real-time in-process measurement techniques were utilized for process optimization. The experimental results and associated measurement uncertainties were analyzed using the Monte Carlo simulation method, providing a robust statistical basis for uncertainty evaluation and process control in precision bearing manufacturing.

In [4], a machine vision–based inspection system was introduced for automated bearing defect monitoring within a production line, eliminating the need for human intervention. By employing image processing techniques and a novel inspection algorithm, the system enabled surface inspection of bearings and facilitated the detection of defects such as deformations, rust, and surface scratches, thereby enhancing inspection accuracy and consistency.

Several researchers have focused on the development of advanced manufacturing methods for bearing rings and rollers. In [5], a highly efficient Trenpro machining process for bearing rings was discussed, with particular emphasis on hybrid machining approaches that integrate hard turning and rolling operations. This hybrid methodology was shown to improve machining efficiency and surface integrity in bearing components.

Structural identification methods have also been implemented in bearing manufacturing for production planning, product design, and process planning activities. As reported in [6], this approach facilitates the selection of optimal activities across different hierarchical levels of the manufacturing process, enabling the identification of an optimal manufacturing path and supporting more effective decision-making.

A simulation-based software model for identifying bottlenecks in bearing production lines was developed in [7]. Through detailed process analysis; the model enables the evaluation of resource utilization, the frequency of technical issues, and the

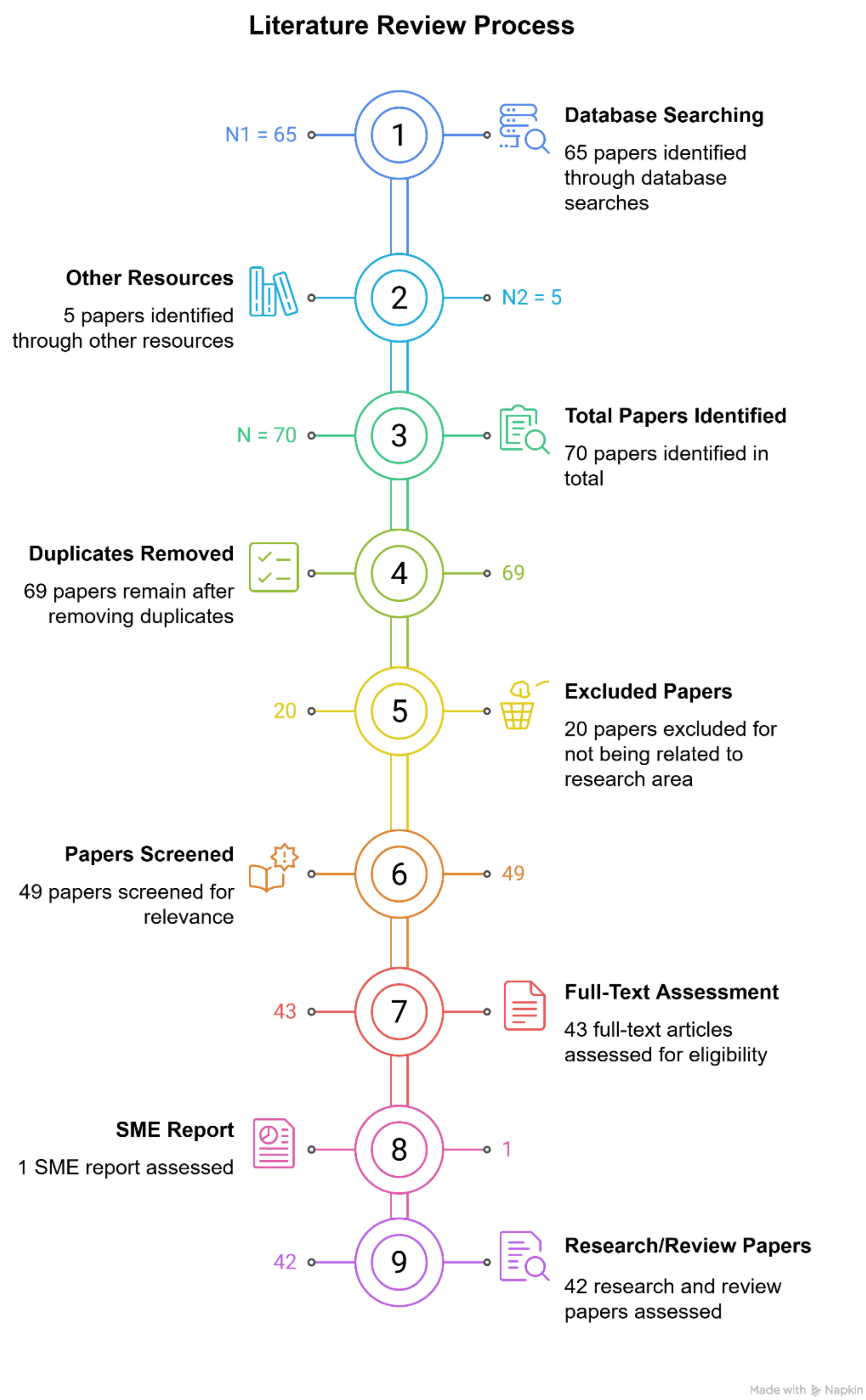

Fig 2. Literature selection process: meta- analysis flow chart [1–47]

impact of external factors on production performance. Such simulation-based tools provide valuable insights for strategic planning and operational improvement in bearing manufacturing systems.

The integration of Supervisory Control and Data Acquisition (SCADA) and IoT-based systems in pneumatic press machines for engine bearing manufacturing has been explored in[8]. This automation framework enables real-time data monitoring and control, resulting in reduced production cycle time, minimized maintenance requirements through fault indication, and enhanced worker safety.

Furthermore, the practical application of Value Stream Mapping (VSM) in the bearing industry for process improvement has been presented in[9]. VSM facilitates the visualization and evaluation of all manufacturing processes, while the implementation of lean manufacturing principles contributes to the reduction of work-in-progress inventory, production lead time, and overall waste.

One of the surveys, as reported in[10], investigated the bearing manufacturing industry in India with keen focus given to the existing manufacturing operations, processes, materials and technology. The authors also projected their research on the global level, outlining the special role of small- and medium-sized businesses and highlighting the strategic value of the partnership with international manufacturers as the means of transferring technologically and undergoing industrial rejuvenation.

A case study is presented in[11] devoted to the improvement of operational efficiency in the automotive manufacturing plant that is an ancillary, with the specific focus on the manufacturing of engine thrust bearings. By the use of the time-study methods, optimization processes, and the simulation techniques, the research determined the most important operations in the surviving manufacturing system. The suggested model brought the measurable results of the increased productivity and operational effectiveness.

The article presented in[12] proposed a simulation-based production improvement model that was specific to the tapered roller bearings manufacturing. Through the concept of the plant simulation as the analytical centre, the authors developed the systematic procedure of the project that involved the choice of products, the control of materials through the belt conveying systems, the analysis of the system, and the optimization of the suggested production plan. The practical results provided the testament of practical usefulness of the simulation-based resolutions in improving the efficiency and capacity of production.

Oil-free, high-speed turbo-machinery deployment e.g. micro turbines and turbo expanders require the invention of foil bearings, which is extremely challenging on technical grounds. In this regard,[13] examined how Multi Jet 3-D printing which is an additive manufacturing process can be used to fabricate bearings. Evaluations were done experimentally with a wide range of bump-foil geometries and the results were confirmed by exhaustive numerical modeling of the additive manufacturing tool using the finite-elements approach, thus bringing to the limelight the feasible potential of additive manufacturing in bearing applications of the future.

The researchers suggested a procedure that would enhance quality inspection and monitoring of plain bearing material used in internal combustion engines[14]. It combines thermal simulations with many thermo physical parameters, and uses its specific software to trace the temperature distribution and the material thickness, a strategy that will enable the quality assurance of bearing material significantly.

A framework operationalised in Six Sigma DMAIC was used in[15] to enhance process capability and the overall manufacturing performance in the production of bearings. To balance the bottleneck parameters of a process and reduce the amount of work going to waste, the methodology combined the statistical methods which were Design of Experiments and Taguchi robust design. It is worth mentioning that the work has shown significant positive changes in process capability indices (Cp and Cpk) of critical-to-quality characteristics that confirm the effectiveness of the improvement of processes with the participation of Six Sigma.

The second variant of hot extrusion indicated in[16] aims at the strengthening of the bonding between aluminium and lead grains in bearing materials of high-powered car engines. Compared to traditional sintering processes, the suggested process drastically increases fatigue strength, load carrying capacity and interfacial bonding properties.

The article[18] discussed the possibility of implementing Industry 4.0 technologies in the sphere of bearing production. The authors outlined how the basic Industry 4.0 enablers, that is, the Internet of Things, advanced robotics, automation, data analytics, and cyber-physical systems, could be used to the production of intelligent interconnected bearing products.

The stopwatch-based time-study methods were used in the assessment of production performance in the bearing manufacturing as realized in[19] through the use of Overall Equipment Effectiveness (OEE) measures. Results highlighted the second-best resource allocation, prudent automation and organized ways of problem-solving to enhance manufacturing performance and operational efficiency.

The additive manufacturing studies to create bearing cages, reported in[20], shed light on the possible advantages, and at the same time showed that the process requires further tuning so that it can ensure the consistency of the part quality and the improved surface finishes, which is a reminder of the ongoing issues in industrial implementations.

Offered an organized structure of the systematic implementation of Industry 4.0 technologies in various units of a medium-sized enterprise bearing manufacturing company [21]. The research suggested a renewed plant design with the use of IoT-enabled devices and cyber-physical systems, and it was argued that the major improvements in productivity and quality might be reached due to the systematic implementation of Industry 4.0.

In [22], the digitalization of the bearing production line was fitted with sensing components in defect recognition during the grinding process and monitoring of the condition of the grinding wheels. The hardware-software system that was used was the integrated version that came with predictive algorithms that could determine waviness on the surface and any thermal damage in the work pieces and, therefore, provide a possibility of proactive quality control during manufacturing.

The instrumental contribution of Industry 4.0 technologies, such as IoT, big data analytics, cloud computing, additive manufacturing, and blockchain, to strengthening the supply chain during the COVID-19 pandemic, was emphasized in a systematic literature review in [23]. It was also noted in the review how these technologies reduce disruptions, increase real-time visibility, and strengthen risk management, as well as identify gaps in terms of sustainability integration, performance metrics, and data security.

Using the Technology-Organization-Environment (TOE) paradigm [24], studied the factors that influenced the adoption of Industry 4.0 in the manufacturing industry in Bangladesh. Empirical data showed that the market pressure and support provided by government, as well as decision making being supported by technology are primary catalysts, and organizational strategy and leadership have a strong positive effect. The results also showed that Industry 4.0 implementation mediates performance increase, which support the assertiveness of the feasibility of the TOE framework in the new economies.

Similarly, [25] empirically confirmed a TOE inspired model of innovation with compatibility, top-management support, and competitive pressure as the critical determinant of Industry 4. 0 adoption. The findings showed that the performance benefits are indirectly expressed through product and process innovation and global involvement in trade moderated the results; the internationally involved firms gained higher benefits as a result of process innovation.

Lastly, artificial intelligence, IoT, big data analytics, and cloud computing are the most popular Industry 4.0 technologies that drive Quality 4.0 initiatives on the list of topics covered by the literature review in [26]. The paper put forward a four-dimensional Quality 4.0 framework that entailed digitalization, predictive quality management, mass personalization, and intelligent quality control, and has also simultaneously clarified persistent issues related to data security, complexity of integration, and human factor.

Researchers carried out a systematic review that identified a collection of data-inspired methods, i.e. Agile methodologies, Value Stream Mapping, process mining, simulation, multi-criteria decision-making, and big data analytics, as part of the Quality4.0 paradigm [27]. The authors furthered a unified DMAIC-based model that aims to reduce the shortcomings of disjointed ones, supplying real-time analytics, increased flexibility, and continuous upgrades providing Industry 4.0 settings.

In a similar effort, the reference [28] conducted a systematic review of Quality 4.0 with an emphasis on the paradigm-shift provided by the quality control of data-driven quality management. The researchers found substantive research gaps, such as the lack of empirical case studies, insufficient numbers of economic analyses, and difficulties in combining these new methods with the current quality standards, e.g. ISO 9001 criterion.

2 REVIEW METHODOLOGY

2.1 Review Methodology

2.1.1. Review Type

To create a connection between the old methodologies of traditional improvement e.g. Six Sigma, Lean, Statistical Process Control (SPC) and automation, additive manufacturing, and Quality4.0 and new technologies like the Internet of Things (IoT), Cyber-Physical Systems (CPS) is used with the help of systematic literature review (SLR) that is supplemented by narrative synthesis.

2.1.2. Search Strategy

Literature sources referenced may be published after 1997, most of the literature reviewed was published after 2019.

1. Time Span: 1997–2025
2. Screening Process: Title and Abstract to Full Paper Assessment.

The criteria used to include and exclude studies were as follows:

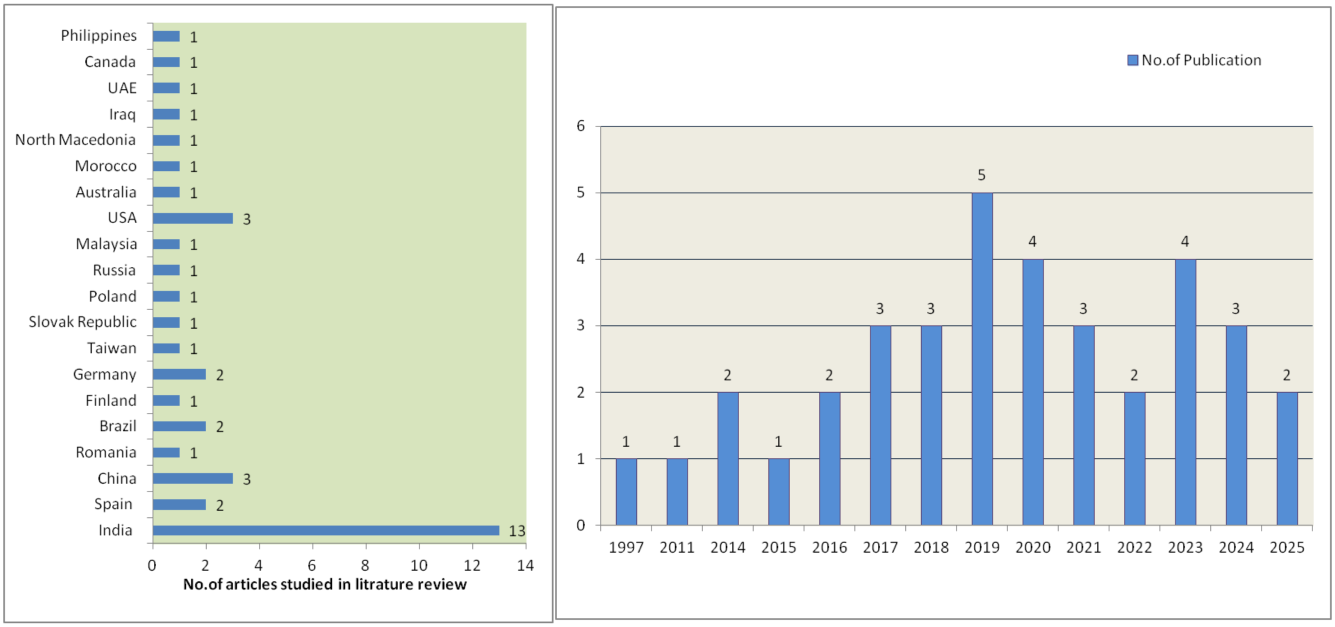

Fig 3. Geographical distribution of research articles [1–47] and Year-wise articles studied [1–47]

Type of literature studied: Peer-review/conference proceedings, empirical case study, Patents, business blogs, Non-reviewed reports.

Focus Area: Manufacturing, inspection, assembly, automation, Industry 4.0

2.1.3. Quality Assessment

Each paper was evaluated for:

1. Industrial relevance
2. Clarity of methodology
3. Measurability and validity of data.
4. Evidence of improvement (e.g., 10 -45% fewer defects, 12 -25% increased productivity)
5. Bearing manufacturing environmental applicability.

Only studies that demonstrated such valid improvements were selected.

2.1.4. Data Synthesis Framework

The identified literature was thematically compiled into five areas:

1. Process Improvement Tools
2. Measurement Technology Inspection Technology
3. Advancements in Shop-floor Systems.
4. Industry 4.0 and Digital Integration.
5. Additive Production/Material Innovation.

The novelty of this review is found in the fact that it considers disparate elements, which have been considered separately in the previous works. It provides a integrative viewpoint where manufacturing issues, improvement systems, and Industry 4.0 systems are discussed in one logical framework. As opposed to the evaluation of methodologies as a stand-off unit, the paper clarifies the relationships between the two and describes how they can be applied and what the benefits are to the bearing of production. This review integrates traditional manufacturing with modern techniques, including Six Sigma, lean, automation, simulation, and Industry 4.0 into a single, cohesive model, which has not been done in the past reviews.

It presents a problem-to-solution mapping system that coordinates industrial problems (defects, bottlenecks, uncertainty, reworks) with the particular tools and digital technologies of improvement. And unlike earlier research where individual tools are considered separately, the current review suggests a sequence in which the tools can be modernized to reflect the conceptions of the IoT-enabled data-driven and smart manufacturing platform to which traditional bearing units can develop.

It provides a logical source of choosing approaches, technologies, and performance tactics in accordance with the specific stages of bearing production. The review serves as a roadmap to research and an implementation guide in industries thus making it very practical in application in addition to theoretical applicability.

The following are the main challenges in bearing manufacturing and the contemporary level of research discussed by the review

1. The lack of a coherent source that connects conventional manufacturing operations with Industry 4.0 – implementations.
2. High rate of defects, rework and rejection due to uncontrolled process factors and variability of measurements.
3. Bottlenecks and delays in machining, inspection, assembly, heat-treatment, etc.
4. Low implementation of online monitoring, automation, and predictive analytics of real-time decision making.
5. Lack of ability to choose appropriate improvement methods because of the divided literature and scattered solutions.
6. Insufficient guidance in the industries that are moving out of the traditional systems and into the smart and data-driven and modernized environments of bearing manufacturing.

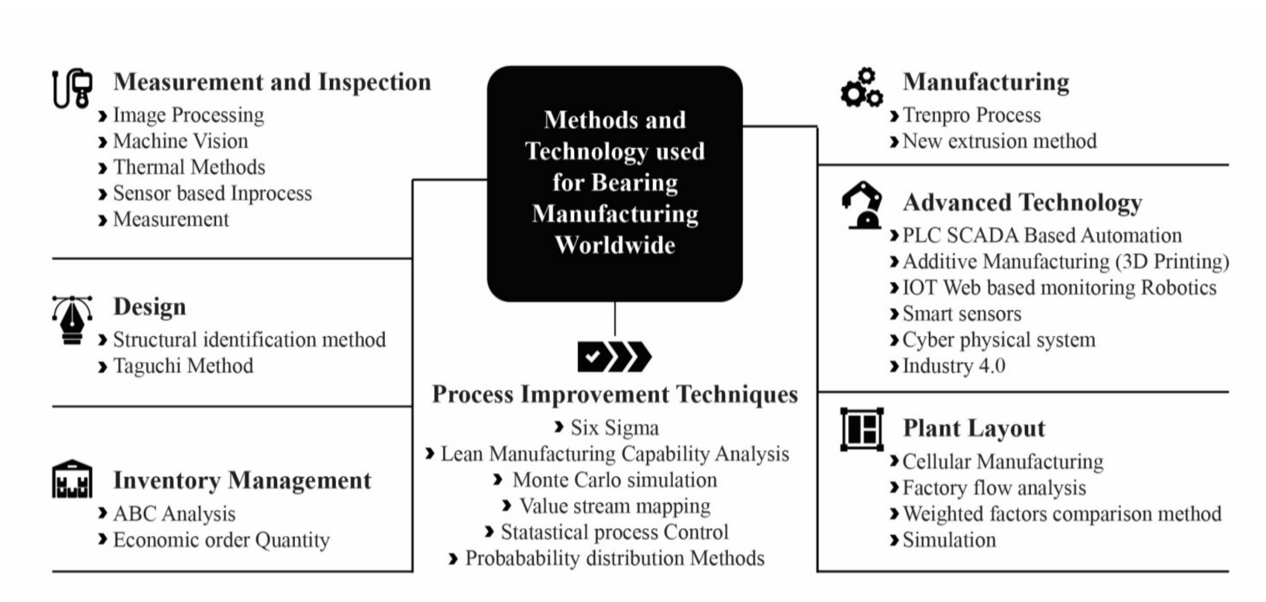

Fig 4. Methods and Technology used for bearing manufacturing worldwide [1–28]

3 OVERVIEW

Table 1. Summary of globally used Tools, processes, Technology and methods for bearing Manufacturing [2] - [29]

Component / product / Parts	Specific Area	Research purpose	Supporting Method or Technology	Software used
Bearing cage and Inner ring	Manufacturing	Process Improvement	Used Six Sigma DMAIC and Capability Analysis to increase rate of production. [2]	Minitab [2]
Bearing Outer ring	Manufacturing and Inspection	Process Improvement	Monte Carlo simulation and Inprocess measurement. [3]	GoldSim, MiniTab [3]

Continued on next page

Table 1 continued

Bearing	Inspection	Introduced technology up gradation	Image processing and machine vision based bearing defect identification. [4]	—
Bearing	Manufacturing	Technology up gradation/Introduce	Introduced Trenpro process in bearing manufacturing. [5]	—
Bearing	Design and Manufacturing	Process Improvement	Optimization and Structural identification method for bearing manufacturing. [6]	—
Bearing	Manufacturing and Inspection	Process Improvement	Simulation, Process Optimization, Identification of bottlenecks,Kolmogorov – Smirnov test-Probability distribution method. [7]	Arena [7]
Bearing	Assembly, Safety	Automation and Productivity improvement	Created a PLC-based automation system for a pneumatic pressing machine utilized in an engine-bearing manufacturing plant. [8]	—-
Bearing	Manufacturing	Water reduction	Applied value stream mapping method with lean manufacturing concept in bearing manufacturing industry for reduction in the WIP (Work in progress) & Production lead time. [9]	—
Bearing	Manufacturing	Technology Study	Recent scenario scope and need of technology up gradation in bearing manufacturing industry. [10]	—
Bearing	Manufacturing	Simulation	Presented study on Simulate the manufacturing process for the existing plant layout of production line. Developed a Simulation based model to minimize the time taken for production. [11]	GPSS Program [11]
Bearing	Manufacturing	Production Simulation and optimization	Proposed a method to improve bearing production using simulation technique. [12]	Siemens PLM (Product Lifecycle Mngt) Tecnomatix [12]
Bearing-Bump foil	Manufacturing	3D Printing	MultiJet Printing 3D Printing technology used for manufacturing of a bump foil – a key part of foil bearings used for high speed applications such as turbo machines. [13]	—-
Plain Bearing	Quality assessment	Thermal method for bearing thickness measurement	Developed a system for monitoring changes in plain bearing thickness and utilized thermal methods to assess the material quality of plain bearings in internal combustion engines. [14]	—-

Continued on next page

Table 1 continued

Bearing	Manufacturing and QC	Six Sigma DMAIC	Taguchi Method is applied for finding the effects of process parameters on process capability of bearing manufacturing process using six sigma technique.[15]	MiniTab[3]
Bearing	Manufacturing	New Extrusion method	Researcher study shows that bearing made from new extrusion method have more fatigue strength compare to conventional extrusion method.[16]	–
Bearing	Measurement	Technology up gradation	Developed the test setup which measures the Radial Clearance of ball bearing during assembly process.[17]	—
Bearing	Manufacturing	Industry 4.0	Suggested Industry 4.0 techniques like cyber physical system, IOT and cloud computing techniques to improve efficiency of bearing manufacturing plant.[18]	–
Bearing	Manufacturing	Time study and Motion study	A case study related to bearing assembly process is discussed. OEE is improved by identifying time consuming activities and solutions are given for a particular problem.[19]	–
Bearing	Manufacturing	3D Printing	Used additive manufacturing methods including fabrication to make the bearing cages. It is challenging to achieve good surface quality.[20]	—
Bearing	Manufacturing	Industry 4.0	Suggested plant layout of Smart bearing factory and various techniques of Industry 4.0 used to improve productivity and quality of manufacturing. Discussed the guidelines and various factors affecting while implementing industry 4.0.[21]	—
Bearing	Inventory Management	ABC analysis and EOQ	Used inventory management technique to find out the optimum level of inventory orders.[29]	–

Table 2. Summary of major issues in bearing manufacturing and suggested solution.[1] - [29]

Year	Manufacturing Process	Type of bearing	Bearing parts associated with it	Major issues	Advancements offered
2018	Machining	Tapered Roller Bearings	Outer race	Manufacturing and Measurement uncertainty.	Process improved using Monte Carlo simulation and In process measurement.[1]
2021	Machining	Rolling Contact Bearing	Bearing cage and Inner ring	Defects during machining, process variability size variation.	Process improvement using Six-Sigma DMAIC methodology.[2]

Continued on next page

Table 2 continued

2021	Trenpro process	Roller bearing	Inner and Outer race	Less productivity : Small-batches production requires long adjustment times.	Introduced high efficient machining process with merging hard turning and rolling process. [5]
2020	Conventional Bearing manufacturing process including assembly, inspection, machining	Rolling Contact Bearing	Inner race,Outer race and rolling elements	Selecting optimal activities and defining optimal technological path from different levels of the manufacturing process.	Structuring of manufacturing activities at all levels. [6]
2021	Assembly Inspection and Lubrication	Deep groove ball bearing	Inner race, Outer race and rolling elements	Bottlenecks in the production line.	Developed simulation model to indentify bottlenecks in the bearing manufacturing process. [7]
2018	Assembly	Engine bearing	Entire Bearing	Time consuming process and manufacturing delay.	Designed and developed PLC based automation system to reduce operation time. [9]
2014	Annealing and ,Machining	Not specified	Inner race,Outer race and rolling elements	Higher cycle time and WIP.	Reduced total processing time by implementing value stream mapping tool. [10]
2023	——	Half engine bearing	Entire Bearing	High resource spoilage,rework and rejection.	Enhanced the process capability of bearing manufacturing through the application of the Six Sigma DMAIC methodology. [15]
2019	Additive manufacturing	Foil bearings	Entire Bearing	Production Difficulties	Proposed a new method of manufacturing using 3D printing technology. [16]
2016	Assembly	Antifriction bearings, roller bearings, Ball Bearing	Inner race, Outer race and rolling elements	Smoothen the radial clearance measurement process.	Created a technique to measure the radial clearance of rolling bearings mounted on a shaft, both before and after assembly. [17]
2015	—-	Roller Bearing	Cone and Inner race	Time consuming activities and high cycle time of cone filling.	Implemented automated Poka yoke system for bearing inspection and Introduced automatic cone filling machine to reduce cone filling time. [29]

Table 3. Critical Analysis of Literature [30] - [34]

Objective and Criterion	Key Strength and Limitations	Impact on Quality and Cost Implications	Work force Impact and Data Usage
Industry 4.0 **Digitalize the manufacturing shop floor with implementing automation and IOT based systems.**	**Key Strength** Real time process monitoring, data driven quick decision making [30], data analytics, reduces paper work. **Limitations** Difficult to implement in Conventional machineries which does not supports and adapt digitalization [30] and Cyber security.	**Impact on Quality** Reduces defects and rework by implementing predictive maintenance, condition monitoring, In-process measurement. **Cost Implications** High initial cost for Technology and Infrastructure establishment	**Work force Impact** Trained and skilled manpower required **Data Usage** Real time process data

Continued on next page

Table 3 continued

Six Sigma **Reduce the defect in manufacturing process and improves the quality.**	**Key Strength** DMAC approach deeply studies the causes of defect and its controlling methods. **Limitations** Time consuming process and slow to impalement, Software and Statistical tools required.	**Impact on Quality** Improves the quality by finding root cause of defect and suggest changes in existing methods. **Cost Implications** High cost and more time required to train the Technical team and managers.	**Work force Impact** Specialized and Experience technical team required for finding causes of defects. **Data Usage** Raw production data and historical data
Lean manufacturing **Reduce the waste in manufacturing process with continuous improvement [31].**	**Key Strength** Reduce the production cost with customer satisfaction, Supports both mass and craft production, Maximizing the effective utilization of the workforce's skills [32]. **Limitations** Difficult to prepare standard framework to reduce waste. Requires huge time for implementation and improvement.	**Impact on Quality** Improves quality with using TPM and TQM approach. **Cost Implications** Lower investment and shorter development time compare to conventional mass production. [32]	**Work force Impact** Training programs required at different level of employees. **Data Usage** Accurate functional data required.
Value Stream mapping **Improves the manufacturing performance by reducing the waste.**	**Key Strength** Represents the visualization of process flow diagram which clearly focuses on finding the bottlenecks. **Limitations** Time consuming process, Labour intensive and limited scope.	**Impact on Quality** Improves quality by eliminating bottlenecks and deeply studying process flow. **Cost Implications** Low cost but time consuming.	**Work force Impact** Experience Technical team requires who having the skills of process assessment and process control. **Data Usage** Data collection required from Process Observation sheet and past production data to understand the process flow.
Capability analysis **Assess the current performance of manufacturing process in terms of quality and productivity by analysing production Process data.**	**Key Strength** Indicates the variations in manufacturing and measurement processes, Highlights the scope of process improvement , Shows Graphical representation with Predefined standards, Important to develop process control methods. **Limitations** Variety of data required, Collection of past production data required, Requires special software to perform capability analysis.	**Impact on Quality** Capability analysis is a important tool used with quality improvement techniques like Six sigma, Lean Manufacturing and MSA. **Cost Implications** Moderate but Need to purchase software and Time consuming process.	**Work force Impact** Experienced Technical team required to analyse processes. **Data Usage** Raw Production data, Qualitative and Quantitative data.

Continued on next page

Table 3 continued

Statistical process control **To monitor and control process variations for ensuring consistent quality and productivity.**	**Key Strength** Shows overall performance and highlights the issues in process, Supports data driven decision making and Data analytics. **Limitations** Requires deep statistical knowledge and depends on software solutions.	**Impact on Quality** Improves quality by reducing defects, process variability and customer satisfaction. **Cost Implications** High initial cost for training of technical persons, Cost savings by reducing waste and rework.	**Work force Impact** Requires a team expertise in data analysis and easy to use statistical software. **Data Usage** Raw Production data and Quantitative data
Additive Manufacturing **Make a physical object layer by layer from 3D digital model with using Computer Aided Design software and 3D Printer.**	**Key Strength** Reduces waste, Smoothly Manufactures Complex geometries compares to traditional manufacturing, Rapid design and manufacturing. **Limitations** Speed of 3D printing affects on mass production [33], Material constraints also present a substantial obstacle [33], More research required to make complex components and material's strength.	**Impact on Quality** Need advanced methods and techniques for inspection and testing to achieve quality, Consistency in quality depends on selection process parameter. **Cost Implications** More initial cost as it requires Advanced design software and 3D Printer, Less operational cost by reducing wastage of material.	**Work force Impact** Needed Technical staff with CAD model designing skills and machine operational skills. **Data Usage** Continuous and real time process data collection improves the performance and data analytics.
Cellular Manufacturing **Smoothen the manufacturing process flow with proper designing of layout using Group technology.**	**Key Strength** Reduces setup time and cycle time [33],Reduces the floor space and material handling time [33].Reduces bottlenecks during production. **Limitations** Difficult to integrate with existing working system and challenging when product variety changes at specific interval specially in batch production.	**Impact on Quality** Reduces defects with proper quality control and supervision. **Cost Implications** Reduces material handling cost, inventory cost and inspection cost as well as capital investment [34].	**Work force Impact** Teamwork and required instant communication between workers and supervisor. **Data Usage** Real time data and data analytics helps to reduce cycle time and optimize cell performance.

3.1 Enhancement observed

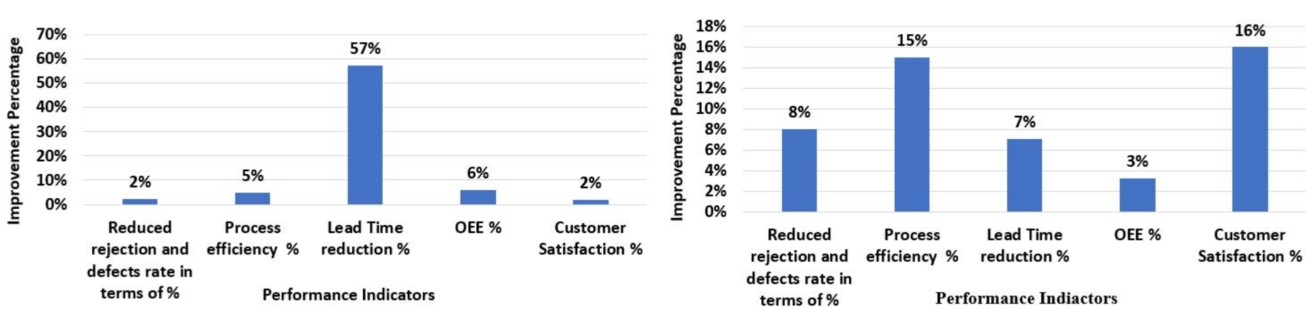

Fig 5. Improvement observed in KPIs after implementing Six Sigma [35–37] and Improvement observed in KPIs after implementing Lean Manufacturing [38–41]

4 INDUSTRY 4.0 IN BEARING MANUFACTURING

The Fourth Industrial Revolution offers significant technological advancements that enhance overall manufacturing efficiency, improve product quality, and reduce equipment downtime. Industry 4.0 technologies—including IoT-based condition monitoring, cyber-physical systems, advanced robotics, artificial intelligence, additive manufacturing (3D printing), digital manufacturing, and smart automation systems—can be effectively implemented in bearing manufacturing plants to minimize defects and improve Overall Equipment Effectiveness (OEE). Empirical observations indicate that several reputed manufacturing organizations have achieved substantial increases in production rates following the adoption of IoT-enabled, web-based monitoring systems. The percentage improvements realized through the implementation of Industry 4.0 technologies are illustrated in Figure 6.

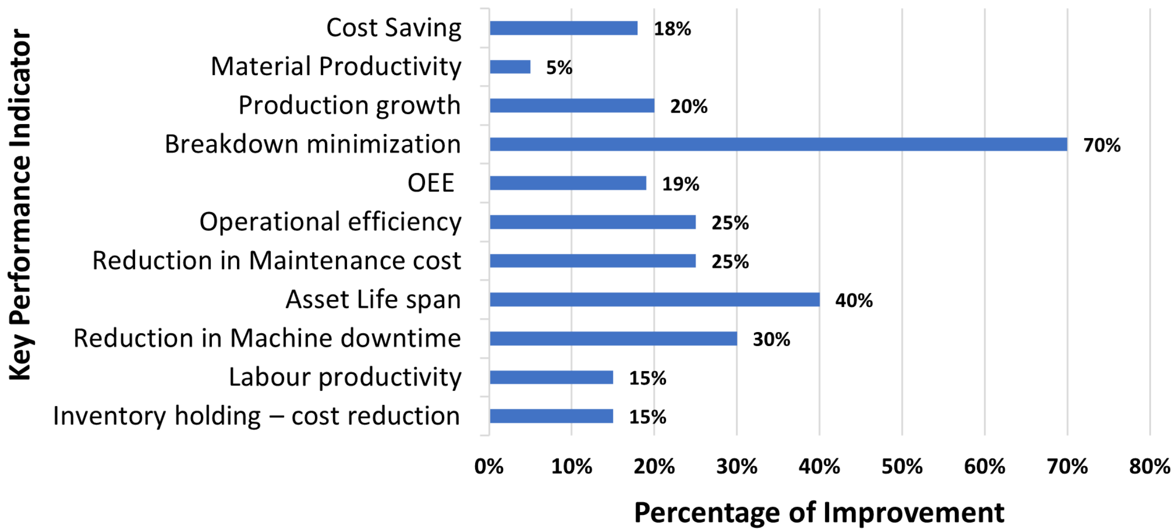

Fig 6. KPI improvement noted with implementing I 4.0 Techniques (42–47)

5 CONCLUSION

This study critically investigates conventional process improvement tools Six Sigma, lean, SPC and VSM and the new technologies: IoT monitoring, simulative planning of the processes, machine-vision inspection, additive manufacturing and Industry 4.0 implementation. The analysis has proven that the implementation of new advanced methods can bring measurable benefits, the level of defect elimination can be decreased by 30-45 % through the application of DMAIC-based practices, the level of productivity can be boosted by 12-25 % through the use of digital monitoring and automation, and the Overall Equipment Effectiveness can improve by 10-18 % when IoT-enabled systems are implemented in manufacturing process. A 6.62 % of O.E.E. improvement is observed while implementing IoT based process monitoring system in manufacturing process of bearing with significant improvement in quality and performance of the machine. The findings indicate the novelty of the review, as it contains a consistent framework that connects challenges of processes with particular technologies and performance indicators. However, the review also admits that there are some limitations: no large-scale industrial validation, differences in outcomes in various manufacturing situations, reliance on qualified staff to do digital integration, and the limited availability of consolidated cost-benefit information. In this regard, future studies are advised to focus on real-time experimental validation in the operational plants, cost modelling of Industry 4.0 application, cyber-physical integration with old equipment, the creation of model AI-predictive defect devices, and the production of a sequential digital transition roadmap that is specific to bearing industries based on MSMEs.

Table 4. Suggested Framework for reducing defects and rework by implementing Industry 4.0 methods in Bearing Manufacturing Industry

Department	Process	Concern Bearing Part	Machine / Equipment	Common defects or Bottlenecks	Suggested I 4.0 Techniques
Production	External Grinding	Cylindrical Roller Inner Race Outer Race	External Grinding Machine	Scratch, Improper Surface finish, Size variation, Chatter marks, Burning, Rough finishing, Grinding mark, Burning	IOT web based monitoring of process by installing sensors Parameters required to monitor : 1) Vibration 2) Cutting Temperature 3) Cutting fluid temperature 4) Speed of Wheel 5) wheel wear rate 6) Cutting speed and feed
Production	External Grinding	Cylind. Roller Inner/ Outer Race	External Grinding Process	Less Productivity and Improper Quality	Develop O.E.E dashboard which continuously monitors the process using IoT based monitoring system with data driven decision making.
Assembly	Riveting Process	Inner & outer race, cage,rolling ele.	Mechanical Punch Press	Cage Bending Cage Marking Rivet Missing Faulty Rivet	IOT web based monitoring of Parameters by installing sensors Parameters required to monitor 1) Vibration 2) Punch force and Cutting force 3) Punch velocity
Heat Treatment	Carburi., Harden., tempe., Subzero treatment	Inner & outer race, Rolling ele	Shaker hearth furnace	Scaling, Burning-Overheating, Expansion, Shrinkage, Hardness, Porosity	IOT web based monitoring and PLC based controlling of Temperature by installing Thermal sensors.

6 ACRONYMS

Always Better Control(ABC); Three-dimensional (3D printing); Nondestructive testing (NDT); United States dollar (USD);Computerized Relationship Layout Planning (CORELAP); Value Stream Mapping (VSM), Process Capability (Cp); process capability index (Cpk); Define, Measure, Analyze, Improve, and Control (DMAIC); General Purpose Simulation System (GPSS); Programmable Logic Controller (PLC);Supervisory Control and Data Acquisition (SCADA);Computer numerical control (CNC);Computerized Relative Allocation of Facilities Technique (CRAFT); Statastical process control (SPC); Statistical process control (SPC); Quality Control (QC) ;WIP (Work In Progress); MSME (Micro,Small,Medium Enterprises) ;Statistical process control (SPC) ;Flow Chart(FC);Industry 4.0 (I4.0) ; Computer Aided Design (CAD) ;Three dimensional Printer (3D Printer) ;Total Quality Management (TQM);Total Productive Maintenance (TPM) ;Measurement System Analysis (MSA) ;(Define,Measure,Control and Analyze (DMAC) ;Internet of Thing (IOT),Overall Equipment Effectiveness (O.E.E),Key Performance Indicator (KPI)

7 ACKNOWLEDGEMENTS

The authors are thankful to Mr.Bharat Khunti, Production Engineer, Austin Engineering Company, Junagadh; Harshad Sinroja, Quality Assurance Engineer,Austin Engineering Company, Junagadh; SurajParmar, H.R.Manager, Austin Engineering Company, Junagadh ; Nasir Patta, Assistant Manager, H.R.Department, Austin Engineering Company and Mr.Pankaj Saroliya, Chief Engineer, Max Bearing, Sapur, Dist., Junagadh for providing continuous and endless support in research survey. The authors record their gratitude to Mr.Amit Gohel, Director and Mr.Jaivik Dhebar,Junior Engineer, Eleics Design Private Limited, Gandhinagar.

References

1) Research P. Bearing market, Report description. 2024 June. Available from: https://www.precedenceresearch.com/bearingmarket#:~:text=The%20global%20The%20bearing%20market,8%25%20from%202023%20to%202032.
2) Bhargava M, Gaur S. Process Improvement Using Six-Sigma (DMAIC Process) in Bearing Manufacturing Industry: A Case Study. *IOP Conference Series: Materials Science and Engineering*. 2021;1017(1):012034. 10.1088/1757-899X/1017/1/012034.
3) Brosed FJ, Zaera AV, Padilla E, Cebrián F, Aguilar JJ. In-process measurement for the process control of the real-time manufacturing of tapered roller bearings. *Materials*. 2018;11(8). 10.3390/ma11081371.
4) Shen H, Li S, Gu D, Chang H. Bearing defect inspection based on machine vision. *Measurement: Journal of the International Measurement Confederation*. 2012;45(4):719–733. 10.1016/j.measurement.2011.12.018.
5) Mehmet I, Dogan G, Chitariu DF, Dumitraş C, Negoescu F. Research on advances in roller bearing manufacturing. *IOP Conference Series: Materials Science and Engineering*. 2021;1182(1):012045. 10.1088/1757-899X/1182/1/012045.
6) Afteni C, Frumusanu GR, Afteni M, Paunoiu V. Structural identification of the bearing manufacturing process - Case-study. *IOP Conference Series: Materials Science and Engineering*. 2020;968(1):012015. 10.1088/1757-899X/968/1/012015.
7) de S Souza LMA, da Silva AM, de Souza JM, Bueno RC, Machado ST, Tanaka WY. A simulation-based approach to identify bottlenecks in the bearing manufacturing process. *Independent Journal of Management & Production*. 2021;12(9):s843–s855. 10.14807/ijmp.v12i9.1635.
8) Singh R, Verma HK. Development of PLC-Based Controller for Pneumatic Pressing Machine in Engine-Bearing Manufacturing Plant. *Procedia Computer Science*. 2018;125:449–458. 10.1016/j.procs.2017.12.059.
9) Saraswat P, Kumar D. Application of Value Stream Mapping Tool to Reduce Wastes in Bearing Industry. *International Journal of Recent Advances in Mechanical Engineering*. 2014;3(4):97–103. 10.14810/ijmech.2014.3409.
10) on Bearing Industry TSR. nd. Available from: https://web-dcmsme.gov.in.
11) Natarajan AR. The Design of a Novel Bearing Manufacturing Line Based on Simulation. *American Journal of Operations Research*. 2016;6(6):425–435. 10.4236/ajor.2016.66039.
12) Malega P, Kadarova J, Kobulnicky J. Improvement of production efficiency of tapered roller bearing by using plant simulation. *International Journal of Simulation Modelling*. 2017;16(4):682–693. 10.2507/IJSIMM16(4)10.405.
13) Zywica G, Bagiński P, Andrearczyk A. A new method of manufacturing a foil bearing using tools made by the rapid prototyping technology. *CIRP Journal of Manufacturing Science and Technology*. 2020;31:514–524. 10.1016/j.cirpj.2020.08.003.
14) Salikhov RF, Akimov VV, Musagitova GN, Negrov DA. A method of quality control of plain bearings by their thermophysical properties. *Journal of Physics: Conference Series*. 2019;1260(6):062021. 10.1088/1742-6596/1260/6/062021.
15) Kulkarni T, Toksha B, Shirsath S, Pankade S, Autee AT. Construction and Praxis of Six Sigma DMAIC for Bearing Manufacturing Process. *Materials Today: Proceedings*. 2023;72:1426–1433. 10.1016/j.matpr.2022.09.342.
16) Ogita Y, Ido Y, Sakamoto M. Improvement of Aluminum-Lead Bearings by New Manufacturing Method. *SAE Technical Paper Series, International Congress and Exposition, Detroit, Michigan*. 1990. 10.4271/900123.
17) Meier N, Georgiadis A. Automatic Assembling of Bearings Including Clearance Measurement. *Procedia CIRP*. 2016;41:242–246. 10.1016/j.procir.2015.12.110.
18) Patkar KS, Panchpor JU, Vaidya SM. Industry 4.0: Implementation in Bearing Manufacturing. *International Journal of Current Engineering and Technology*. nd;9(1):45. 10.14741/ijcet/v.9.1.6.
19) Patel N. Reduction in product cycle time in bearing manufacturing company. *International Journal of Engineering Research and General Science*. nd;3(3). Available from: http://www.ijergs.org.
20) Richardson B, Love L, Tate JG. Additive Manufacturing for Low Volume Bearings. 2017. Available from: http://www.osti.gov/scitech/.
21) Manan BR, Hirenkumar J. Categorical framework for implementation of industry 4.0 techniques in medium-scale bearing manufacturing industries. *Materials Today: Proceedings*. 2022;65:3531–3537. 10.1016/j.matpr.2022.06.090.
22) Gaspar V, Romeo JA, Cebrian F, Camacho AM, García-Manrique JA. Digitalization of an Industrial Process for Bearing Production. *Sensors*. 2024;24(23):7783. 10.3390/s24237783.
23) Reza MNH, et al. The implications of Industry 4.0 on supply chains amid the COVID-19 pandemic: a systematic review. *F1000Research*. 2022;10:1008. 10.12688/f1000research.73138.2.
24) Al-Amin A, et al. The adoption of Industry 4.0 technologies by using the technology organizational environment framework: The mediating role to manufacturing performance in a developing country. *Business Strategy and Development*. 2024;7(2):e363. 10.1002/bsd2.363.
25) Zhong Y, Moon HC. Investigating the Impact of Industry 4.0 Technology through a TOE-Based Innovation Model. *Systems*. 2023;11(6):277. 10.3390/systems11060277.
26) Hafid A, Sebtaoui FE, Mouchtachi A. Evaluating the impact of industry 4.0 technologies on quality management systems: applications, challenges, and future directions. *International Journal of Advanced Manufacturing Technology*. 2025;139:3637–3655. 10.1007/s00170-025-16122-5.
27) Baiochi R, Lizot M, Santos EAP. A review of quality improvement framework for industry 4.0. *Procedia CIRP*. 2025;132:13–18. 10.1016/j.procir.2025.01.003.
28) Saihi A, Awad M, Ben-Daya M. Quality 4.0: leveraging Industry 4.0 technologies to improve quality management practices – a systematic review. *International Journal of Quality & Reliability Management*. 2023;40(2):628–650. 10.1108/IJQRM-09-2021-0305.
29) Pujara A, Makwana P, Prajapati P. Reduction in Capital Requirement through Adoption of Inventory Management for Bearing Manufacturing Industry: A Case Study. *61st National Convention of Indian Institution of Industrial Engineering & 5th International Conference on Industrial Engineering (ICIE-2019)*. 2019. Available from: https://www.scribd.com/document/939083963/FullICIE2019SuratProceedingBookDrRaviKant.
30) Anackovski F, Nusev S, Pasic R. Impact of Industry 4.0 on Achieving Operational Excellence in Lean Production: Real Time OEE Monitoring System. *TEMTEL-ij*. nd;4(2). Available from: https://www.researchgate.net/publication/354896616.
31) Bhamu J, Sangwan KS. Lean manufacturing: literature review and research issues. *International Journal of Operations & Production Management*. 2014;34(7). 10.1108/IJOPM-08-2012-0315.
32) Dankbaar B. Lean production: denial, confirmation or extension of socio-technical systems design? *Human Relations*. 1997;50(5):567–583. 10.1177/001872679705000505.
33) Zhou L, Miller J, Vezza J, Mayster M, Raffay M, Justice Q, et al. Additive Manufacturing: A Comprehensive Review. *Sensors*. 2024;24:2668. 10.3390/s2409266.

34) Sakran HK, Mahbuba HM, Jafer AS. A review of a basic concept of cellular manufacturing. *International Journal of Design and Manufacturing Technology (IJDMT)*. 2017;8(1):30–37. 10.34218/IJDMT.8.1.2017.004.
35) Mittal A, Gupta P, Kumar V, Owad AA, Mahlawat S, Singh S. The performance improvement analysis using Six Sigma DMAIC methodology: A case study on Indian manufacturing company. *Heliyon*. 2023;9(3):e14625. 10.1016/j.heliyon.2023.e14625.
36) Widiwati ITB, Liman SD, Nurprihatin F. The implementation of Lean Six Sigma approach to minimize waste at a food manufacturing industry. *Journal of Engineering Research*. 2024;7:1–16. 10.1016/j.jer.2024.01.022.
37) Gomaa AH. Improving Supply Chain Management Using Lean Six Sigma: A Case Study. *International Journal of Applied and Physical Sciences*. 2023;9:9–25. 10.20469/ijaps.9.50002.
38) Habib MA, Rizvan R, Ahmed S. Implementing lean manufacturing for improvement of operational performance in a labeling and packaging plant: A case study in Bangladesh. *Results in Engineering*. 2023;17:100818. 10.1016/j.rineng.2022.100818.
39) Barrientos-Ramos N, Tapia-Cayetano L, Maradiegue-Tuesta F, Raymundo-Ibañez CA. Lean Manufacturing Model of Waste Reduction Using Standardized Work to Reduce the Defect Rate in Textile MSEs. *18th LACCEI International Multi-Conference for Engineering, Education, and Technology*. nd.
40) Haddad T, Shaheen BW, Németh I. Improving Overall Equipment Effectiveness (OEE) of Extrusion Machine Using Lean Manufacturing Approach. *Manufacturing Technology*. 2021;21(1):56–64. 10.21062/mft.2021.006.
41) Onaga-Nishimura AS, Rosa-Reyna NADL, Collao-Diaz MF, Ruiz-Ruiz MF. Service Management Model Based on Lean Service and Systematic Layout Planning for the Improvement of Customer Satisfaction in an SME in the Restaurant Sector in Peru. ACM. 2022. 10.1145/3568834.3568853.
42) Company M. Capturing the true value of Industry 4.0. 2025 Mar. Available from: https://www.mckinsey.com/capabilities/operations/our-insights/capturing-the-true-value-of-industry-four-point-zero.
43) SAP. What is Industry 4.0? 2025 Mar. Available from: https://www.sap.com/india/products/scm/industry-4-0/what-is-industry-4-0.html.
44) Psico-Smart. The impact of IoT on real-time performance evaluation systems and tools. 2025 Mar. Available from: https://psico-smart.com/en/blogs/blog-the-impact-of-iot-on-realtime-performance-evaluation-systems-and-tools-162329.
45) bdullatif Ben Hassan, Abdul-Kader W. Contribution of Industry 4.0 to OEE Improvement. IEOM Society. 2020. Available from: http://www.ieomsociety.org/detroit2020/papers/592.pdf.
46) Fernandez JR, Prasetyo YT, Persada SF, Redi AANP. Automation of predictive maintenance using internet of things (IoT) technology-based O&M project. *International Journal of Information and Education Technology*. 2021 Jul;11(7). 10.18178/ijiet.2021.11.7.1531.
47) Rane SB, Wavhal S, Potdar PR. Integration of Lean Six Sigma with Internet of Things (IoT) for productivity improvement: a case study of contactor manufacturing industry. *International Journal of System Assurance Engineering and Management*. 2023 Oct;14(5):1990–2018. 10.1007/s13198-023-01980-7.