
An Exploratory study on CNC machine Technologies, Barriers and Opportunities on adopting Industry 4.0: A Review

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Abstract: Industry 4.0 represents a complete digital transformation in the way companies operate, incorporating advanced technologies. It includes or integrates new technological advances such as Additive Manufacturing, Artificial Intelligence, Augmented Reality, Cyber-physical systems, Blockchain, Cybersecurity and other technologies. While Industry 4.0 and similar technologies offer many conceivable benefits for production, automated machines are essential for driving industries forward. This article proposes an exploratory investigation in the adoption of Industry 4.0 by CNC machine users, focusing on main barriers and opportunities, exploring the challenges faced by these companies and identifying the potential opportunities arising from adoption. It is based on an exploratory systematic review of the literature. The consolidated factors were grouped into categories to help understand the challenges faced by companies in the transition to Industry 4.0. This research identified several barriers for companies using CNC machines, while also highlighting numerous opportunities related to the adoption of Industry 4.0.

Keywords: CNC; Technology; Industry 4.0; Barriers; Opportunities; Review.

1 Introduction and Conceptual Background

Industry 4.0 has significant implications for CNC (Computer Numerical Control) machining, introducing various technologies that enhance automation, efficiency, and connectivity in the manufacturing process (Sang and Xu, 2017; Adu-amankwa *et al.*, 2019). Industry 4.0 for CNC machines will come from the integration of all the productive resources of manufacturing, which will be managing many production orders, which must be synchronized between several production centres, ordering the manufacturing, of the same order simultaneously, guaranteeing customer service (Couto, 2019; Büchi *et al.*, 2020). The incorporation of Advanced Robotics, Machine-Machine Connection Systems, the Internet of Things and the Sensors and Actuators used in these equipment enables machines to “talk” throughout industrial operations. This can allow the generation of information and the connection of the various stages of the value chain, from the development of new products, projects, production, to after-sales (Couto, 2019; Pratina, Sudha and Suresh, 2020)

Industry 4.0 is primarily based on 'Cyber-Physical systems', based on data and its use in knowledge integration (Wang, Törngren and Onori, 2015; Leitão, Colombo and Karnouskos, 2016; Pratina, Sudha and Suresh, 2020). Also, Industry 4.0 and similar technologies offer many conceivable benefits for production and automated machines are essential for driving industries forward (Zhou, Liu and Zhou, 2016; Büchi *et al.*, 2020; Engineers Ireland, 2020). In the context of Industry 4.0, CNC (Computer Numerical Control) machines are becoming increasingly advanced and interconnected, incorporating various technologies to enhance efficiency, automation, and data exchange, such as: Data Integration and Connectivity; Advanced Automation; Machine Learning and AI; Customization and Flexibility; Cybersecurity; or Human-Machine Collaboration (Neto, 2018; Herwan *et al.*, 2019a; Martinov, Ljubimov and Martinova, 2020). So, these considerations constitute the motivation for an exploratory investigation into CNC machine technologies, focusing on main barriers and opportunities in the adoption of Industry 4.0, and exploring the challenges highlighted by these studies and identifying the potential opportunities arising from this adoption. Additionally, we will examine the main technologies used and the behaviour of countries with high, upper, middle, and lower incomes regarding the adoption of Industry 4.0 with CNC machines.

Research published between 2019 and 2023 was reviewed to summarize the barriers and opportunities faced by companies around the world. So far, most studies have been a) focused on the particular barriers faced for the adoption of Industry 4.0 not related to CNC Machines e.g. (Uchihiro *et al.*, 2015; Zhou, Liu and Zhou, 2016; Chen *et al.*, 2020); b) have focused on analyzing some specific technologies on CNC machines not directly related to the adoption of Industry 4.0 (Aduamankwa *et al.*, 2019; Herwan *et al.*, 2019a; Martinov, Ljubimov and Martinova, 2020); c) have demonstrated the potential benefits of I4.0 for companies e.g. (Elhusseiny and Crispim, 2021; Government of Ireland, 2022, 2023); d) focused on the particular barriers faced by CNC machines related to the adoption of the Industry 4.0 e.g. (Sung and Carlsson, 2003; Mourtzis *et al.*, 2018a; Herwan *et al.*, 2019a). The scope of the review was defined by the following research questions (RQ):

RQ1: What are the main barriers preventing the adoption of Industry 4.0 with CNC machines?

RQ2: What are the main opportunities for Industry 4.0 adoption with CNC machines?

RQ3: What are the main technologies implemented to CNC machines on the adoption of Industry 4.0?

2 Research Approach

The research approach, based on a systematic literature review, has followed the recommendations of (Siddaway, Wood and Hedges, 2019) that is divided on three steps: 1) scope, 2) planning (through PRISMA following (Moher *et al.*, 2009)), and 3) study quality (Fig.1), based on the approach/proposals from (Elhusseiny and Crispim, 2021). The research was based on a systematic search to find all relevant papers that could answer RQ1, RQ2 and RQ3. The inclusion and exclusion criteria used in the research are described on Table 1, based on the approach/proposals from (Elhusseiny and Crispim, 2021).

The selected research terms were taken from recent studies related to CNC, and Industry 4.0 (Fig.1) [Title/Abstract]: "CNC" OR "Computer Numerical Control" AND "Industry 4.0" OR "I4.0" OR "Fourth industrial revolution" OR "Digitalization" OR "Smart Manufacturing". The main platform databases used during the research were B-ON from University of Minho, which includes access to the main scientific databases (including Web of Science, Scopus, Business Source, DOAJ, and many others including the main scientific editors), Science Direct and Emerald Insights. The research returned 877 documents and 47 articles were eligible for full reading and inclusion in the research review.

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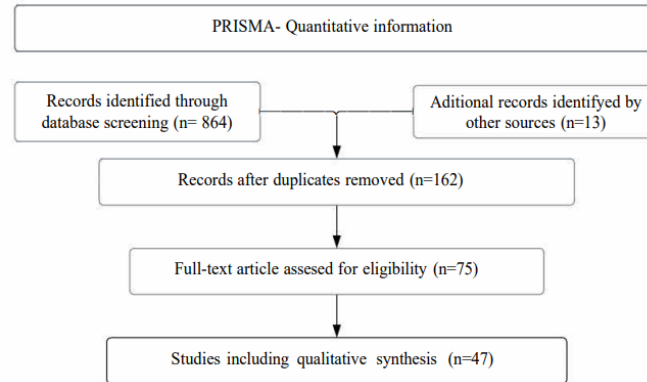


Fig. 1. PRISMA

The following table synthesises the selection process.

TABLE I. EXPLANATION OF THE CRITERIA USED

Exclusion/ Inclusion	Criteria	Explanation
Exclusion	NR- Not Related	NR1- Research result was not matching with this study
		NR2- Studies about I4.0 and not related to CNC machines
		NR3- Not related to academic paper.
	LR- Loosely Related	LR1- I4.0 generally discussed
		LR2- I4.0 is only used as a reference
		LR3- I4.0 challenges not related to CNC
		LR4- CNC challenges not related to I4.0
		LR5- I4.0 opportunities not related to CNC
		LR6- CNC opportunities not related to I4.0
Inclusion	CR- Closely Related	CR1- Research paper is mainly dedicated to I4.0 adoption contributed to CNC
	PR- Partially Related	PR1- Opportunities/Challenges related to I4.0 and CNC
		PR2- Studies related to Opportunities/Challenges of adopting of I.4 technologies for CNC e.g., IoT/AR/Cloud-computing
		PR3- I4.0 adoption using technologies for implementation CNC machines discussed or surveyed or reviewed

3 Classification of the opportunities and barriers

At the heart of modern manufacturing, CNC machines are the foundation of precision engineering, shaping raw materials into complex components with unparalleled precision. As industries evolve in the wake of the Fourth Industrial Revolution, the synergy between CNC technologies and Industry 4.0 presents a compelling narrative of innovation and transformation. This article embarks on an in-depth exploration of the world of CNC machine technologies, dissecting the barriers that prevent their perfect integration into the industry 4.0 panorama and consequently highlighting the main opportunities. The adaptation of CNC machines from the traditional use of CNC machines to the concept of Smart Manufacturing can bring many benefits to companies such as increasing productivity, collecting data in real-time and reducing costs, but they also require investment and change in work culture. Trained workers, high costs and general vision of the future are some of the obstacles for many companies.

We start by presenting and synthesising the opportunities identified in the literature review.

3.1- Classification of the opportunities

Table II shows the classification and definition of the opportunities mentioned on the studies analysed.

TABLE II. CLASSIFICATION OF THE OPPORTUNITIES

Opportunities	Classification
Real-time data	Instant data collection optimizes efficiency, minimizes errors, aids decision-making, and opens avenues for numerous industry benefits.
Efficiency	Accurate data enhances operations, reducing machine downtime and enhancing overall efficiency during manufacturing processes.
Cost effectiveness	Strategic data utilization reduces costs; efficient planning, maintenance insights, and smart resource allocation lead to substantial savings.
Vertical integration	Integration within enterprises, utilizing technologies like Augmented Reality, streamlines communication, enhances control, and improves quality.
Horizontal integration	Adoption of IT, IoT, and Big Data Analytics fosters market competitiveness, enhances efficiency, expands market access, and boosts revenue.
Automation	Automated data collection, connecting production to the cloud, eliminates operator intervention, ensuring seamless and efficient data gathering.
Predictive analytics	Analysing historical and real-time data enhances efficiency, minimizes downtimes, and improves the final product quality in CNC machine operations.
Proactive maintenance	Access to real-time machine data optimizes maintenance planning, preventing reactive actions, reducing costs, and ensuring proactive maintenance strategies.
Sustainability	Industry 4.0 technologies promote waste reduction, recycling, and energy efficiency, contributing significantly to sustainable manufacturing practices.
Interconnectivity	Flexible data models enable seamless interconnection between software, machines, and sensors, facilitating internal data exchange and analysis.

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System adaptability	Application of new technologies enhances existing methods, enabling adaptability in manufacturing systems, especially in real shop floor scenarios.
Standardization	Technology resolves communication inconsistencies, integrating CNC systems into Smart manufacturing environments by harmonizing protocols and data formats.
Data reliability	Advanced technologies ensure complete, accurate data transmission, enhancing reliability and trust, even in challenging internet environments.

3.2- Classification of the barriers

Also, the study of CNC machine technologies in the context of Industry 4.0 is a fundamental examination of the meeting of traditional processes with innovation, of mechanical precision converging with digital intelligence, because the smart factory concept is a fundamental answer to dramatic changes in business that require information to be increasingly faster and of better quality. With this, we investigated the complexities of CNC systems, deciphering the main barriers and challenges faced or mentioned by studies. The classification of the barriers analysed on the studies can be seen on Table III.

TABLE III. CLASSIFICATION OF THE BARRIERS

Challenges	Definition
Lack of Knowledge	Limited understanding of Industry 4.0 technologies and processes. Inexperience with new technologies causes slow digitization, hindering collaborative maintenance.
Infrastructure	Outdated CNC machines lack competence for modernization. Adapting to smart manufacturing poses challenges due to high costs and technical gaps.
High Cost	Replacing old machinery demands significant investment, straining small businesses. Costs extend beyond structural changes, requiring substantial human resource investments.
Lack of Standardization	Obsolete CNC machines lack the capacity to modernize. Adapting to smart manufacturing involves challenges due to high costs and technical gaps.
Investment	Inadequate management of investment decisions, lacking knowledge in equipment replacement and cybersecurity. Insufficient prevention measures contribute to future problems.
Skilled Employees	Increasing complexity in industry 4.0 demands skilled operators. Manual processes hinder data accuracy. Operators miss relevant data, affecting capacity and production efficiency.
Data Security	Advanced machine learning in CNC faces cybersecurity challenges. Vulnerable control systems risk unauthorized access, potentially causing irreversible economic and safety losses.
Management Decision	Lack of systematic approach hampers business digitization. Absence of integration standards further delays IT system investments.
Lack of Methods and Tools	Insufficient understanding of Industry 4.0 and lacking transformation tools, especially for SMEs. Limited knowledge impedes comprehensive process optimization.

4 Discussion and Results

Through thoughtful research and analysis, we uncover the technical complexities, organizational obstacles, and skills gaps that prevent the full adoption of Industry 4.0 principles in CNC machining.

During the research it was possible to analyse four main points, which include the main barriers, the main opportunities, the main technologies. A look at regional characteristics was also made. In this study, “technology” is referring to the types of technologies, type of process and individual combinations of technological systems presented to the implementation of Industry 4.0 on CNC machines. Additionally, we will show how was the most mentioned barriers and opportunities by region, considering the high, upper, medium, and lower income countries, following the definition of (World Bank Group, 2017). Those points are summarized on Table IV, which includes all the articles selected according to the criteria presented in Table 1.

TABLE IV. BARRIERS, OPPORTUNITIES, TECHNOLOGIES, COUNTRIES

No.	Ref	Technology	Barriers	Opportunities	Country
1	(Jandyal <i>et al.</i> , 2022)	FDM- Fusion Deposition Modeling	High cost, Lack of standardization	Automation, Horizontal integration, Vertical integration, Cost effectiveness, Sustainability	India
2	(Karnik <i>et al.</i> , 2022)	AR- Augmented reality	Lack of Knowledge, Data security, Skilled employees	Automation, Efficiency	India
3	(de Paula Ferreira <i>et al.</i> , 2022)	Process Management	Lack of Knowledge, Infrastructure, Lack of methods and tools, Hight cost	Interconnectivity, Efficiency, Cost effectiveness	Canada
4	(García, Bregon and Martínez-Prieto, 2022)	Process Management	Lack of Knowledge, Infrastructure, skilled employees	Flexibility, Automation	Spain
5	(Böttjer <i>et al.</i> , 2023)	CAD	Lack of Knowledge, Lack of standardization, Infrastructure	Automatization, Efficiency, Sustainability	Denmark
6	(Korkmaz <i>et al.</i> , 2022)	AI	Not mentioned	System adaptability, Efficiency, Automation	Spain
7	(Okwudire <i>et al.</i> , 2020)	Cloud-based	Infrastructure	Cost effectiveness	USA
8	(Romulo G. Lins <i>et al.</i> , 2020)	IoT	Infrastructure, Lack of standardization, Skilled employees	System adaptability, real-time data, Cost effectiveness, Vertical integration	Brazil
9	(Deveci <i>et al.</i> , 2022)	SMART-CNC, Qu4lit, IoT, MTConnect	Hight cost, Lack of standardization	Cost effectiveness, Efficiency	Turkey
10	(Lu, Kumaravelu and Okwudire, 2019)	Cloud-based	Infrastructure	Data reliability, Cost effectiveness, Standardization	USA
11	(Mourtzis <i>et al.</i> , 2018b)	AR- Augmented reality	Not mentioned	Horizontal integration, Vertical integration, Real-time data	Greece

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12	(Eswaran and Bahubalendruni, 2022)	AR- Augmented reality, VR- Virtual Reality	Infrastructure, Lack of standardization	Horizontal integration, Vertical integration, Real-time data	India
13	(Martins <i>et al.</i> , 2023)	OPC UA	Lack of Knowledge, Lack of standardization, High costs	Standardization, Automation, Horizontal integration	Portugal
14	(Ali Laghari and Mekid, 2023)	IoT	Lack of Knowledge, High Cost	Real-time data, Sustainability, Quality of the product	Saudi Arabia
15	(Al-Naggar <i>et al.</i> , 2021)	IoT	Not mentioned	Proactive maintenance planning, Real-time data, Automation	Malaysia
16	(Corallo, Lazoi and Lezzi, 2020)	Cybersecurity	Hight cost, Data security	NOT MENTIONED	Italy
17	(Czvetkó <i>et al.</i> , 2022)	IoT, AI, ML,	Investment, Management decision	Predictive analytics, Optimization, Vertical integration, Horizontal integration	Hungary
18	(Sayyad <i>et al.</i> , 2021)	AI, Big-Data, Cloud-based,	Infrastructure, Lack of knowledge, Investment	Proactive maintenance planning, Cost effectiveness	India
19	(Nguyen-Vinh, Hattotuwa and Dewasurendra, 2023)	CAD, CAM	Not mentioned	Automation, Efficiency	Vietnam
20	(Mourtzis, Angelopoulos and Dimitrakopoulos, 2020)	CAD, UR10 Robot Arm- Cell collaboration	Infrastructure, Lack of knowledge, Investment	Automation	Greece
21	(Martins <i>et al.</i> , 2021)	OPC UA	Investment	Vertical integration, Real-time data	Portugal
22	(Shukla <i>et al.</i> , 2021)	OPC UA, AI, DT	Skilled Employees, Lack of knowledge	Efficiency	India
23	(Demko <i>et al.</i> , 2023)	OPC UA	Skilled Employees, Lack of knowledge	Cost effectiveness, Efficiency	Slovakia
24	(Cserteg <i>et al.</i> , 2023)	CAD	Skilled Employees, Lack of knowledge	Efficiency	Hungary
25	(ElMaraghy <i>et al.</i> , 2021)	IoT	Not mentioned	Vertical integration, Real-time data, Proactive maintenance planning	Canada
26	(Zheng <i>et al.</i> , 2023)	AI, ML	Not mentioned	Cost effectiveness, efficiency	Switzerland
27	(Araujo, Moreira and Landon, 2023)	SinuCom NC	Not mentioned	Real-Time data	Brazil

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28	(Adetunla and Madonsela, 2021)	Cloud-based	Infrastructure	Horizontal integration, Vertical integration, Cost effectiveness	South Africa
29	(Mauthner <i>et al.</i> , 2023)	CAD, CAM, ML	Lack of standardization	Horizontal integration, Vertical integration	Austria
30	(Ntemi <i>et al.</i> , 2022)	AI, ML	Not mentioned	Cost effectiveness, Efficiency	Greece
31	(Justus and G R, 2022)	Process Management	Not mentioned	Cost effectiveness, Real-time data, Proactive maintenance planning, Efficiency, Sustainability	India
32	(Siddhartha <i>et al.</i> , 2021)	IoT, Cloud-based	Not mentioned	Real-time data	India
33	(Reis <i>et al.</i> , 2023)	AM Additive Manufacturing	Not mentioned	Sustainability	Portugal
34	(Soori, Arezoo and Dastres, 2023)	ML, AI	Data security	Efficiency, Predictive analytics	Turkey
35	(Tran <i>et al.</i> , 2023)	IoT, Cloud-based, ML	Not mentioned	Real-time data	Taiwan
36	(Cui, Kara and Chan, 2020)	OPC UA, ML	Data Security	Real-time data	Australia
37	(Erazo Navas <i>et al.</i> , 2021)	MTConnect	Not mentioned	Real-time data	Colombia
38	(Ullah, Hassan and Ali, 2022)	Process Management	Not mentioned	Real-time data, Predictive analytics, Vertical integration, Sustainability	Ireland
39	(Centea <i>et al.</i> , 2020)	AM Additive Manufacturing	Not mentioned	Efficiency	Canada
40	(Zhao <i>et al.</i> , 2020)	IoT, AI	Lack of Knowledge	Real-time data, Cost effectiveness	China
41	(Haoyu Yu <i>et al.</i> , 2019)	OPC UA	Infrastructure, Lack of standardization	Standardization	China
42	(Herwan <i>et al.</i> , 2019b)	IoT, ML	Not mentioned	Efficiency	Japan
43	(Prathima B A, Suresh P M and Sudha P N, 2020)	IoT, Cloud-based	Hight cost, skilled employees	Real-time data, Automation	India
44	(Tnani, Feil and Diepold, 2022)	IoT, Cloud-based, ML	Not mentioned	Efficiency	Germany
45	(Doyle and Cosgrove, 2019)	Cloud-based	Lack of Knowledge, Management decision, Lack of standardization	Horizontal integration, Vertical integration, Real-time data	Ireland
46	(Doyle and Cosgrove, 2019)	ML	Lack of Knowledge, Investment	Proactive maintenance planning, Predictive analytics	Germany

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47	(Mourtzis, Milas and Athinaios, 2018)	OPC UA	Lack of Knowledge, Investment	Real-time data	Greece
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Each study mentioned one or more barriers on the implementation of industry 4.0 on CNC machines. The most mentioned barriers are related to lack of knowledge appearing in 32% of the studies, infrastructure appearing in 28% of the studies, lack of standardisation appearing in 23% of the studies.

High-cost concerns are evident in several countries, emphasizing the economic challenges associated with adopting advanced technologies. Network infrastructure is identified as a challenge in some countries, highlighting the importance of investing in technological infrastructure to support the adoption of advanced technologies. Lack of standardization is a common barrier, indicating the importance of establishing industry standards to facilitate interoperability and compatibility. Lack of knowledge is a recurring barrier, suggesting the need for educational initiatives and training programs. The Barriers faced by CNC machines for the implementation of Industry 4.0 can be seen on Fig.2.

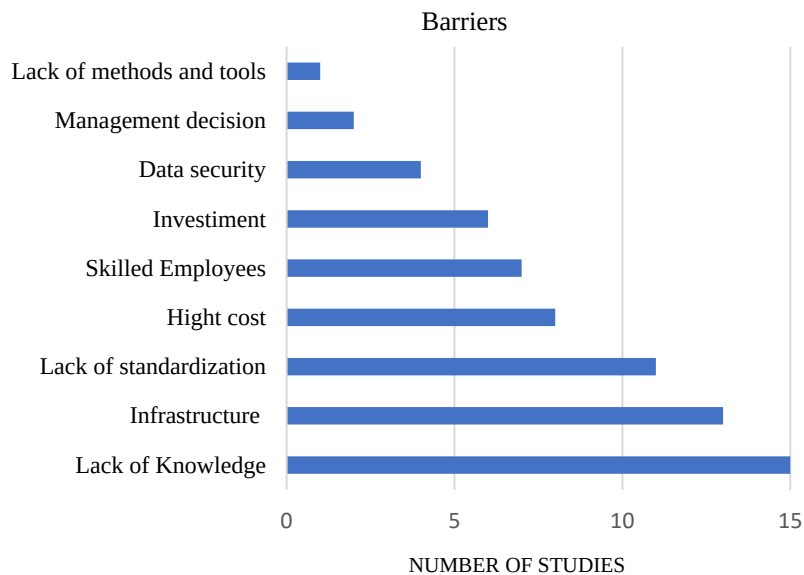


Fig. 2. Barriers for Industry 4.0 implementation on CNC Machines

The opportunities identified suggest a global readiness to embrace Industry 4.0, with a focus on technological integration, efficiency, cost-effectiveness, sustainability, and strategic collaboration. Addressing challenges and strategically leveraging these opportunities can propel the adoption of Industry 4.0 technologies in manufacturing and industrial sectors worldwide. Real-time data utilization is a recurring theme, indicating the potential for harnessing data-driven insights to make informed decisions and improve overall operational efficiency. Opportunities are identified in automation, efficiency, and process optimization. Technologies such as AI, ML, and IoT are repeatedly mentioned in this context, highlighting their potential for enhancing industrial processes. The widespread consideration of Industry 4.0 technologies across different countries signals a global acknowledgment of the importance of advanced manufacturing and smart technologies. Efficiency and real-time data are represented in 40% of the studies, cost effectiveness, vertical integration, and automation are recurrent opportunities mentioned all technologies and counties appearing in more than 25% of the studies. The most occurrences of opportunities in the implementation of industry 4.0 on CNC machines can be seen on Fig.3.

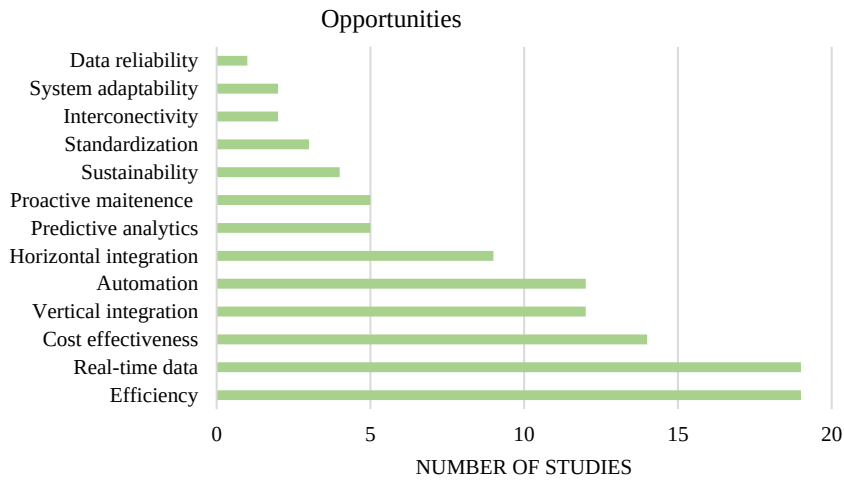


Fig. 3. Opportunities for CNC machines with Industry 4.0 implementation

In summary, the table offers insights into the technological landscape, highlighting both common challenges and opportunities for countries to advance their technological capabilities. The findings can inform strategic decisions, policy formulations, and collaborative efforts to address barriers and foster technological innovation on a global scale. The main technologies presented in the studies were AI/ML, IoT, Cloud-Based, OPC-UA, CAD, and Process management, representing 76.32% of the most implemented technologies contributing to the implementation of Industry 4.0 in CNC machines, as shown in Fig. 4.

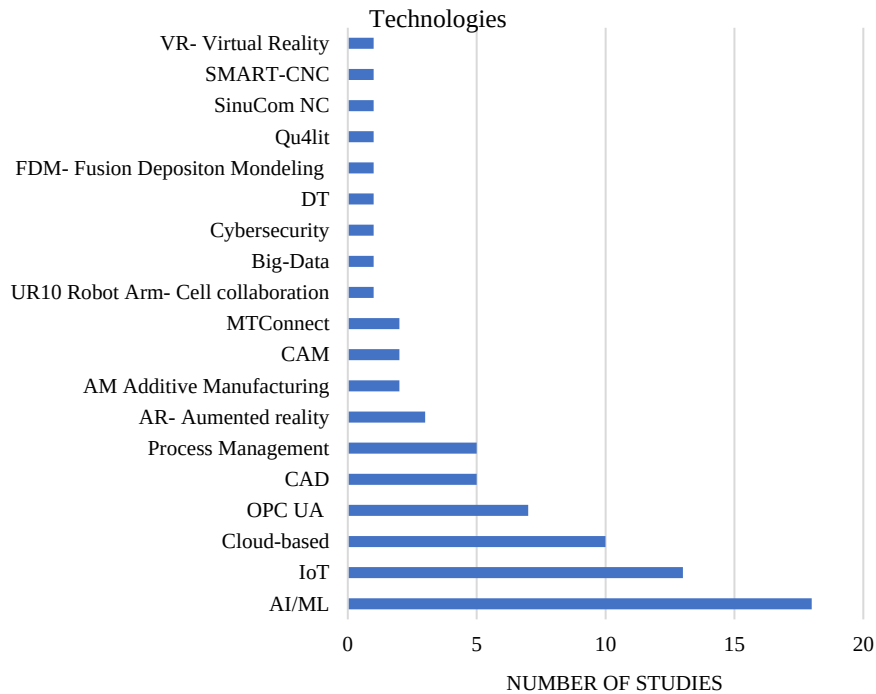


Fig. 4. Technologies presented on the studies

5 Classification of opportunities and barriers by income

Table IV reflects a diverse global technology landscape, with countries across different income levels actively engaging in various technologies. Several studies were conducted using a combination of one or more of these technologies. AI/ML, IoT, Cloud-Based, OPC-UA, and CAD stand out as the primary technologies utilized in the studies, together representing 76% of the technologies studied. This suggests a strong emphasis on these technologies in the context of Industry 4.0.

Many technologies, such as IoT, Cloud-based solutions, AI, and ML, present opportunities for cost effectiveness, efficiency improvements, and real-time data utilization. Technologies such as IoT (Internet of Things), Cloud-based solutions, AI (Artificial Intelligence), and ML (Machine Learning) are prevalent across multiple countries, indicating their universal relevance. The data suggests potential shifts in industries, with a focus on technologies like AR (Augmented Reality), CAD (Computer-Aided Design), CAM (Computer-Aided Manufacturing), and others. These technologies often contribute to automation, efficiency, and integration.

Additionally, analysing the table IV by region, considering the High-income, Upper-income, Medium-income, and Lower-income countries, and following the definition of (World Bank Group, 2017), this work classified the countries into two groups, having in consideration the number of studies, as can be seen on Table V. The first group includes Upper, Middle, and Lower-income countries while the second group consists solely of High-income countries. Typically, high-income countries have more resources to invest in research, as a result, they directly contributed more studies compared to their counterparts in Upper, Middle, and Lower-income categories.

TABLE V. COUNTRIES CLASSIFICATION BY INCOME

Country	Classification
Australia	High-income
Austria	High-income
Canada	High-income
Denmark	High-income
Germany	High-income
Greece	High-income
Hungary	High-income
Ireland	High-income
Italy	High-income
Japan	High-income
Portugal	High-income
Saudi Arabia	High-income
Slovakia	High-income
Spain	High-income
Switzerland	High-income
Taiwan	High-income
USA	High-income
Brazil	Upper, Middle, or Lower-income

China	Upper, Middle, or Lower-income
Colombia	Upper, Middle, or Lower-income
India	Upper, Middle, or Lower-income
Malaysia	Upper, Middle, or Lower-income
South Africa	Upper, Middle, or Lower-income
Turkey	Upper, Middle, or Lower-income
Vietnam	Upper, Middle, or Lower-income

The behaviour of High-income, Upper-income and Middle-lower-income countries concerning Industry 4.0 adoption can vary significantly due to their economic, technological, and infrastructural differences. Higher-income countries typically have more resources to invest in research, development, and implementation of Industry 4.0 technologies. They often lead in innovation and have advanced infrastructures. These countries usually have a highly skilled workforce and better access to quality education, fostering innovation and the development of Industry 4.0 technologies. High-income countries are more likely to adopt Industry 4.0 practices early, leveraging advanced technologies like AI, IoT, and automation to enhance manufacturing efficiency and competitiveness. But, analysing the studies for the implementation on Industry 4.0 on CNC Machines, lack of knowledge, Infrastructure high costs and investment are still the main barriers of the High-Income countries as shown on Fig.5

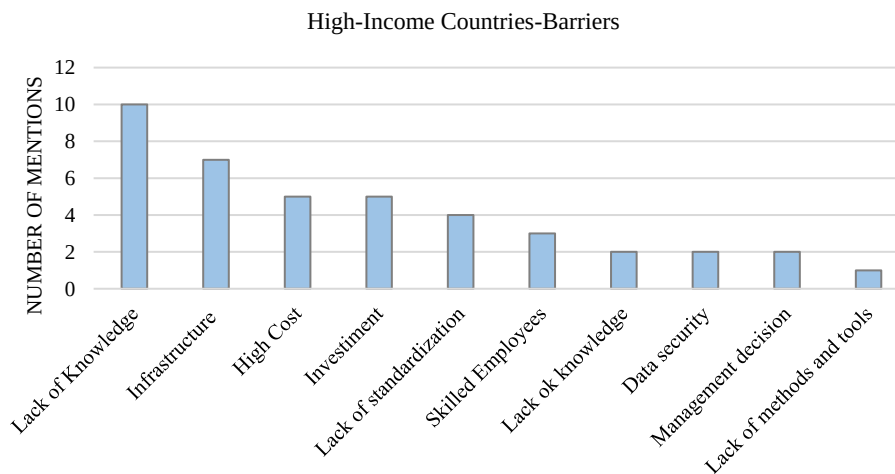


Fig. 5. Barriers for Industry 4.0 implementation on CNC Machines on High-Income Countries.

Upper, Middle, and Lower-income countries often face the challenge of balancing the adoption of Industry 4.0 technologies with other developmental priorities. Limited resources might slow down the implementation process. Those countries face significant resource constraints, limiting their ability to invest in cutting-edge Industry 4.0 technologies and infrastructure. Also, they can suffer with limited access to reliable electricity, internet connectivity, and basic infrastructure that can impede the widespread adoption of Industry 4.0 technologies.

This study found that the main barriers of the Upper, Middle, and Lower-income countries are Infrastructure, Skilled Employees, and lack of standardization, representing 71% of the barriers as shown on Fig.6.

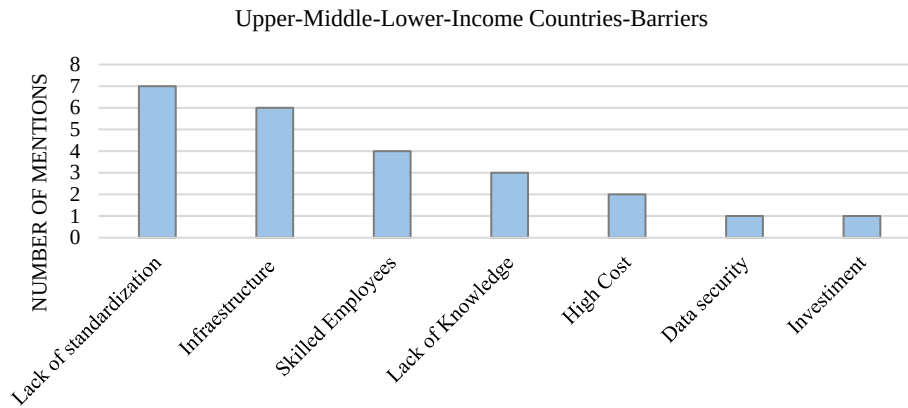


Fig. 6. Barriers for Industry 4.0 implementation on CNC Machines on Upper, Middle and Lower-Income Countries.

6 Conclusion

This study brings unique contributions to knowledge in this area. It has thoroughly identified the primary challenges and opportunities for implementing Industry 4.0 on CNC machines. Conducting a systematic literature review, the paper meticulously examines the barriers and opportunities faced by companies worldwide in adopting Industry 4.0 technologies in CNC machines. It outlines various opportunities stemming from the fusion of Industry 4.0 principles with CNC machines, including real-time data utilization, efficiency improvements, cost-effectiveness, and sustainability efforts. These opportunities are categorized to provide actionable insights for industries to leverage technological advancements for competitive advantage and operational excellence. Additionally, the study conducts a comprehensive analysis of the technological landscape, identifying key technologies such as Artificial Intelligence (AI), Machine Learning (ML), Internet of Things (IoT), and Cloud-Based solutions driving Industry 4.0 adoption in CNC machines. Furthermore, it presents a comparative analysis of Industry 4.0 adoption across various income levels and regions, highlighting the global implications of technological advancements in CNC machining and fostering a nuanced understanding of socio-economic factors influencing technological adoption worldwide.

However, the adoption and success of Industry 4.0 initiatives vary significantly across countries, particularly in the context of upper, middle, and lower-income nations. Higher-income countries, with ample resources, often lead in innovation and infrastructure. Yet, challenges persist, especially concerning knowledge gaps, investment, and infrastructure limitations. Upper, middle, and lower-income nations face hurdles in balancing technological adoption with other developmental needs. Limited resources and inadequate infrastructure hinder the seamless integration of Industry 4.0 technologies. Challenges for these countries include not only technological constraints but also issues related to education, standardization, and basic amenities. These challenges, depicted graphically, emphasize the critical barriers to overcome for a widespread, inclusive, and successful implementation of Industry 4.0 on CNC machines, underscoring the importance of addressing knowledge gaps, infrastructure deficiencies, and standardization issues to foster a global technological transformation.

The research, while comprehensive, has certain limitations that warrant acknowledgment. The temporal scope of the review might eventually overlook recent developments or emerging trends in Industry 4.0 adoption within CNC machining. Furthermore, the exclusion criteria applied in the study could potentially overlook relevant research that might offer valuable insights into the barriers and

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opportunities of Industry 4.0 adoption in CNC machines. Moreover, the classification of opportunities and barriers, while informative, may oversimplify the intricate dynamics within different industries and regions.

In summary, this paper makes a significant contribution to the scholarly discourse on Industry 4.0 and CNC machines by offering a comprehensive analysis of barriers, opportunities, and technological trends. By synthesizing empirical evidence and providing actionable insights, the paper empowers industries to navigate the complexities of technological integration, drive innovation, and achieve sustainable growth in the era of the fourth industrial revolution.

A potential future research direction for this paper could involve conducting empirical studies and/or case studies to validate and complement the findings derived from the systematic literature review. This approach would entail gathering primary data from industries actively engaged in adopting Industry 4.0 technologies in CNC machining, allowing for a deeper understanding of the challenges, opportunities, and technological trends observed in real-world settings.

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Attachment

Abbreviations:

AI - Artificial Intelligence

AM - Additive Manufacturing

AR - Augmented Reality

CAD - Computer-Aided Design

CAM - Computer-Aided Manufacturing

Cloud-based - Cloud Based System

CNC - Computer Numerical Control

CPS - Cyber-physical systems

DT - Digital Twin

FDM - Fusion Deposition Modeling

IoT - Internet of Things

ML - Machine Learning

OPC UA - OPC Unified Architecture

VR - Virtual Reality