RAIRO-Oper. Res. 58 (2024) 5185–5209
https://doi.org/10.1051/ro/2024172

RAIRO Operations Research
www.rairo-ro.org

DEVELOPMENT OF INDUSTRY 4.0 BASED TECHNOLOGY SELECTION INDEX USING MULTI CRITERIA DECISION MAKING

Karan Vohra, Amit Kumar Sinha* and Ankush Anand

Abstract. Selecting an appropriate technology to perform a specific operation has always been an uphill task while setting up a new industry. There exist a large number of decision making challenges, while selecting a technology related to industry 4.0 in a manufacturing environment, as it augments the analysis of various technological elements, which are otherwise not considered in traditional manufacturing systems. The analysis of attributes is a holistic exercise, which needs understanding the co-relationship among the identified attributes from industry 4.0 perspective (*i.e.*, data analysis, cloud, IIoT, real time data monitoring, sensors, etc). In this research paper, an effort has been made to address the issue of selecting appropriate technology using graph theory based multi criteria decision making approach in industry 4.0 environment. The proposed methodology has been applied to two case studies. The first case study is for illustration purpose. However, to validate the concept, the second case study has been included for the benefit of readers.

Received August 12, 2023. Accepted August 30, 2024.

1. Introduction

The recent advancements in the industrial environment have led to a significant shift from the traditionally applied manufacturing systems to more clustered manufacturing technologies including Industry 4.0. Elements of industry 4.0 include: big data analytics, robots, simulation, horizontal and vertical system integration, internet of things (IoT), cyber security and cyber physical systems (CPS), cloud technology, additive manufacturing, virtual reality (VR) and augmented reality (AR) [67]. These elements of industry 4.0 make the product and equipment communicate effectively for better productivity with lesser errors. Proper selection and integration of these elements not only increase the efficiency of industry, but also provide an improved human machine interface [25]. Hernandez-de-Menendez *et al.* [32] presented an assessment model considering different competencies related to Industry 4.0 workforce, knowledge and education related to Industry 4.0, its engineering elements and, other transversal competencies. Jain and Ajmera [34] proposed 17 enablers which directly impact the adoption of industry 4.0 in Indian Industry. A framework of cyber-physical system in construction industry was proposed by You and Feng [71]. These require an IT educated team to handle data modelling and data analysis [56]. Also, an IoT enabled design engineering process is required alongwith a cyber secure smart system using 3D printing.

There are many new technologies to execute manufacturing operations with great precision and accountability. Barbosa *et al.* [10] developed a technique about economical virtual and hybrid scenario by using integrated,

Keywords. Industry 4.0, Multi criteria decision making, technology selection index, big data handling, graph theory.

School of Mechanical Engineering, Shri Mata Vaishno Devi University, Katra 182320, Jammu and Kashmir, India.
*Corresponding author: amitsinha5050@gmail.com

digital manufacturing methods. Narula *et al.* [52] presented some critical factors and sub-factors for industry 4.0 implementation *i.e.*, strategy, leadership and culture for transformation towards Industry 4.0. Moreover, other attributes, such as design and development in the digital twin, virtual testing and simulations also play important role in this context.

The main feature of industry 4.0 manufacturing system is the consumer eccentric customized production in less time that involves the human integration [53, 54]. The key human integration factors in industry 4.0 are: physical aspect, physiological aspect, skill level of employee *i.e.*, knowledge of IT, and new technological advancements in manufacturing. Zolotová *et al.* [72] carried out a research study on Human integrated Cyber Physical Production System, and Industry 4.0 ready operators. From a bunch of operators 4.0 team, analytical operator uses real time data from Big Data analytics, which is a method of collection, sorting and analyzing the data to get valuable information that may be in the form of customer feedback, sales and marketing statistics etc. and forecast about the product's future market performance.

The technology supporting openers have more chances to produce better opportunities for local production units with lower cost and lesser errors with improved product quality and consumer satisfaction [16]. The companies willing for Industry 4.0 should first include technologies such as: Cyber-Physical Systems and Big Data & Analytics, which will provide companies with sufficient information to analyse its manufacturing process [19, 33]. Rinat *et al.* [58] reported a comparative study of big data computing in industry 4.0 and industry 5.0 based manufacturing environment. The study revealed that there is better man-machine integration in industry 5.0 environments than industry 4.0.

Different countries are exploring the technological and strategic requirements for successful industry 4.0 implementation. Some nations have declared their policies with timeline for reaching their target, whereas other surveyed nations are in the process of execution [70]. Make-in-India initiative, has been undertaken by government of India to make the manufacturing industry technology ready for Industry 4.0. Along with the Make-in-India, Germany's Industry 4.0 and China's Made-in-China (2025) were also differentiated. Technology readiness index and degree of readiness calculated from extensive literature review and mathematical formulas showed that, Make-in-India has a strong sectorial focus with emphasis on societal objectives [30]. The investigation showed that higher production and lower cost are the major benefits of digitalized manufacturing in Indian Manufacturing Industry [63].

The European manufacturing units aim to implement higher levels of Industry 4.0 [48,59]. The lack of financial help from the government posed a major challenge to the implementation of circular economy practices in leather supply chains [49].

There are however, several barriers in implementation of technologies in Industry 4.0 practice in emerging nations. Javaid *et al.* [37] investigated the key barriers in Industry 4.0 implementation and identified 22 barriers for successful Industry 4.0 adoption in new manufacturing industry. In this research investigation, technology and infrastructure cost and management modification emerged as major barriers. In another research carried out on Brazil manufacturing sector [18], the authors revealed that Brazilian industry need much stronger IT infrastructure with resources for execution and investment to build better connected and digitalized shop-floor, with basic investments in industry 4.0 enabling technologies, along with cyber security AI and big data analytics.

Both developed and developing countries have different impact of these barriers. The most crucial factor emerged as lack of standards, regulations, and forms of certification (IR6) between two nations [57]. Some important factors and sub-factors for Industry 4.0 implementation in manufacturing units are work strategy, leadership in organization and work culture. Lack of digitization and intelligence were two major obstacles in improving the automation competence [44]. Good leadership is the most crucial criteria into decision making for best technique, information system and IoT were ranked at last alternatives [23]. The authors concluded that Industry 4.0 directly impacts the sustainable industrial performance [68].

The Industry 4.0 manufacturing system employ some of the newest technologies such as AM (Additive Manufacturing), AI, (BDA) Big Data Analysis, Building Information Modelling (BIM), Blockchain technology (BCT), Digital Twin, Geographical information system (GIS) and Internet of Things (IoT), which contributes in making circular economy in construction industry [66]. Additive manufacturing as a subject gives an important insight and strongly linked with Industry 4.0 [50].

There is a need for adoption of advanced technologies, equipments, procedures and operations for better production results. Cloud technology enables to achieve the Industry 4.0 implementation in micro, small and medium manufacturing units [65]. There are contemporary communication technologies for digital manufacturing processes in industry 4.0 context, such as cloud computing (CC), fog computing (FC), and edge computing (EC) which are most common to describe information about computation locations [42].

Das and Dey [20] developed a framework of a digital platform suitable for international production units to understand concept to prefer between maintaining and building upon firm-level capabilities. From Supply chain 4.0 perspective, the decision-maker could choose to move the PSPs (Payment Service Providers) to a common cloud ERP (Enterprise Resource Planning) system under the Industry 4.0 environment, resilience of supply chain from disruption by managing the ripple effect in the Industry 4.0. This enhances the economic performance which might slash the high promotional investment [21].

In Industry 4.0 manufacturing system, smart predictive maintenance system is important for fault allocation, diagnosis and prognosis in machine center. It can play a pivotal role in effective predictive maintenance in machine centers depending upon the problem complexity and level of accuracy of machining [43].

Cognitive skills emerged as the most significance human capital followed by emotional and behavioral skills of industry 4.0 manufacturing organizations [62]. There is a need to impart both technical and personal skills to the human workforce for industry 4.0 [13].

Industry 4.0 can successfully drive sustainable manufacturing and unlock circular economy, and can reorganize value chains in evolving circular economy industrial structures. United Nations sustainable development goals (UNSDG) include financial, ecological and societal attributes [8]. There are various other factors to be looked after, which include developing the system, techniques to reduce waste and reuse of materials and resources system, and draw the sustainability standard line and achieve it [47]. Industry 4.0 technologies impact towards improving green innovation in manufactured goods and processes. This also promotes the open innovation which improve green innovation performance and in turn, improves the green innovation performance [51]. Bai *et al.* [9] reported that mobile machinery has the maximum impact on sustainability in all industries, and nanotechnology, mobile technology, simulation and drones have the highest influence on sustainability in the automotive, electronics, food and beverage, and textile, apparel and footwear industries, respectively. Arnal *et al.* [7] investigated the implications and retrofitting of natural gas melting and the heating furnaces, for sustainable manufacturing and industry 4.0. The study showed that in the heating furnace, enhancement of the furnace refractory is the most cost-effective solution.

Pansare *et al.* [55] carried out a research study on integration of Industry 4.0 technologies with Operational Excellence strategy that can help to enhance the performance of manufacturing industries.

Liu *et al.* [45] presented a solution to new Scheduling-Location (ScheLoc) problem of machine location and job scheduling, with intention to increase profit to organization than the given margin in industry 4.0 environment. Sangiorgio *et al.* [60] presented a new technique named Card Game Analysis (CGA) to carry out MCDM analysis. In CGA technique, cards are issued as per rank of importance of different criteria; from less important to the most important in ascending order.

The literature survey carried out in this research study provides a comprehensive overview on how Industry 4.0 methodology is being implemented in different components of an industry, *i.e.*, production, sustainability, maintenance, employees, information management, etc. The above discussed literature survey is presented at a glance in the form of Table A.1 (please see in the appendix). Table A.1 provides information about current status of research carried out in the domain of implementation of Industry 4.0 in sustainable manufacturing systems. Different researchers have considered different aspects of Industry 4.0 in manufacturing systems. However, on the basis of Table A.1, it is observed that a holistic approach for implementation of Industry 4.0 in sustainable manufacturing systems is required. Table 1 presents the existing research gap on the basis of literature survey (see Tab. A.1). Based upon the comparative literature survey which is presented in the form of Tables A.1 and 1 is developed. Research gap is identified in Table 1. It clearly shows that multi attribute

TABLE 1. Literature review based on key aspects of manufacturing systems in Industry 4.0.

S.No.	Design aspects	Contributors	Points examined	Research gap
1	Industry 4.0: Enablers, Technologies	Barbosa *et al.* [10], Vaidya *et al.* [67], Javaid *et al.* [38], Wankhede *et al.* [68], Li *et al.* [43], Jain and Ajmera [34].	Implementation of Advanced Robots, Drones; Intelligent predictive maintenance, Modelling of Indian manufacturing industry, cloud technology in MSME.	Framework Validation, FUZZY Model, Validation with Artificial Neural Networks.
2	Technology Implementation In Industry 4.0	Contieri *et al.* [18], Yang and Gu [70], Narula *et al.* [52], Erdogan *et al.* [23], Dev *et al.* [21], Lopes and Martins [46].	Technology requirements in emerging nations, International policies, Supply Chain, performance measurement system.	Suitable MCDM techniques selection, Cost consideration, Development of Intelligent Decision Making technique.
3	Sustainable Manufacturing and Industry 4.0	Bag and Pretorius [8], Machado *et al.* [47], Mubarak *et al.* [51], Moktadir *et al.* [49], Bai *et al.* [9], Harikannan *et al.* [31], Kamble *et al.* [40].	Value chain in circular economy, green innovation, Circular Economy in Leather Industry.	Explore the opportunities to link the Industry 4.0 and Sustainable manufacturing in different domains, Framework Validation required, Integration of technologies need to be examined.
4	Industry 4.0 in Different nations	Goswami and Yash Daultani [30], Kurfess *et al.* [42], Das and Dey [20], Rossini *et al.* [59], Singhal [63], Felsberger *et al.* [25].	cloud computing (CC), fog computing (FC), and edge computing (EC), CPC, Big data, Framework of digital platform.	Implementation depending upon Firm size, Additive manufacturing and CNC machines.
5	Barriers of Industry 4.0 Adoption	Raj *et al.* [57], Motyl and Filippi [50].	15 Barriers for developed and developing countries.	Govt. policies for smooth transition, MADM techniques for solutions, Upgrading Education System.
6	New Product Design	Pessoa and Becker [56].	IoT enabled design engineering process.	Study focuses on recent and under-developed situations.
7	Technologies and Methods in Industry 4.0	Hincapié *et al.* [33], You and Feng (2017), Buchi *et al.* (2020), Bongomin *et al.* [13], Rinat *et al.* [58].	Teaching techniques using virtual and hybrid digital manufacturing tools, CPS in construction industry, smart factories, man-machine integration Industry 5.0.	CPS Framework, education and skill support to human workforce.
8	Methodology	Pansare *et al.* [55], Sangiorgio *et al.* [60].	Integrating industry 4.0 Operational Excellence strategy, MADM used.	CGA technique not beat shortcomings of other MCDM methodologies.

decision making (MADM)/multi criteria decision making (MCDM) is a versatile tool to evaluate the diverse problems that take place in industry 4.0 based manufacturing systems and provide the optimum solution. Therefore, a multi criteria decision making based holistic model for implementation of Industry 4.0 in sustainable manufacturing systems is developed in this research paper.

It is evident from the above research studies that technology plays a vital role in industry 4.0 environment. Tables A.1 and 1 shows the various aspects discussed in literature review and key discussion factors with research gaps. The studies carried out so far have not considered the integration of all important factors from industry 4.0 perspective. The major thrust should however be given to developing and analysing the relationship among various industry 4.0 factors in a holistic manner. The selection of appropriate manufacturing/product development technologies needs to be done involving a large number of factors. Thus, it is inferred that selection of technologies for industry 4.0 based manufacturing systems is essentially a multi criteria decision making problem. An effort has been made through this research paper to address this issue. For this purpose, systematic handling and representation of various industry 4.0 factors have been carried out using the concept of graph theory. An integral framework for technology selection under the domain of Industry 4.0 is proposed in Figure 1.

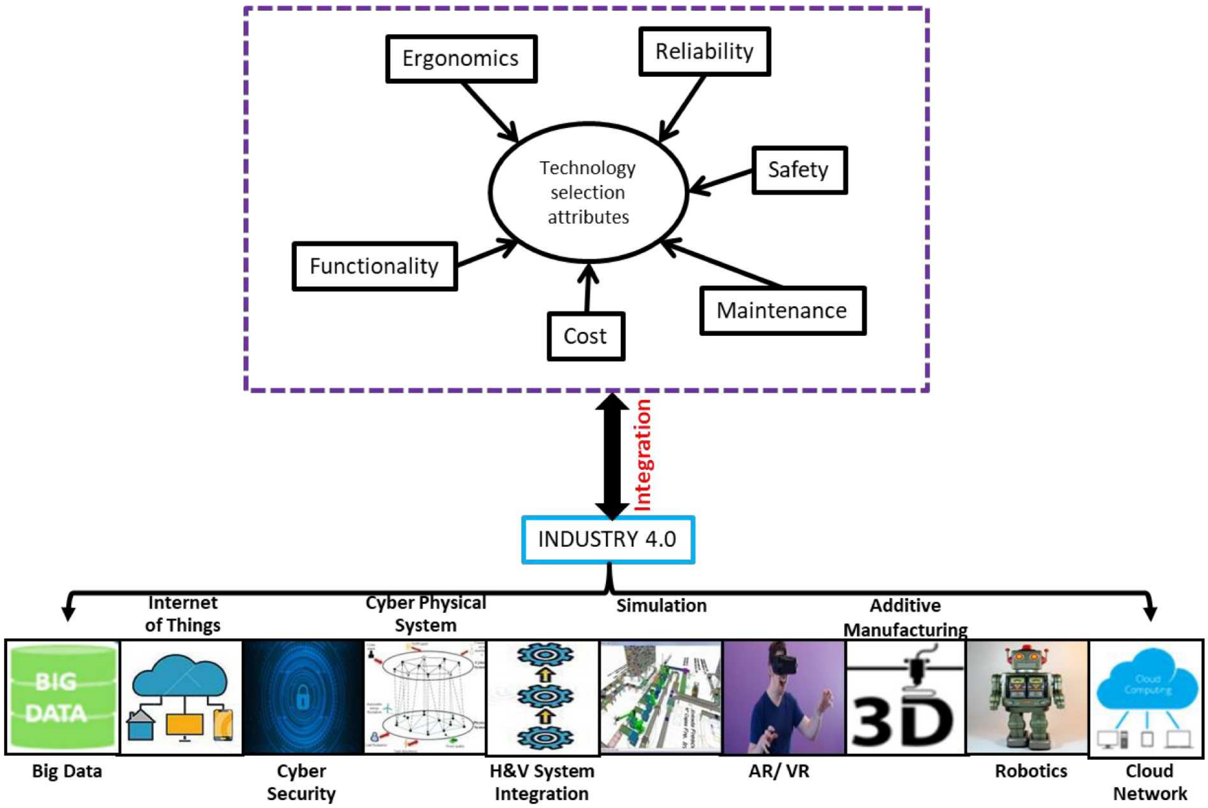


FIGURE 1. An integral framework for technology selection under the domain of Industry 4.0.

Graph theory based multi criteria decision making framework has been proposed for selection of industry 4.0 based technologies in manufacturing systems. Therefore, proper selection of the elements of industry 4.0 is a challenging task for manufacturers, practitioners and design engineers.

There are several Multi Criteria Decision Making techniques available to select from; such as; Analytic Hierarchy Process (AHP), Best-Worst Method (BWM), Analytic Network Process (ANP), Multi-Attribute Utility Theory (MAUT), Simple Multi-Attribute Rating Technique (SMART), and Data Envelopment Analysis (DEA) etc [4]. Also, large number of factors can be constraint in terms of selection and handling of factors/parameters can be considered without any difficulty and mathematical solution can be provided for the problem under consideration. This method deals with variety of problems *i.e.*, product life cycle modeling and evaluation [5], supply chain modelling [64], drone technology assessment [4], risk assessment modeling [6], and has emerged as a powerful tool in handling large number of problems.

Abolfathi and Ebadian [1] carried out a research study on Multiple Attribute Group Decision Making (MAGDM) problem using picture fuzzy set methodology. The authors demonstrated the problem of air-quality assessment of a football ground in Tehran and found the best alternative.

Many available MCDM techniques are complex in nature when the number of attributes increase for decision making while considering preferences; and complexity further increases with an increase in the size of the multiple criteria in the problem [22].

Wani and Anand [69] used Digraph and Matrix approach for life cycle assessment (LCA) of a self lubricating plain bearing. LCA takes in consideration the environment impact of a technology or product over the period of usage. Same approach was used by Sezer *et al.* [61] to investigate the resilient supply chain factors. The author considered the Graph theory as a framework of graphs that visualize the interrelations of categorize attributes; and the whole scenario of a system is easily understandable by means of graph. By identifying the systems and sub-systems, this methodology helps in effective decision making through complex problems.

Gadakh and Shinde [26] used the graph theory and matrix approach in manufacturing operations for cutting parameters selection. The author concluded that the methodology helped in most appropriate parameter selection from large number of alternates available. The author emphasized that graph theory and matrix technique is easy, generic and less computational, but at the same time; it can be used for critical analysis with large number of objective and subjective attributes.

Gandhi and Aggarwal [27] carried out a research study on failure cause analysis in a system using Digraph and Matrix approch. This technique was used to analyze, evaluate and compare the design alternatives. The results provide the researchers, a direction to reduce the causes of failure so as to improve the system reliability.

Bordoloi and Kalita [14] presented a methodology to develop the area specific correlation model and converted in to a graph database model. In data base designing, the key use of Graph database are an index free adjacency storage system. This work as a very accurate yet easy tool for factors interconnection, for graph like-problems, for associative data sets that map more directly to the structure of object-oriented applications.

One of the feature of graph theory is to give formulations for many diverse looking problems [28]. Graph theory is a logical and systematical approach that is very practical for modeling and analyzing different systems and problem in numerous areas of science and technology.

Graph theory has a strong potential in dealing with various problems of engineering and technology [6]. When there are large number of attributes, and the graph becomes complex, the computation is performed using another method called matrix approach.

Graph theory has emerged as a methodology that serve a great purpose in modelling of different physical systems, network analysis, functional representation, reliability analysis, tribological, analysis, failure diagnosis. Matrix representation and solution of graph provides an excellent tool for qualitative or quantitative analysis.

2. Parameters for technology selection

There are many aspects taken into consideration while selecting a specific technology for an application *i.e.*, process design, mass manufacturing, economics, flexibility, reliability, sustainability, safety, etc. There are some significant factors which are found to have direct impact towards appropriate decision making for suitable technology selection (Tab. 2). The parameters are discussed below.

(a) **Functionality (FN):** functionality of equipment or a system is essentially an ability to perform the required operation without any error. This is a basic feature that a machine should have. A manufacturing system should perform the assigned task with high accuracy, within prescribed time. In addition to this, technology should be well connected with other industrial devices and equipments with the help of sensors and cloud from industry 4.0 perspective *i.e.*, Cloud Manufacturing [3]. In this environment, the operational flexibility has opened the doors of mass product customization. Functionality is the first attribute and is abbreviated as (FN). Automation, Robotics, Artificial Intelligence, Digital twin, Big data handling, Virtual and Augmented reality, etc. act as a key enablers of Industry 4.0 in the domain of manufacturing systems [29].

(b) **Ergonomics (ER):** productivity of an industry revolves around good physical and mental health of its workers and workplace ergonomics plays a pivotal role in maintaining this (Karuppiah *et al.* [41]). Ergonomics of a manufacturing system can be considered as ease of operating the equipment without causing fatigue, and with minimal risk to operator. Ergonomically designed equipments are more efficient as they have simple user interface, robust controlling features and good aesthetics. Ergonomics is the second attribute and is abbreviated as (ER).

(c) **Safety (SF):** safety is the foremost priority in any industry. Guarantying the equipment safety, worker safety and overall safety of a system are the prerequisites on any new established industry. Being an intelligent work system, Industry 4.0 environment is safer than traditional manufacturing setup. It provides absolutely no risk to the worker. However, big-data security, IIoT connectivity and sensor equipped machines has introduced new safety concerns which should be looked up to maintain the secrecy of industry's production and marketing strategies [67]. Safety is the third attribute and is abbreviated as (SF).

(d) **Reliability (RL):** reliability can be defined as the attribute of a machine that how well it executes its intended function to meet the target without risk to failure. Higher the reliability, lower the chances of system failure. A reliable system is the one that work continuously without failure and leading to zero production lag time. It should be robust enough to withstand the prescribed loads and fluctuating loads without malfunction. The equipment/system must collect record and produce broad evaluated data which help in production planning and supply chain management [67]. Reliability is the fourth attribute and is abbreviated as (RL).

(e) **Maintenance (MT):** maintenance is to keep the equipment in good working condition to perform required task appropriately. Low maintenance requirement (AI), self maintainability, low production downtime etc are the characteristics which are expected from an industrial system in industry 4.0 environments [35]. All equipments and systems are interconnected by IIoT and their mutual communication follows best possible processes all times. The main feature of industrial maintenance 4.0 is that it includes overall data sources, connect, collect the data, analyze and suggest appropriate actions to take. Maintenance is the fifth attribute and is abbreviated as (MT). Ahmed *et al.* [2] developed the test bed which is utilized for product development starting from conceptual design stage up to the virtual product testing through product simulation. Jan *et al.* [36] developed a holistic approach based on Industry 4.0 which is helpful for maintaining the productivity of the manufacturing systems using Artificial intelligence, Machine learning, Internet of things, Digital twin, Cloud computing, Data analytics, Sensor networks etc.

(f) **Cost (CT):** cost is the most crucial aspect of any manufacturing industry. Lower the manufacturing cost, higher is the profit to the industry. Industry 4.0 infrastructure setup require a large investment [67]. While selecting a technology for industry 4.0 environment, its economic implications should match with the purpose it serve *i.e.*, repetitive nature of work, load variations, continuous or project wise work, working conditions, flexibility, intelligent system, data recording, cloud connectivity, lower maintenance cost, cost of spares, ease of operation etc. Cost is the sixth attribute and is abbreviated as (CT).

3. Technology selection digraph

This research work focuses on some Industry 4.0 Technology Selection for a manufacturing. These attributes are Functionality, Ergonomics, Safety, Reliability, Maintenance and Cost. Based on these technology selection (TS) attributes, the model of the TS is developed by means of a directed graph (Fig. 2). A directed graph or digraph, G having some set of vertices $V^g\{V_1^g, V_2^g, \ldots\}$, with the set of edges $E^g = \{e_{11}^g, e_{12}^g, \ldots\}$ and, a mapping function that joins every edge to pair of vertices (V_i^g, V_j^g). When the graph become complex, another approach called matrix approach, is used for further investigation which helps to synthesizing the Industry 4.0 Technology Selection equation and its index value.

Graph theory has been widely used in different areas of science and technology for the system analysis [17]. It is the study of graphs which are mathematical structures used to model pairwise relations between attributes.

4. Matrix based representation of Industry 4.0 based technology selection attributes digraph

It is evident based on the six technology selection factors that its representation of digraph becomes complex. Therefore, matrix approach is the alternative mode of showing this complex structure. In this section, the TS in matrix form is represented considering all the TS factors/attributes *i.e.*, Functionality (FN), Ergonomics (ER), Safety (SF), Reliability (RL), Maintenance (MT) and Cost (CT).

Based on the intensity of dependence among these factors, the TS equation can be generated. The TS of six identified factors is generated, which is shown in Figure 1.

Table 2. Design attributes contributing factors for technology selection in Industry 4.0 based manufacturing system.

Design attributes	Contributing factors
Functionality	Less effort high output, Lower error, Less heat generation, Lower wear, High workability without breakdown, Less effect of fluctuating loads, Easy operation ability of device, Lower material wastage, Easy machine interface, Lower maintenance before prescribed servicing schedule, Reduced energy consumption, Longevity, Ease of handling/storage, Operatability characteristics, Reduced weight, size and dimensional characteristics, Adaptability to design modification, Technological compatibility, Mode of operation (automatic/semiautomatic), automation, Robotization, Noiseless working, bio-compatible/green technologies, process and operations.
Ergonomics	Ease of comfort while operating, User safety, Increased worker's productivity, Weight Volume and Size factors, Minimum operator movements, Noise control measures, Proper selection and usage of material handling systems, Easy to use design, Ease of maintenance, Part complexity, Analysis of factors related to human capital.
Safety	Material Selection, Reduced toxic harm rate, Produce no harmful gases, Shockproof/auto cut at higher voltages or overloads, Safety measures for high speed rotating equipments, Green manufacturing standards, Reliable safety controls, Periodic inspection of safety, controls, Insulation and Leak Proof systems, Enhanced safety, Risk free design, Weight Volume and Size factors.
Reliability	Failure free design, Fault Tree Analysis (FTA), FMECA, Design Tree, Long operating hours without error, Easy maintainability, Confidential data protection, Not hackable, Alarms for various requirements of machine to avoid production lag, Workable in different terrain conditions, Failure rate of actuating parts of robots, Alarms for sensor fault.
Maintenance	Easy to assemble/open the equipment for repair, Spares should be easily available, Less complex construction, Extended warranties, Ease of fault diagnosis. Virtual product testing, Product simulation, Digital twin.
Cost	Cost competitiveness, Economical, Market dynamics, Global economy, Societal beliefs/segmentation, good quality at lower cost, Less material consumption, Low running equipment cost, Ease of adaptability/up gradation without spending extra money, Extended warranties, Cheaper spare parts, Less periodic maintenance required, Good technical support network for equipment repair.

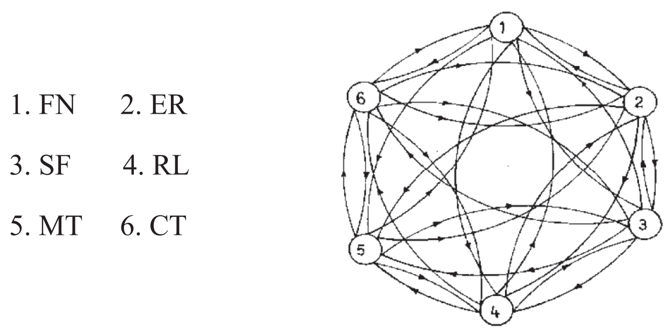


Figure 2. Industry 4.0 technology selection attributes relationship digraph.

A digraph TS with N nodes is considered here in this section. The TS may be written as a binary matrix $[a_{ij}]$ of Nth order.

Such that,

a_{ij} = intensity of dependence among ith & jth attribute/parameter/factor.

If

$a_{ij} = 1$ (ith attribute is related to jth attribute)

else;

$a_{ij} = 0$ (an attribute may not have self relationship).

The TS as shown in Figure 1 is expressed as:

$$\mathrm{TS} = \begin{bmatrix} 0 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 & 1 & 0 \end{bmatrix}. \tag{1}$$

It may be observed from equation -1 that:

All diagonal elements have "0" value.

All off diagonal element has "1" value.

This is on the basis of intensity of dependence among these factors. Thus, the TS matrix is defined.

The TS matrix which represents various factors of TS shown in equation (2) is written as as:

$$\mathrm{Q} = [\mathrm{AI} + \mathrm{TS}] = \begin{bmatrix} \mathrm{TS} & 1 & 1 & 1 & 1 & 1 \\ 1 & \mathrm{TS} & 1 & 1 & 1 & 1 \\ 1 & 1 & \mathrm{TS} & 1 & 1 & 1 \\ 1 & 1 & 1 & \mathrm{TS} & 1 & 1 \\ 1 & 1 & 1 & 1 & \mathrm{TS} & 1 \\ 1 & 1 & 1 & 1 & 1 & \mathrm{TS} \end{bmatrix} \tag{2}$$

where,

"I" = Identity matrix;

"S" = Value of TS factors.

Equation (2) of matrix above has "TS" value, assigned to every diagonal element. This indicates that every SS factor is given a same value. However, practically it may not be possible.

Based on the intensity of dependence among these factors, the individual score value to s_{ij} may be assigned. Therefore, it becomes customary to consider a general TS factor value (*i.e.*, diagonal elements S_i) and (off diagonal elements s_{ij}) while determining the TS matrix equation. This becomes possible with the help of a matrix called Variable Technology selection Relationship Permanent Matrix ($\mathrm{VSM}^{\mathrm{per}}$). Applying the concept of permanent function (combinatorics), as used in mathematical science may be helpful in this direction. A Permanent represents an analogous of a determinant, with all positive terms, while expanding the equation [39].

Let us consider

s_{ij} = value of every off diagonal element for "matrix Q".

Such that,

ith attribute = jth attribute.

Also,

S_i = value of diagonal element for "matrix Q".

A maximum score value can be given, if the factor has exceptionally meets all the requirements. Similarly, values to other attributes can be given, which is a traditional approach.

The Variable TSA attributes Relationship Permanent Matrix of the TS shown in equation (1) is given as:

$$Q=[H+F]=\begin{bmatrix} \mathrm{TS}_1 & ts_{12} & ts_{13} & ts_{14} & ts_{15} & ts_{16}\\ ts_{21} & \mathrm{TS}_2 & ts_{23} & ts_{24} & ts_{25} & ts_{26}\\ ts_{31} & ts_{32} & \mathrm{TS}_3 & ts_{34} & ts_{35} & ts_{36}\\ ts_{41} & ts_{42} & ts_{43} & \mathrm{TS}_4 & ts_{45} & ts_{46}\\ ts_{51} & ts_{52} & ts_{53} & ts_{54} & \mathrm{TS}_5 & ts_{56}\\ ts_{61} & ts_{62} & ts_{63} & ts_{64} & ts_{65} & \mathrm{TS}_6 \end{bmatrix}. \tag{3}$$

Matrix equation (3) represents technology selection design factors (TS_i's) and the intensity of dependence (ts_{ij}'s) of technology selection factors while determining the design evaluation index. Permanent of equation (3) or Per (TS) *i.e.*, $\mathrm{VTS}^{\mathrm{per}}$, called variable technology selection design attributes dependence permanent function is, represented by VTS-s. The VTS-s is a tree having various terms which, describes the required information about the product. Using the permanent function in technology selection will enable decision makers to logically exhibit the data in a structured manner.

Also, due to the presence of all non negative signs in the sigma equation, there is no loss of any important information/data.

VTS-s of matrix equation (3) is expressed here in sigma form as equation (4):

$$\begin{aligned}
\mathrm{Per}(M) = {} & \prod_{i=1}^{6}\mathrm{TS} + \sum_{i=1}^{5}\sum_{j=1+1}^{6}\sum_{k=1}^{3}\sum_{l=k+1}^{4}\sum_{m=1}^{5}\sum_{n=m+1}^{6}(ts_{ij}ts_{ji})\mathrm{TS}_k\mathrm{TS}_l\mathrm{TS}_m\mathrm{TS}_n\\
& \sum_{i=1}^{3}\sum_{j=1+1}^{6}\sum_{k=j+1}^{5}\sum_{l=1}^{6}\sum_{m=l+1}^{5}\sum_{n=m+1}^{6}(ts_{ij}ts_{jk}ts_{ki}+ts_{ik}ts_{kj}ts_{ji})\mathrm{TS}_l\mathrm{TS}_m\mathrm{TS}_n\\
& + \left(\begin{array}{l} \displaystyle\sum_{i=1}^{3}\sum_{j=i+1}^{6}\sum_{k=i+1}^{5}\sum_{l=i+2}^{6}\sum_{m=1}^{5}\sum_{n=m+1}^{6}(ts_{ij}ts_{ji})(ts_{kl}ts_{ji})\mathrm{TS}_m\mathrm{TS}_n\\ \displaystyle +\sum_{i=1}^{3}\sum_{j=i+1}^{5}\sum_{k=i+1}^{6}\sum_{l=j+1}^{6}\sum_{m=1}^{5}\sum_{n=m+1}^{6}(ts_{ij}ts_{jk}ts_{kl}ts_{li}+ts_{il}ts_{lk}ts_{jk}ts_{ji})\mathrm{TS}_m\mathrm{TS}_n \end{array}\right)\\
& + \left(\begin{array}{l} \displaystyle\sum_{i=1}^{4}\sum_{j=i+1}^{5}\sum_{k=j+1}^{6}\sum_{l=1}^{5}\sum_{m=l+1}^{6}\sum_{n=1}^{6}(ts_{ij}ts_{jk}ts_{ki}+ts_{ik}ts_{kj}ts_{ji})(ts_{lm}ts_{ml})\mathrm{TS}_n\\ \displaystyle +\sum_{i=1}^{3}\sum_{j=i+1}^{5}\sum_{k=i+1}^{6}\sum_{l=i+1}^{6}\sum_{m=j+1}^{5}\sum_{n=1}^{6}(ts_{ij}ts_{jk}ts_{kl}ts_{lm}ts_{mi}+ts_{im}ts_{ml}ts_{lk}ts_{kj}ts_{ji})\mathrm{TS}_n \end{array}\right)\\
& + \left(\begin{array}{l} \displaystyle\sum_{i=1}^{3}\sum_{j=i+1}^{5}\sum_{k=i+1}^{6}\sum_{l=j+1}^{6}\sum_{m=1}^{5}\sum_{n=m+1}^{6}(ts_{ij}ts_{jk}ts_{kl}ts_{li}+ts_{il}ts_{lk}ts_{jk}ts_{ji})(ts_{nn}ts_{nn})\\ \displaystyle +\sum_{i=1}^{1}\sum_{j=i+1}^{5}\sum_{k=j+1}^{6}\sum_{l=1}^{4}\sum_{m=l+1}^{5}\sum_{n=m+1}^{6}(ts_{ij}ts_{jk}ts_{ki}+ts_{ik}ts_{kj}ts_{ji})\\ (ts_{lm}ts_{nn}ts_{nl}+ts_{\ln}ts_{nn}ts_{nl})\\ \displaystyle +\sum_{i=1}^{1}\sum_{j=i+1}^{6}\sum_{k=i+1}^{3}\sum_{l=i+2}^{6}\sum_{m=k+1}^{5}\sum_{n=k+2}^{6}(ts_{ij}ts_{ji})(ts_{kl}ts_{lk})(ts_{nn}ts_{nn})\\ \displaystyle +\sum_{i=1}^{1}\sum_{j=i+1}^{5}\sum_{k=i+1}^{6}\sum_{l=i+1}^{6}\sum_{m=i+1}^{6}\sum_{n=1}^{6}(ts_{ij}ts_{jk}ts_{kl}ts_{lm}ts_{nn}ts_{ni}+ts_{in}ts_{nn}ts_{ml}ts_{lk}ts_{kj}ts_{ji}) \end{array}\right).
\end{aligned} \tag{4}$$

TABLE 3. Criteria for assigning weights.

S.No.	Interrelationship of attributes	Score
1	Strong	4
2	Medium	3
3	Wear	2
4	None	0

TABLE 4. Industry 4.0 technology selection attributes and their degree of relationship.

S.No.	Technology selection attribute	Nomenclature	Degree of relationship among attributes			
			Strong ($\text{TS}_{ij} = 4$)	Medium ($\text{TS}_{ij} = 3$)	Weak ($\text{TS}_{ij} = 2$)	None ($\text{TS}_{ij} = 0$)
1	Functionality	FN	2–6	–	–	–
2	Ergonomics	ER	$1, 3, 6$	$4, 5$	–	–
3	Safety	SF	$1, 2, 4, 6$	5	–	–
4	Reliability	RL	$1, 3, 6$	$2, 5$	–	–
5	Maintenance	MT	$1, 2, 3, 4, 6$	–	–	–
6	Cost	CT	$1, 2, 3, 4, 5$	–	–	–

5. Technology Selection Index For Industry 4.0 (TSI-1)

To select the suitable technology for a system, an index is developed, named Industry 4.0 Technology Selection Index (TS-I). This index has a numeric value which describes its adaptability in a system. It is denoted by I_i^{TS}.

When the index value is highest, the developed model is considered best. When a system is evaluated for an index value, the researcher should consider the value of all Technology Selection attributes and their degree of interrelationship (Tabs. 3 and 4). The VPF-TS obtained above represents the TS ability of a product and is used for Technology Selection assessment Index value evaluation. Also, there are all non-negative terms in the VPF-TS equation.

Hence, larger the value of TS attribute and degree of interrelationship within attributes, lower is the VPF-TS value. Hence, VPF-TS, *i.e.*, permanent of VTS^{per} is used for TS in a system. It is worth mentioning that a lower scale may be ideal to decrease subjectivity when score value is assigned to attributes. When doing technological selection, quantitative or qualitative values are assigned to TS_i and TS_{ij} with some suitable scale. The attributes and their values are shown in Table 3 and a technology selection model is proposed further.

The researchers may look upto the previously developed methods to assign score values to the attributes ([5], Roaf *et al.*, 2016, [64]). According to the system design characteristic, the scale selected a score value $(4, 3, 2, 0)$ as shown in the Table 3 (TS_i^{TS}). Score value of 4 is assigned when the attribute have strong interrelationship with another attribute and major reason to get selected for a system. Similarly, score values of 3, 2, and 0 are for medium, weak and absolute no inter-relationship between attributes.

However, this process will be convenient if a team of designers, engineers, product analysts, manufacturers and, experts from the engineering field are actively integrated for TS, than individuals. Industry 4.0 Technology Selection Index (ITS-I) is the single numeric value of permanent (VITS^{per}) function, which refer to the ease by which the ITS is performed.

Ideal index value for TS-I is found by using VPF-TS, *i.e.*, equation (4). The diagonal elements (TS_1 to TS_6) in the matrix are allocated with the same value equal to 1, whereas diagonal attributes are assigned with values mentioned in Table 2 of degree of relationship.

For TS comparison and assessment, the index ideal value *i.e.*, $I_{\text{ideal}}^{\text{TS}}$ is calculated as 1 978 816. The rank of TS value of a product (I_i^{TS}) may be comparatively made by the ideal value $I_{\text{ideal}}^{\text{TS}}$. The comparison shows that at what level the technological compatibility is achieved of the ideal value of TS.

The equation comes up as:

$$I_r^{ts} = \frac{I_i^{ts}}{I_{\text{ideal}}^{ts}} \times 100\%. \tag{5}$$

The relative index value of TS (I_r^{TS}) in equation (5) shows the TS value in a system and provide the index ideal value (%). A suitable range may be used where a lower value of scale is usually taken to reach a manageable index value. The general TS will not get affected by using dis-similar scale.

6. Steps in technology selection analysis and index evaluation

To carry out the Technology Selection process, the procedure proposed in this research work is shown in Figure 3.

7. Example

7.1. Example 1

In this research work, to demonstrate the proposed model, the problem of a Material Handling System has been considered. The Material Handling System in an industry is a key component of its manufacturing system and serve different purposes *i.e.*, in supply chain, manufacturing and assembly line, part storage, part distribution, etc. In industry 4.0 smart factory environment, the Material Handling System has bigger role to play besides lifting the raw material, parts to be assembled or final product. It has several advanced features like – cloud connected with other equipments, software controlled, sensors equipped, information storage, flexible, data recorder, self maintainable, etc.

In Industry 4.0 manufacturing facility, manufacturing and supply chain system make Cyber Physical Production System (CPPS) which utilize the world wide accessible information and communication network (cloud based system). This interconnectivity of business strategies and production operations by automated information exchange enhanced the quality and speed of taking decisions [67].

In this example, three different Material Handling Systems are selected:

(a) Robot;
(b) Conveyer;
(c) Automated Guided Vehicle (AGV).

There are six major attributes which are found to have direct impact towards appropriate decision making for suitable Material Handling System selection previously identified in Section 2 are considered here for evaluation of these 3 material handling systems from industry 4.0 perspective. These include: Functionality (FN), Ergonomics (ER), Safety (SF), Reliability (RL), Maintenance (MT) and Cost (CT). All the attributes have been given score according to Table 2. Factors that contribute for attribute score are mentioned in Table 5.

Robot

Robot technology has come a long way, from its industrial usage in 1937 to modern time's *robots*, which perform major task in industry 4.0 from manufacturing to operation to material handling. Some key manufacturers of industrial robots of contemporary times are – YASKAWA, FANUC, MOTOMAN, ABB, KUKA, etc. [10,51].

Robots are equipped with different sensors *i.e.*, vision sensors, temperature sensors, tactile sensors, feedback sensors, positioning sensors, gyroscope sensors, calibration sensors. These sensors enable robot to perform the

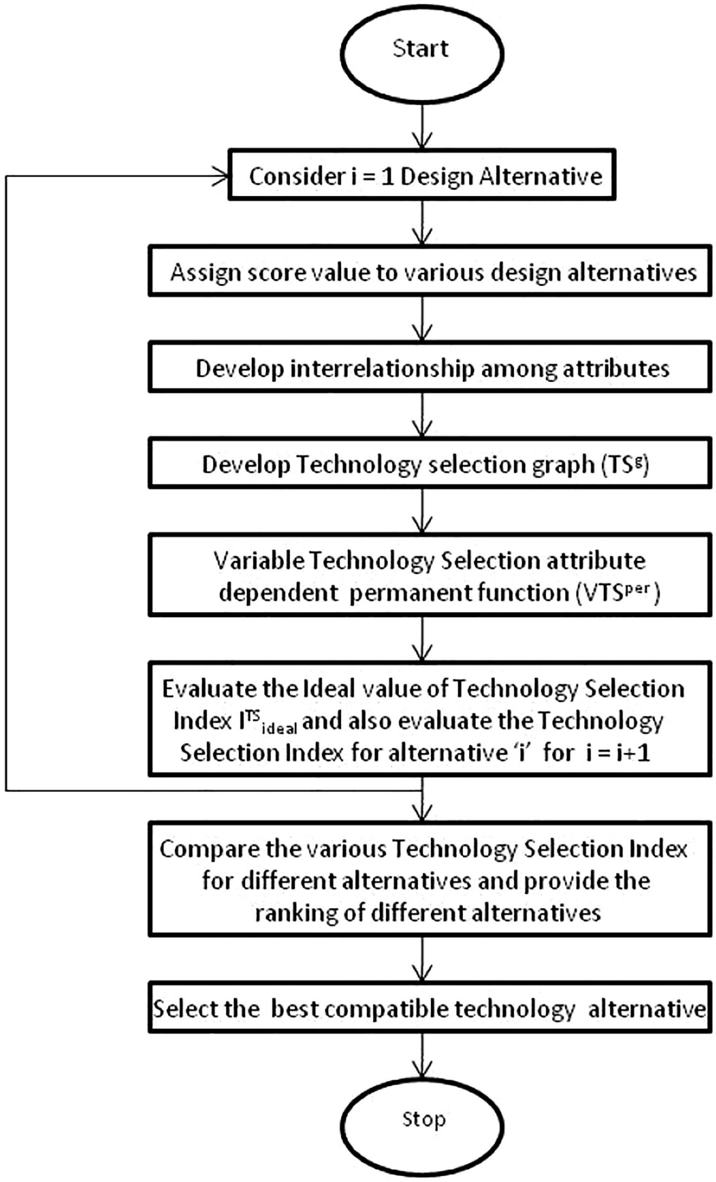


FIGURE 3. Step by step procedure for analysing technology selection.

real time operation with high accuracy, which is not possible by human *i.e.*, working in hazardous environment [15]. To make the machines work 24*7, it is important keep them in good working condition by periodic cleaning and checkups. Different problem can occur in robot functioning; depending upon the sensor application in diverse working atmospheres. Bigaj *et al.* [12] presented a semi-autonomy algorithm to access the sensor failures quickly after it occurs. The algorithm assessed different cases where (a) all sensors OK, (b) failure of laser rangefinder and, (c) failure of laser scanner. The results showed poor quality in laser rangefinder output, and due to the laser scanner failure; the robots took a different path at lower speed.

In material handling work, Robots have various significant functional features from industry 4.0 perspective *i.e.*, operation accuracy, adaptable to dynamic changes, longer working hours, work without supervision, high speed, efficient data flow control, versatile, data security, capable to work in hazardous environments, Industry 4.0 enable (real time data, cloud, IoT, CPC connectivity) etc. Therefore, the score assigned to the attribute is (4).

Also, the robots are easy to operate and have a well defined user interface, low operator risk, sensors equipped and auto stop function for overload and power fluctuations. Hence, the attribute score for an ergonomically well made design is assigned as (3).

Similarly, the score from safety perspective is (4). Safety is the foremost priority of any industry. The robots, as a Material Handling System, contribute to industrial safety in many aspects *i.e.*, employee safety, safety alarms, environment friendly, product safety, no chances of collision, multiple robots remotely controlled, etc.

Reliability is another important aspect of an efficient Material handling System. It should be robust structure and be able to handle load fluctuations without any error, low product lag-time than manual, work in different terrain conditions and provide real time data without error, etc. Robot has been assigned the score (4).

Robots have very low maintenance requirements depending upon working conditions and usage of machine. The robots maintenance requires special machine specific trained technicians required. However, there is possibility of production obstruction when malfunction occurs to the machine. The assigned score to maintenance is (3).

Robots are costly to buy, but have lower production cost. The spares are costly as most of the components are imported from different nations, but they have low running cost and prove productive for continuous work. The assigned score to cost is (3).

Conveyor

Conveyers are considered as a conventional and fixed material handling systems. Simple installation process, easy and rigid control, easy operatability, inflexible, less adaptability etc are the main features of this technology. This is suitable for carrying material in bulk and difficult to re-use one Material Handling System for different project.

Conveyer can be made compatible with Cyber Physical Systems (CPC) cloud technology, IIoT, sensors etc. by integrating the communication and computational systems in industry 4.0 environment [24]. This can make conveyor an autonomous device that can communicate with other equipments in the industry. However, for in house inter logistic works, more flexibility in functioning is required with different ability to pick and place different lot sizes of materials. Keeping these things in view, the score of (2) is given to conveyor as an Industry 4.0 Material Handling Device.

Ergonomically, the conveyor is easy to operate but produce noise while in operation, therefore, it feels disturbing to operator. There are options of both automatic and manual conveyor system as per manufacturing requirements. Keeping in view the industry 4.0 structure, the ergonomics score of (2) is given.

Safety is a key feature to look for while performing technology selection process. Conveyor is equipped with electrical safety gears to avoid any malfunction to equipment. However, it has rotating parts, which can prove hazardous if it drags in something. Another safety measure need to be taken are is noise control. Conveyor gets a safety score of (3).

Reliability is another aspect of conveyor system as an Industry 4.0 Material Handling Device. It has high efficiency and proves effective in rigid work environment *i.e.*, in coal mines, assembly line in manufacturing etc (3). Maintenance score (4) and Cost score at (4).

Automated Guided Vehicle (AGV)

AGVs are emerging as important part of logistic work in modern manufacturing industry *i.e.*, industry 4.0. The industry and warehouse facility layout is mapped according to the AGV path of work [11]. Exact distance and route is prime concern to minimize the vehicles collisions and quick task completion. AGVs are intelligent, sensors equipped, cloud compatible and CPS communication connected that read the real time need of spares

TABLE 5. Design attributes for technology selection evaluation of material handling systems.

S.No.	Alternatives → / Design attributes ↓	Robot	Conveyer	A.G.V.
1	Functionality	Accuracy, longer operation hours, work without supervision, high speed, versatile, data security, work in hazardous environments, Industry 4.0 enable (cloud, IoT, data security).	Easy installation, simple control, easy operatibility, less flexible, suitable for carrying material in bulk, difficult to re-use for different project.	Intelligent manufacturing logistics, cloud connected, high accuracy, special warehouse design, High load carrying capacity, suited to difficult working conditions (chemical industry)
2	Ergonomics	Easy User interface, low operator risk, sensors equipped, auto stop for overload/power fluctuations.	Operator required, Ease of operation, user safety, Noisy operation, option of auto and manual system	Easy UI, unmanned versions (AGC), navigation, low noise (battery operated)
3	Safety	Employee safety, multiple robots remotely controlled safety alarms, environment friendly, and product safety.	Electrical safety measures, rotating parts, noise control, comfort conditioning required.	Equipped with sensors, cameras, lasers for safety, Environment friendly, no harmful gasses emission, product safety, high precision work, product safety.
4	Reliability	Low product lag-time than manual, work in different terrain conditions, robust structure, Provide real time data without error.	High efficiency, no skilled labour required, less components.	High efficiency, Big production units, less margin for error, 24*7 running capability without fatigue, less machine downtime.
5	Maintenance	Low maintenance requirement, machine specific trained technicians required, self maintenance equipments, possible downtime when machine malfunction occurs.	Repair takes less time, readily available spares.	Low malfunction occurrence, trained technicians required, costly spares and not always readily available, any sudden error can result high machine downtime.
6	Cost	High cost of equipment, costly spares, low running cost and proves productive for continuous work.	Comparatively low cost, low maintenance cost.	Very high cost, suited for repetitive jobs.

or raw material and automatically complete the job without any lag. For these important characteristics, the AGV gets the Functionality score of 4.

In Ergonomic, it scored 4 for its ease in operatability and UI, unmanned versions (AGC), navigation ability and lower noise level. Similarly, in safety it scored 3 for no harmful gasses emission, safety sensors, cameras, environment friendly, product safety, high precision work etc. it is also highly efficient, high accuracy with 24*7 running capability, and low machine downtime. So it gets Reliability score of 4. AGV have very low chances of malfunction occurrence but whenever it happens, trained technicians are required and spares are costly and not readily available. Any sudden error can result high machine downtime. So its maintenance and cost score both comes as (3) and (2) respectively.

These material handling systems performs same task in many different ways. All three Material Handling Systems are evaluated as per the design attributes which are earlier discussed in Section 2. This evaluation is done on the bases of industry 4.0 capability of the available technology. All three technologies taken into consideration are thoroughly studied and their applications in different industry 4.0 concept based industries are holistically analyzed as mentioned in Table 5 and based on the capability of individual system, performance score is given to each alternative score is given in Table 6. The interpretation of the score value which is assigned in the Table 6 can be seen from the Table 2.

The equation of score matrix equation is illustrated in equation (3).

Table 6. Design attributes and score assigned to respective material handling systems.

S.No.	Alternatives → / Design attributes ↓	Robot	Conveyer	A.G.V.
1	Functionality	4	2	4
2	Ergonomics	3	2	4
3	Safety	4	3	3
4	Reliability	4	3	4
5	Cost	3	3	3
6	Maintenance	3	4	2

Table 7. Ranking of design alternatives of Example 1.

Design alternative	Index value (Ideal value 1 978 816)	Ranking
Robot	1 708 956	2
Conveyor	1 565 888	3
A.G.V	1 717 424	1

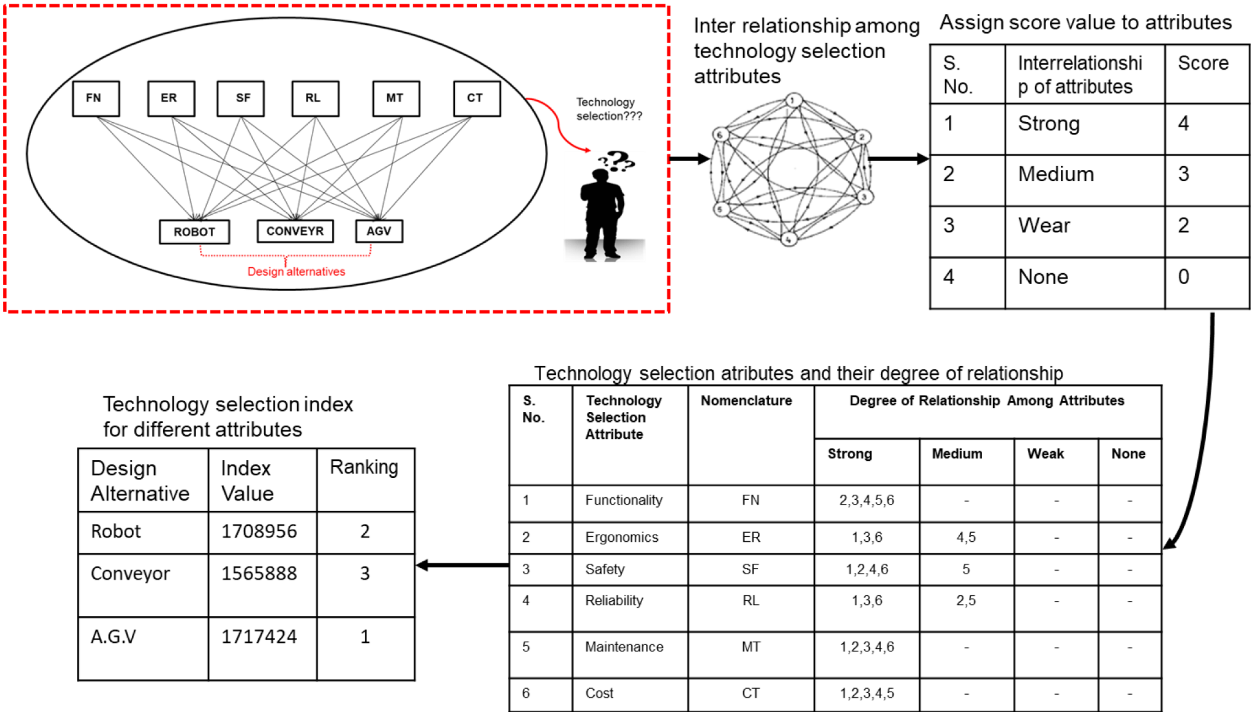
Score Matrix equations (6)–(8) of three design alternatives are mentioned below:

$$\begin{bmatrix} 4 & 4 & 4 & 4 & 4 & 4 \\ 4 & 3 & 4 & 3 & 3 & 4 \\ 4 & 4 & 4 & 4 & 3 & 4 \\ 4 & 3 & 4 & 4 & 3 & 4 \\ 4 & 3 & 3 & 3 & 3 & 3 \\ 4 & 4 & 4 & 4 & 4 & 3 \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} 3 & 4 & 4 & 4 & 4 & 4 \\ 4 & 3 & 4 & 3 & 3 & 4 \\ 4 & 4 & 3 & 4 & 3 & 4 \\ 4 & 3 & 4 & 3 & 3 & 4 \\ 4 & 3 & 3 & 3 & 3 & 3 \\ 4 & 4 & 4 & 4 & 4 & 4 \end{bmatrix} \tag{7}$$

$$\begin{bmatrix} 4 & 4 & 4 & 4 & 4 & 4 \\ 4 & 4 & 4 & 3 & 3 & 4 \\ 4 & 4 & 3 & 4 & 3 & 4 \\ 4 & 3 & 4 & 4 & 3 & 4 \\ 4 & 3 & 3 & 3 & 3 & 3 \\ 4 & 4 & 4 & 4 & 4 & 2 \end{bmatrix}. \tag{8}$$

Based on the index values obtained for all three desigh alternatives *i.e.*, Robot, Conveyor and A.G.V are 1 708 956, 1 565 888, and 1 717 424 respectively (see Tab. 7) while A.G.V has the highest index value and is therefore the first design preference. Robot emerges as second preffered alternative for industry 4.0 environment. Similarly, Conveyer with the least index value has least preference from industry 4.0 poin of view. Figure 4 illustrate the roadmap of the solution methodology which will be helpful for reader to understand how the proposed methodology have been implemented.



S. No.	Interrelationship of attributes	Score
1	Strong	4
2	Medium	3
3	Wear	2
4	None	0

S. No.	Technology Selection Attribute	Nomenclature	Degree of Relationship Among Attributes			
			Strong	Medium	Weak	None
1	Functionality	FN	2,3,4,5,6	-	-	-
2	Ergonomics	ER	1,3,6	4,5	-	-
3	Safety	SF	1,2,4,6	5	-	-
4	Reliability	RL	1,3,6	2,5	-	-
5	Maintenance	MT	1,2,3,4,6	-	-	-
6	Cost	CT	1,2,3,4,5	-	-	-

Design Alternative	Index Value	Ranking
Robot	1708956	2
Conveyor	1565888	3
A.G.V	1717424	1

FIGURE 4. Roadmap for implementation of proposed methodology for technology selection.

7.2. Example 2

An example is taken from digital products manufacturing companies from Serbia that perform the assessment of contemperory digital equipments in industry 4.0 based manufacturing facility [48]. The data is collected by European Manufacturing Survey (EMS) that include the advanced digital technologies applied in the industry 4.0 and what are the manufacturing features of the companies. In this research the author used a Hybrid fuzzy multi-attribute decision making model (HF-MADM).

This technological assessment was based on various design alternatives alternatives as given below:

(A1) Mobile Technology/wireless equipments for programming and controlling the equipments.
(A2) Digital methods to provide designs, work schedules or work ordersstraight on production line.
(A3) Software used for production planning and scheduling.
(A4) Real time exchange of product/process data between all stakeholders *i.e.*, customers, vendors, production, marketing team etc (*e.g.*, supply chain management).
(A5) Real-time production control by systems of centralized equipment operation and data acquisition.
(A6) Automated internal logistic management system.
(A7) Product Life Cyclemanagement (LCM) system.
(A8) Virtual reality (VR) technology or simulation for product design and/or new product development.

The score assigned to all eight design alternatives is given in Table 8.

Brief discription about all eight designe alternatives (A1 to A8) along with their score matrix is as follows:

(A1) Mobile Technology/wireless equipments for programming and controlling the equipments.

Industry 4.0 implementation demand the usage of IT-assisted connections between people, equipments and systems, for a real time data exchange using IoT enabled equipments and Cyber Physical Systems [68]. The

TABLE 8. Design attributes and score assigned to respective attribute (A1 to A8).

S.No.	Alternatives → / Design attributes ↓	Score assigned to respective design alternatives							
		A1	A2	A3	A4	A5	A6	A7	A8
1	Functionality	3	3	4	4	3	3	2	4
2	Ergonomics	2	3	4	3	0	3	2	2
3	Safety	3	3	3	4	2	3	3	3
4	Reliability	3	4	4	4	5	3	2	2
5	Maintenance	2	2	2	2	2	2	0	2
6	Cost	3	3	3	4	3	4	3	3

information generated from sensors or wireless networks, radio frequency identification (RFID), etc., enhances the range evaluation ability of available information. This data based decision making approch helps in making customer centric products and customized production and effictive use of machinery increases productivity with reduceed inventory expenditure. Equation (9) is the design score matrix of (A1).

$$\begin{bmatrix} 3 & 4 & 4 & 4 & 4 & 4 \\ 4 & 2 & 4 & 3 & 3 & 4 \\ 4 & 4 & 3 & 4 & 3 & 4 \\ 4 & 3 & 4 & 3 & 3 & 4 \\ 4 & 3 & 3 & 3 & 2 & 3 \\ 4 & 4 & 4 & 4 & 4 & 3 \end{bmatrix}. \tag{9}$$

(A2) Digital methods to provide designs, work schedules or work orders straight on production line

Industry 4.0 is a technology selection environment with self learning and intelligent equipments, the changes in product design can be made by consumer suggestions and as marketing team provide real time data of product related feedback. The other feature is cloud manufacturing which enables software as a service, production planning, customer response tracking system and data analysis [70]. By this interconnectivity between consumer feedback and manufacturing line, customized products can be made in less time by additive manufacturing systems thatl reduce transport distances and raw material stock [67]. Equation (10) shows the design score matrix of (A2).

$$\begin{bmatrix} 3 & 4 & 4 & 4 & 4 & 4 \\ 4 & 2 & 4 & 3 & 3 & 4 \\ 4 & 4 & 2 & 4 & 3 & 4 \\ 4 & 3 & 4 & 2 & 3 & 4 \\ 4 & 3 & 3 & 3 & 2 & 3 \\ 4 & 4 & 4 & 4 & 4 & 3 \end{bmatrix}. \tag{10}$$

(A3) Software used for production planning and scheduling

(*e.g.*, ERP system). Equation (11) is the design score matrix of (A3).

$$\begin{bmatrix} 4 & 4 & 4 & 4 & 4 & 4 \\ 4 & 4 & 4 & 3 & 3 & 4 \\ 4 & 4 & 3 & 4 & 3 & 4 \\ 4 & 3 & 4 & 4 & 3 & 4 \\ 4 & 3 & 3 & 3 & 2 & 3 \\ 4 & 4 & 4 & 4 & 4 & 3 \end{bmatrix}. \tag{11}$$

(A4) Real time exchange of product/process data between all stakeholders *i.e.*, customers, vendors, production, marketing team etc (*e.g.*, supply chain management)

Industry 4.0 refers to the establishment of the digital environment by the massive deployment of sensors along with the application of I4.0 technologies, namely, big data techniques, additive manufacturing, machine learning techniques, robotics and the industrial internet of things (IIoT) for enabling connectivity between customers and suppliers across complete value. Equation (12) is the design score matrix of (A4).

$$\begin{bmatrix} 4 & 4 & 4 & 4 & 4 & 4 \\ 4 & 3 & 4 & 3 & 3 & 4 \\ 4 & 4 & 2 & 4 & 3 & 4 \\ 4 & 3 & 4 & 4 & 3 & 4 \\ 4 & 3 & 3 & 3 & 2 & 3 \\ 4 & 4 & 4 & 4 & 4 & 4 \end{bmatrix}. \tag{12}$$

(A5) Real-time production control by systems of centralized equipment operation and data acquisition

Advanced Cloud and information technology based Cyber Physical System CPS) provide the desired speed and accuracy in industry 4.0. Real-time data acquisition and storage helps in analysing the problems more quickly and improves the reliability and efficiency of machinery and methods. Automated data generated from the system reduces human error and facilitates quality control in automotive manufacturing organizations. Equation (13) is the design score matrix of (A5).

$$\begin{bmatrix} 3 & 4 & 4 & 4 & 4 & 4 \\ 4 & 0 & 4 & 3 & 3 & 4 \\ 4 & 4 & 2 & 4 & 3 & 4 \\ 4 & 3 & 4 & 2 & 3 & 4 \\ 4 & 3 & 3 & 3 & 2 & 3 \\ 4 & 4 & 4 & 4 & 4 & 3 \end{bmatrix}. \tag{13}$$

(A6) Automated internal logistic management system

Logistics of an industry 4.0 scenario based factory are ment to be work in real time manufacturing pace. Modern industrial logistic 4.0 have automatic material storage systems, sensor equipped shelves (to provide exect requirement of raw material), AGVs/robots for material handling and automatic part sorting-selecting-packaging arrangement. management. The seamless flow in logistics information enables the timely order complition and improved order scheduling in industry (Javaid *et al.* 2021, [70]). Equation (14) is the design score matrix of (A6).

$$\begin{bmatrix} 3 & 4 & 4 & 4 & 4 & 4 \\ 4 & 3 & 4 & 3 & 3 & 4 \\ 4 & 4 & 3 & 4 & 3 & 4 \\ 4 & 3 & 4 & 3 & 3 & 4 \\ 4 & 3 & 3 & 3 & 2 & 3 \\ 4 & 4 & 4 & 4 & 4 & 4 \end{bmatrix}. \tag{14}$$

(A7) Product Life Cycle management (LCM) system

LCM of a product is to manage the complete journey of a product from conceptual design to its end of life after serving the purpose of manufacturing the product at fullest. There are various tools available for Product Life Cycle management *i.e.*, Centric Retail PLM, Aras PLM, Productboard etc. Equation (15) is the design

TABLE 9. Ranking of Design alternatives (A1–A8) of Example 2.

S.No.	Design alternative	Index value	Ranking
1	A1	1 088 468	8
2	A2	1 235 129	4
3	A3	1 687 356	2
4	A4	1 792 942	1
5	A5	1 420 592	3
6	A6	1 217 294	5
7	A7	1 095 282	7
8	A8	1 209 726	6

score matrix of (A7).

$$\begin{bmatrix} 2 & 4 & 4 & 4 & 4 & 4 \\ 4 & 2 & 4 & 3 & 3 & 4 \\ 4 & 4 & 3 & 4 & 3 & 4 \\ 4 & 3 & 4 & 2 & 3 & 4 \\ 4 & 3 & 3 & 3 & 0 & 3 \\ 4 & 4 & 4 & 4 & 4 & 3 \end{bmatrix}. \tag{15}$$

(A8) Virtual reality (VR) technology or simulation for product design and/or new product development

Virtual reality (VR) has become an essential tool for new product design. By simulating the design idea, it becomes easy to understand the product function and its application behaviour. Simulating the model improves the decision making for product selection and nessery changes can be done without actually making the product and saving the time and effort [3]. Following equation (16) is the score matrixs from attribute (A8):

$$\begin{bmatrix} 2 & 4 & 4 & 4 & 4 & 4 \\ 4 & 2 & 4 & 3 & 3 & 4 \\ 4 & 4 & 2 & 4 & 3 & 4 \\ 4 & 3 & 4 & 2 & 3 & 4 \\ 4 & 3 & 3 & 3 & 3 & 3 \\ 4 & 4 & 4 & 4 & 4 & 2 \end{bmatrix}. \tag{16}$$

Based on the index values obtained for all the eight design alternatives (A1–A8), A4 has the highest index value and, is therefore the most preferred design alternative (see Tab. 9). Similarly, A1 with the least index value will be last design alternative preference from industry 4.0 point of view.

8. Conclusion

The macro scale based evolution of technological advancements during the past few decades have revolutionized the dynamics of manufacturing environment, causing a significant momentum in the industrial sector. The integration of emerging technologies in manufacturing activities have widened the scope for facilities and systems promising better product quality, increased productivity, atomization, zero defects, fault diagnosis, greater system efficiency and, incremental profit trend. The systematic selection and implementation of technologies like IoT in the manufacturing environment, have paved way for nearly error free systems, with real time data mapping and realization, which further enhances the potential of manufacturing systems in a circular economy. A holistic framework for manufacturing systems in the domain of industry 4.0 has been presented in this research work, where the use of artificial intelligence, big data analytics, sensors and signal systems, machine learning, cloud computing, digital twin and, online monitoring systems can be used for better efficacy of technology selection approach. The proposed methodology will facilitate product designers in understanding various dimensions of industry 4.0-based manufacturing systems starting from conceptual design stage, to the virtual product testing mode through virtual and augmented reality, which leads towards better technology selection in manufacturing systems and lastly facilitate industrial engineers in effective decision making while implementing the industry 4.0-based manufacturing systems.

Two examples have been taken for demonstration and validation of the proposed technology selection model, in the domain of Industry 4.0. However, the proposed model can handle large number of technology selection parameters, used in decision making approach. The relationship and the correlations among various technology selection parameters are established through graph theory concept. Therefore, the proposed model can be implemented in other areas, such as defence, hospital management, scheduling sequencing problem, pathway variation analysis considering large number of manufacturing systems.

Appendix A.

Table A.1. Comparative literature survey based on multi criteria decision making model for implementation of Industry 4.0 in sustainable manufacturing systems.

Contributors (Authors)	Year of Publication	Manufacturing 4.0	Cloud Technology	Maintenance	Human resources in Industry 4.0	Sustainable Manufacturing 4.0/ Circular Economy
Talla and McIlwaine	2024	✓				
Rinat *et al.*	2024	✓			✓	
Pansare *et al.*	2024					
Abolfathi and Ebadian	2023					
Ali *et al.*	2023	✓	✓			
Jan *et al.*	2023	✓	✓			
Sezer *et al.*	2023					✓
Liu *et al.*	2023	✓				
Contieri *et al.*	2022	✓		✓		✓
Dhurkari	2022					
Javaid *et al.*	2022	✓				
Felsberger *et al.*	2022	✓				✓
Das and Dey	2021	✓				
Dev *et al.*	2021	✓	✓			✓
Jamwal *et al.*	2021					
Javaid *et al.*	2021	✓				✓
Goswami and Daultani	2021	✓	✓			
Lopes and Martins	2021	✓				
Singhal	2021	✓			✓	
Singh *et al.*	2021	✓			✓	
Wankhede and Vinodh	2021	✓				
Yang and Gu	2021	✓	✓			
Subramanian *et al.*	2021	✓				
Sangiorgio *et al.*	2021					
Tseng *et al.*	2021	✓	✓			✓
Mubarak *et al.*	2021	✓				✓
Neumann *et al.*	2021	✓	✓	✓	✓	
Motyl and Filippi	2021	✓				
Alcacer and Machado	2019	✓	✓			✓
Arnal *et al.*	2020	✓				✓
Bag and Pretorius	2020					✓

TABLE A.1. continued.

Contributors (Authors)	Year of Publication	Manufacturing 4.0	Cloud Technology	Maintenance	Human resources in Industry 4.0	Sustainable Manufacturing 4.0/ Circular Economy
Bai *et al.*	2020	✓				✓
Barbosa *et al.*	2020	✓				
Bongomin *et al.*	2020	✓	✓		✓	✓
Buchi *et al.*	2020	✓				
Harikannan *et al.*	2020	✓				✓
Hernandez-de-menendez *et al.*	2020	✓	✓		✓	
Hincapié *et al.*	2020	✓	✓		✓	
Jain and Ajmera	2020	✓				
Kamble *et al.*	2020	✓				✓
Karuppiah *et al.*	2020					✓
Kurfess *et al.*	2020	✓	✓			
Pessoa *et al.*	2020	✓		✓		
Raj *et al.*	2020	✓				
Machado *et al.*	2020	✓				✓
Moktadir *et al.*	2020					✓
Narula *et al.*	2020	✓				
You and Feng	2020	✓		✓		
Zolotová *et al.*	2020		✓			
Rossini *et al.*	2019	✓				✓
Medic *et al.*	2019					
Dalmarco *et al.*	2019	✓	✓			
Erdogan *et al.*	2018	✓	✓			
Fedorko *et al.*	2018					
Vaidya *et al.*	2018	✓		✓	✓	
Sinha and Anand	2017					✓
Geetha and Sekar	2017					
Li *et al.*	2017	✓		✓		
Bechtsis *et al.*	2017	✓				✓
Liu *et al.*	2017	✓				
Anand *et al.*	2016					✓
Bigaj *et al.*	2014	✓		✓		
Bordoloi and Kalita	2013					
Gadakh and Shinde	2011					
Anand and Wani	2010					✓
Borenstein *et al.*	1997					
Chen	1997					
Jurkat and Ryser	1966					

REFERENCES

[1] M.A. Abolfathi and A. Ebadian, Interval-valued picture fuzzy aggregation information based on Frank operators and their application in group decision making. *RAIRO-Oper. Res.* **57** (2023) 3191–3222.

[2] M.B. Ahmed, F. Majeed, C. Sanin and E. Szczerbicki, Smart virtual product development (SVPD) system to support product inspection planning in industry 4.0. *Proc. Comput. Sci.* **176** (2020) 2596–2604.

[3] V. Alcácer and V. Cruz-Machado, Scanning the industry 4.0: a literature review on technologies for manufacturing systems. *Eng. Sci. Technol. Int. J.* **22** (2019) 899–919.

[4] S.S. Ali, R. Kaur and S. Khan, Identification of innovative technology enablers and drone technology determinants adoption: a graph theory matrix analysis framework. *Oper. Manage. Res.* **16** (2023) 830–852.

[5] A. Anand and M.F. Wani, Product life-cycle modeling and evaluation at the conceptual design stage: a digraph and matrix approach, *J. Mech. Design* **132** (2010) 091010.

[6] A. Anand, R.A. Khan and M.F. Wani, Development of a sustainability risk assessment index of a mechanical system at conceptual design stage. *J. Clean. Prod.* **139** (2016) 258–266.

[7] Á.J. Arnal, M. Díaz-Ramírez, L. Acevedo, V.J. Ferreira, T. García-Armingol, A.M. López-Sabirón and G. Ferreira, Multicriteria analysis for retrofitting of natural gas melting and heating furnaces for sustainable manufacturing and industry 4.0. *J. Energy Res. Technol.* **142** (2020) 022203.

[8] S. Bag and J.H.C. Pretorius, Relationships between industry 4.0, sustainable manufacturing and circular economy: proposal of a research framework. *Int. J. Org. Anal.* **30** (2020) 864–898.
[9] C. Bai, P. Dallasega, G. Orzes and J. Sarkis, Industry 4.0 technologies assessment: a sustainability perspective. *Int. J. Prod. Econ.* **229** (2020) 107776.
[10] W.S. Barbosa, M.M. Gioia, V.G. Natividade, R.F. Wanderley, M.R. Chaves, F.C. Gouvea and F.M. Gonçalves, Industry 4.0: examples of the use of the robotic arm for digital manufacturing processes. *Int. J. Interact. Design Manuf.* **14** (2020) 1569–1575.
[11] D. Bechtsis, N. Tsolakis, D. Vlachos and E. Iakovou, Sustainable supply chain management in the digitalisation era: the impact of Automated Guided Vehicles. *J. Clean. Prod.* **142** (2017) 3970–3984.
[12] P. Bigaj, J. Bartoszek and M. Trojnacki, The analysis of influence of sensors' failure on the performance of mobile robot autonomy. *J. Autom. Mobile Rob. Intell. Syst.* **8** (2014) 31–39.
[13] O. Bongomin, G. Gilibrays Ocen, E. Oyondi Nganyi, A. Musinguzi and T. Omara, Exponential disruptive technologies and the required skills of industry 4.0. *J. Eng.* (2020). DOI 10.1155/2020/4280156.
[14] S. Bordoloi and B. Kalita, Designing graph database models from existing relational databases. *Int. J. Comput. App.* **74** (2013) 25–31.
[15] J. Borenstein, H.R. Everett, L. Feng and D. Wehe, Mobile robot positioning: sensors and techniques. *J. Rob. Syst.* **14** (1997) 231–249.
[16] G. Büchi, M. Cugno and R. Castagnoli, Smart factory performance and industry 4.0. *Technol. Forecasting Soc. Change* **150** (2020) 119790.
[17] W.K. Chen, Graph Theory and its Engineering Applications. Vol. 5. World Scientific (1997).
[18] P.G.S. Contieri, R. Anholon and L.A. De Santa-Eulalia, Industry 4.0 enabling technologies in manufacturing: implementation priorities and difficulties in an emerging country. *Technol. Anal. Strategic Manage.* **34** (2022) 489–503.
[19] G. Dalmarco, F.R. Ramalho, A.C. Barros and A.L. Soares, Providing industry 4.0 technologies: the case of a production technology cluster. *J. High Technol. Manage. Res.* **30** (2019) 100355.
[20] A. Das and S. Dey, Global manufacturing value networks: assessing the critical roles of platform ecosystems and Industry 4.0. *J. Manuf. Technol. Manage.* **32** (2021) 1290–1311.
[21] N.K. Dev, R. Shankar, Z.G. Zacharia and S. Swami, Supply chain resilience for managing the ripple effect in Industry 4.0 for green product diffusion. *Int. J. Phys. Distrib. Logistics Manage.* **51** (2021) 897–930.
[22] R.K. Dhurkari, MCDM methods: practical difficulties and future directions for improvement. *RAIRO-Oper. Res.* **56** (2022) 2221–2233.
[23] M. Erdogan, B. Ozkan, A. Karasan and I. Kaya, Selecting the best strategy for industry 4.0 applications with a case study, in Industrial Engineering In The Industry 4.0 Era. Springer, Cham (2018) 109–119.
[24] G. Fedorko, V. Molnár, S. Honus, M. Beluško and M. Tomašková, Influence of selected characteristics on failures of the conveyor belt cover layer material. *Eng. Failure Anal.* **94** (2018) 145–156.
[25] A. Felsberger, F.H. Qaiser, A. Choudhary and G. Reiner, The impact of Industry 4.0 on the reconciliation of dynamic capabilities: evidence from the European manufacturing industries. *Prod. Planning Control* **33** (2022) 277–300.
[26] V.S. Gadakh and V.B. Shinde, Selection of cutting parameters in side milling operation using graph theory and matrix approach. *Int. J. Adv. Manuf. Technol.* **56** (2011) 857–863.
[27] O.P. Gandhi and V.P. Agrawal, Failure cause analysis – a structural approach. *J. Pressure Vessel Technol.* **118** (1996) 434–440.
[28] N.K. Geetha and P. Sekar, Graph theory matrix approach – a qualitative decision making tool. *Mater. Today: Proc.* **4** (2017) 7741–7749.
[29] R. Goel and P. Gupta, Robotics and industry 4.0, in A Roadmap to Industry 4.0: Smart Production, Sharp Business and Sustainable Development. (2020) 157–169.
[30] M. Goswami and Y. Daultani, Make-in-India and Industry 4.0: technology readiness of select firms, barriers and socio-technical implications. *TQM J.* (2021). DOI: 10.1108/TQM-06-2021-0179.
[31] N. Harikannan, S. Vinodh and A. Gurumurthy, Sustainable industry 4.0an exploratory study for uncovering the drivers for integration. *J. Model. Manag.* **16** (2020) 357–376.
[32] M. Hernandez-de-Menendez, R. Morales-Menendez, C.A. Escobar and M. McGovern, Competencies for industry 4.0. *Int. J. Interact. Design Manuf.* **14** (2020) 1511–1524.
[33] M. Hincapié, A. Valdez, D. Güemes-Castorena and M. Ramírez, Use of laboratory scenarios as a strategy to develop smart factories for Industry 4.0. *Int. J. Interact. Design Manuf.* **14** (2020) 1285–1304.
[34] V. Jain and P. Ajmera, Modelling the enablers of industry 4.0 in the Indian manufacturing industry. *Int. J. Prod. Perf. Manage.* **70** (2020) 1233–1262.

[35] A. Jamwal, R. Agrawal, M. Sharma and A. Giallanza, Industry 4.0 technologies for manufacturing sustainability: a systematic review and future research directions. *Appl. Sci.* **11** (2021) 5725.

[36] Z. Jan, F. Ahamed, W. Mayer, N. Patel, G. Grossmann, M. Stumptner and A. Kuusk, Artificial intelligence for industry 4.0: systematic review of applications, challenges, and opportunities. *Expert Syst. App.* **216** (2023) 119456.

[37] M. Javaid, S. Khan, A. Haleem and S. Rab, Adoption of modern technologies for implementing industry 4.0: an integrated MCDM approach. *Benchmarking Int. J.* **30** (2022) 3753–3790.

[38] M. Javaid, I.H. Khan, R.P. Singh, S. Rab and R. Suman, Exploring contributions of drones towards Industry 4.0. Industrial Robot: *Int. J. Robot. Res. Appl.* **49** (2021) 476–490.

[39] W.B. Jurkat and H.J. Ryser, Matrix factorizations of determinants and permanents. *J. Algebra* **3** (1966) 1–27.

[40] S. Kamble, A. Gunasekaran and N.C. Dhone, Industry 4.0 and lean manufacturing practices for sustainable organisational performance in Indian manufacturing companies. *Int. J. Prod. Res.* **58** (2020) 1319–1337.

[41] K. Karuppiah, B. Sankaranarayanan, S.M. Ali, P. Chowdhury and S.K. Paul, An integrated approach to modeling the barriers in implementing green manufacturing practices in SMEs. *J. Clean. Prod.* **265** (2020) 121737.

[42] T.R. Kurfess, C. Saldana, K. Saleeby and M.P. Dezfouli, A review of modern communication technologies for digital manufacturing processes in industry 4.0. *J. Manuf. Sci. Eng.* **142** (2020) 1–8.

[43] Z. Li, Y. Wang and K.S. Wang, Intelligent predictive maintenance for fault diagnosis and prognosis in machine centers: Industry 4.0 scenario. *Adv. Manuf.* **5** (2017) 377–387.

[44] Y. Liu, X. Ma, L. Shu, G.P. Hancke and A.M. Abu-Mahfouz, From Industry 4.0 to Agriculture 4.0: current status, enabling technologies, and research challenges. *IEEE Trans. Ind. Inf.* **17** (2020) 4322–4334.

[45] M. Liu, T. Lin, F. Chu, F. Zheng and C. Chu, A new and general stochastic parallel machine ScheLoc problem with limited location capacity and customer credit risk. *RAIRO-Oper. Res.* **57** (2023) 1179–1193.

[46] M.A. Lopes and R.A. Martins, Mapping the impacts of industry 4.0 on performance measurement systems. *IEEE Lat. Am. Trans.* **19** (2021) 1912–1923.

[47] C.G. Machado, M.P. Winroth and E.H.D. Ribeiro da Silva, Sustainable manufacturing in Industry 4.0: an emerging research agenda. *Int. J. Prod. Res.* **58** (2020) 1462–1484.

[48] N. Medić, Z. Anišić, B. Lalić, U. Marjanović and M. Brezocnik, Hybrid fuzzy multi-attribute decision making model for evaluation of advanced digital technologies in manufacturing: Industry 4.0 perspective. *Adv. Prod. Eng. Manage.* **14** (2019) 483–493.

[49] M.A. Moktadir, H.B. Ahmadi, R. Sultana, J.J. Liou and J. Rezaei, Circular economy practices in the leather industry: a practical step towards sustainable development. *J. Clean. Prod.* **251** (2020) 119737.

[50] B. Motyl and S. Filippi, Trends in engineering education for additive manufacturing in the industry 4.0 era: a systematic literature review. *Int. J. Interact. Design Manuf.* **15** (2021) 103–106.

[51] M.F. Mubarak, S. Tiwari, M. Petraite, M. Mubarik and R.Z.R.M. Rasi, 2021. How Industry 4.0 technologies and open innovation can improve green innovation performance? *Manage. Environ. Qual. Int. J.* **32** (2021) 1007–1022.

[52] S. Narula, S. Prakash, M. Dwivedy, V. Talwar and S.P. Tiwari, Industry 4.0 adoption key factors: an empirical study on manufacturing industry. *J. Adv. Manage. Res.* **17** (2020) 697–725.

[53] S. Narula, H. Puppala, A. Kumar, G.F. Frederico, M. Dwivedy, S. Prakash and V. Talwar, Applicability of industry 4.0 technologies in the adoption of global reporting initiative standards for achieving sustainability. *J. Clean. Prod.* **305** (2021) 127141.

[54] W.P. Neumann, S. Winkelhaus, E.H. Grosse and C.H. Glock, Industry 4.0 and the human factor – a systems framework and analysis methodology for successful development. *Int. J. Prod. Econ.* **233** (2021) 107992.

[55] R. Pansare, G. Yadav and M.R. Nagare, Integrating operational excellence strategies with Industry 4.0 technologies through reconfigurable manufacturing system practices. *TQM J.* **36** (2024) 3–23.

[56] M.P. Pessôa and J.J. Becker, Smart design engineering: a literature review of the impact of the 4th industrial revolution on product design and development. *Res. Eng. Design* **31** (2020) 175–195.

[57] A. Raj, G. Dwivedi, A. Sharma, A.B.L. de Sousa Jabbour and S. Rajak, Barriers to the adoption of industry 4.0 technologies in the manufacturing sector: an inter-country comparative perspective. *Int. J. Prod. Econ.* **224** (2020) 107546.

[58] K. Rinat, G. Thakur, M. Gupta, T.N.P. Madhuri and S. Bansal, Comparative analysis of big data computing in Industry 4.0 and Industry 5.0: an experimental study, in BIO Web of Conferences. Vol. 86. EDP Sciences (2024) 01068.

[59] M. Rossini, F. Costa, G.L. Tortorella and A. Portioli-Staudacher, The interrelation between Industry 4.0 and lean production: an empirical study on European manufacturers. *Int. J. Adv. Manuf. Technol.* **102** (2019) 3963–3976.

[60] V. Sangiorgio, B. Di Pierro, M. Roccotelli and B. Silvestri, Card game analysis for fast multi-criteria decision making. *RAIRO-Oper. Res.* **55** (2021) 1213–1229.

[61] M.D. Sezer, M. Ozbiltekin-Pala, Y. Kazancoglu, J.A. Garza-Reyes, A. Kumar and V. Kumar, Investigating the role of knowledge-based supply chains for supply chain resilience by graph theory matrix approach. *Oper. Manage. Res.* **16** (2023) 1220–1230.

[62] R.K. Singh, S. Agrawal and S. Modgil, Developing human capital 4.0 in emerging economies: an industry 4.0 perspective. *Int. J. Manpower* **43** (2021) 286–309.

[63] N. Singhal, An empirical investigation of Industry 4.0 preparedness in India. *Vision* **25** (2021) 300–311.

[64] A.K. Sinha and A. Anand, Towards fuzzy preference relationship based on decision making approach to access the performance of suppliers in environmental conscious manufacturing domain. *Comput. Ind. Eng.* **105** (2017) 39–54.

[65] G. Subramanian, B.T. Patil and B.B. Gardas, Evaluation of enablers of cloud technology to boost industry 4.0 adoption in the manufacturing micro, small and medium enterprises. *J. Modell. Manage.* **16** (2021) 944–962.

[66] A. Talla and S. McIlwaine, Industry 4.0 and the circular economy: using design-stage digital technology to reduce construction waste. *Smart Sustain. Built Environ.* **13** (2024) 179–198.

[67] S. Vaidya, P. Ambad and S. Bhosle, Industry 4.0 – a glimpse. *Proc. Manuf.* **20** (2018) 233–238.

[68] V.A. Wankhede and S. Vinodh, State of the art review on Industry 4.0 in manufacturing with the focus on automotive sector. *Int. J. Lean Six Sigma* **13** (2021) 692–732.

[69] M.F. Wani and A. Anand, Life-cycle assessment modelling and life-cycle assessment evaluation of a triboelement. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, **224** (2021) 1209–1220.

[70] F. Yang and S. Gu, Industry 4.0, a revolution that requires technology and national strategies. *Complex Intell. Syst.* **7** (2021) 1311–1325.

[71] Z. You and L. Feng, Integration of industry 4.0 related technologies in construction industry: A framework of cyber-physical system. *IEEE Access* **8** (2020) 122908–122922.

[72] I. Zolotová, P. Papcun, E. Kajáti, M. Miškuf and J. Mocnej, Smart and cognitive solutions for Operator 4.0: laboratory H-CPPS case studies. *Comput. Ind. Eng.* **139** (2020) 105471.