EASR

Engineering and Applied Science Research

https://www.tci-thaijo.org/index.php/easr/index

Published by the Faculty of Engineering, Khon Kaen University, Thailand

Analysis of knowledge and skills essential for industrial engineers in context of Industry 4.0 within Thai automobile sector

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Received 29 October 2023
Revised 20 December 2023
Accepted 26 December 2023

Abstract

Industry 4.0 has rapidly transformed traditional industries and manufacturing processes by seamlessly integrating digital technologies, automation, data analytics, and the Internet of Things. It represents a profound shift in business operations, emphasizing efficiency, flexibility, and responsiveness to customers. As a result, the required knowledge and skills are evolving for all relevant personnel including industrial engineers (IEs), to achieve success in the Industry 4.0 era. Preparing a capable IE workforce to meet these changing demands is a persistent challenge, particularly in a rapidly evolving environment. This study aims to identify the needs of Thai automobile companies regarding the knowledge and skills of IEs for Industry 4.0. Furthermore, it aims to rank these IE knowledge and skills in terms of importance. In this study, a questionnaire was developed and used as a tool for the research. Respondents representing 31 companies in the Thai automobile industry were asked to rate the importance of each knowledge area and skill. Questions in the knowledge section were divided into 15 knowledge areas across four categories: core subjects, global subjects, engineering subjects, and technological fundamentals. The questions in the skill section were divided into 18 skills spanning five categories: communication, system thinking, creative thinking/ adaptation/ decision-making, learning, and technical proficiency. There are also 12 questions asking respondents to evaluate their level of Industry 4.0 adoption. The findings indicate that the importance rankings for essential IE knowledge and skills vary across a distinct group of Industry 4.0 adoption levels. The rankings of vital IE knowledge and skills across these diverse adoption levels are comparatively analyzed and discussed. While this study primarily centers on the automotive industry, it has the potential to illuminate broader trends that extend to other sectors as well.

Keywords: Industry 4.0, Industrial engineer, Knowledge, Skills

1. Introduction

Industry 4.0 is the integration of industrial systems with information communication technologies (ICT) and other industrial technologies to provide the information for making effective and optimal decisions through faster and more precise processes, which can significantly add value both upstream and downstream of the supply chain [1-6]. In addition, Industry 4.0 creates better real-time flexibility and connectivity in the production processes by giving the machine the ability to virtually visualize and decentralize the system, which has a great many implications [1-6]. To complete the interoperation of the system, the production processes involve technologies such as sensor- and cloud-based technologies, Internet of Things (IoT), cyber-physical systems (CPS), and big data [1-6]. Other frequently cited technologies of Industry 4.0 are autonomous robots, artificial intelligence (AI), augmented reality (AR) and virtual reality (VR), data security/cybersecurity, simulation, additive manufacturing, and horizontal and vertical integration [7-13]. The applications of technologies can vary depending on an organization’s characteristics, even within the same industrial sector [14-18].

Although the advanced applications of Industry 4.0 technologies can enable an organization to transform its processes, the difficulty of adapting human resources to work in the Industry 4.0 environment is still a major challenge [19, 20]. Actions are needed to deliver competent human resources, a key opportunity factor for an organization to maintain competitiveness in the era of Industry 4.0 [21-23].

Currently, the Thai government has a policy to promote the transformation of the country’s industry into an innovative and value-based market for 12 industries, including the automotive industry, which accounts for about 12% of Thailand’s economic growth and employs over 850,000 people [24, 25]. Thailand has been attracting all of the world’s most renowned assemblers and manufacturers of automotive and automotive components, which account for a significant share of the country’s annual car production of around two million units [25, 26]. The automotive industry includes the manufacture of automobiles for the carriage of passengers or freight, the manufacture of other parts and accessories for automobiles, and the manufacture of bodies for automobiles, including trailers and semitrailers [27]. Although the global pandemic that occurred in 2019 caused a reduction in the country’s GDP, it did not impact the growing demand for green vehicles. The Thai government has increased its export capacity and has aggressively encouraged international manufacturers to use Thailand as a regional green vehicle manufacturing base [24]. It has been the largest country in the Association of Southeast Asian Nations (ASEAN) for automotive manufacturing and an export hub for more than 50 years [24, 25].

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doi: 10.14456/easr.2024.19

There is a growing demand for competent human resources to support Thailand's competitive position in the automotive industry. Industry 4.0 applications have already had a huge impact on the automotive industry. The Thai government expects research and development (R&D) in technologies [24, 28] as well as competent human resources [24, 29, 30] to enable the country's competitive potential. The requirements from the Thai government are to encourage a requisite roadmap and policy for human resources in the era of Industry 4.0, especially in the automotive industry.

Using the concepts and techniques of engineering analysis, industrial engineers (IE) are responsible for the design, improvements, and installation of an integrated system of people, materials, machines, methods, and information [31]. The role of the IE in industry is particularly important, as it necessitates designing operational solutions based on simulation and optimization to meet the customers' requirements, selecting techniques and technologies to support shop-floor activities using logical procedures with finite resources, and implementing changes in operations that lead to digitalization and automation [3, 6, 32]. Therefore, it is important to prepare the IEs that the industry needs, and particularly IEs for Industry 4.0.

A specific job requires a specific set of knowledge and skills. Knowledge and skills are two separate but related factors that affect a person's performance and competency. Knowledge is the theoretical understanding of concepts, facts, principles, information, and a subject relevant to a certain field of work or study acquired through learning, education, and experience [33-35]. Skills, however, refer to the ability to apply knowledge to specific situations. Skills are developed through practice, training or hands-on experience [33-35]. To the best of our knowledge, although quite a number of studies have been done on the IE qualifications required for Industry 4.0 [36-43], none have studied the needs of a specific industry such as the automotive industry, particularly in the Thai context. This research thus aims to identify important IE knowledge and skills required for Industry 4.0 for the Thai automobile industry.

2. Research methodology

This research used a questionnaire to prioritize and identify the important knowledge and skills of an IE that the automobile industry needs to support Industry 4.0. Representatives of companies in the automobile industry in Thailand were asked to rate the importance of each knowledge and skill area in the questionnaire.

2.1 Questionnaire development

Lists of knowledge and skills were compiled from previous research related to knowledge and skills in the 21st century, engineers' competencies to support Industry 4.0, and IE competencies for Industry 4.0. Once compiled, the researchers then grouped and adapted them to the context of IE and Industry 4.0. Table 1 shows the main categories, and knowledge and skills in each category. Details of each knowledge area and skill and pertinent references are described below. These lists of knowledge and skills were later used in the questionnaire.

Table 1 Main categories, and knowledge and skills in each category

Main categories		Knowledge/skill
1. Knowledge	1.1 Core subjects	1.1.1 Mathematics and statistics fundamentals 1.1.2 Physical and chemical sciences 1.1.3 Economics and business 1.1.4 Foreign languages 1.1.5 Law and politics
	1.2 Global subjects	1.2.1 Civic literacy 1.2.2 Health literacy 1.2.3 Environmental literacy 1.2.4 Global awareness
	1.3 Engineering subjects	1.3.1 Engineering fundamentals 1.3.2 Engineers' laws, regulations, and standards 1.3.3 Specialized knowledge in industrial engineering
	1.4 Technological fundamentals	1.4.1 Technology application 1.4.2 Information literacy 1.4.3 Recent innovation trends
2. Skills	2.1 Communication skills	2.1.1 Speaking and listening 2.1.2 Presentation
	2.2 System thinking skills	2.2.1 Component interaction understanding 2.2.2 Critical thinking 2.2.3 Analytical thinking 2.2.4 Problem-solving
	2.3 Creative thinking, adaptation, and decision-making skills	2.3.1 Creative thinking 2.3.2 Adaptation 2.3.3 Decision-making
	2.4 Learning skills	2.4.1 Good questioning 2.4.2 Cross-disciplinary skills 2.4.3 Lifelong learning 2.4.4 Research skills
	2.5 Technical skills	2.5.1 Operational planning 2.5.2 Choosing the right tool 2.5.3 Managing and prioritizing 2.5.4 Skills in using tools 2.5.5 Supervising the use of tools

1. *Knowledge*: consists of 4 main categories: core subjects, global subjects, engineering subjects, and technological fundamentals. These main categories can be further divided into 15 items as shown in Table 1.

1.1 Core subjects ground the foundations for developing other knowledge. Knowledge in this category includes:

1.1.1 Mathematics and statistics fundamentals [40, 41, 43-53]

1.1.2 Physical and chemical sciences [32, 41, 43-62]

1.1.3 Economics and business [32, 38, 43-50, 52-55, 57, 59-61, 63]

1.1.4 Foreign languages [32, 40, 43-50, 55, 57-64]

1.1.5 Law and politics [43, 45, 46, 48-51, 54, 57-61, 63, 65, 66].

1.2 Global subjects include contemporary issues in all modern societies. Knowledge in this category includes:

1.2.1 Civic literacy [32, 38, 41, 43-46, 48-50, 52-65, 67]

1.2.2 Health literacy [32, 38, 41, 45, 46, 49, 51-53, 55, 59-61, 63]

1.2.3 Environmental literacy [32, 43, 45, 49, 50, 52-55, 59-61, 63, 65]

1.2.4 Global awareness [32, 41, 43-46, 49-56, 58-60, 62-66].

1.3 Engineering subjects are used in real professional practice, and extend the understanding of core subjects. Engineering knowledge includes not only the fundamentals of engineering, but also specialized knowledge of IE and the knowledge that links to Industry 4.0. Knowledge in this category includes the following:

1.3.1 Engineering fundamentals include (1) applied mathematics, computer and simulations, (2) mechanics, (3) thermal sciences and fluid mechanics, (4) chemistry and materials, (5) energy, (6) electricity and electronics, (7) system management, and (8) biology, health, and environment [32, 38, 40, 41, 43-47, 49, 51, 53, 55, 58-62, 65, 67].

1.3.2 Engineers' laws, regulations, and standards include (1) specifications and inspection standards, (2) measurement systems, (3) engineering codes of practice and ethics, (4) role of an engineer, and (5) laws and regulations for the practice of engineering [32, 43-45, 49, 51, 53, 60, 62, 68].

1.3.3 Specialized knowledge in industrial engineering includes 9 branches of IE professions, which are (1) materials and manufacturing processes, (2) work systems and safety, (3) quality systems, (4) economics and finance, (5) production and operations management, (6) integration of industrial engineering techniques, (7) data analytics, (8) integration of ICT systems, and (9) industrial robotics [38, 41, 43-45, 47, 49, 51, 53, 57-60, 62, 65].

1.4 Technological fundamentals include digitized manufacturing components and their capabilities, implementation, and the utilization of technologies of Industry 4.0. Knowledge in this category includes the following:

1.4.1 Technology application relates to the creation and utilization of technology facilities and their relationships to life, society, and the environment by studying the capabilities of technologies when implemented with existing systems and processes [32, 38, 40, 41, 43-54, 56-63, 67, 69-71].

1.4.2 Information literacy includes such processes as selection, access, integration, analysis, integrity, and sharing of data in socially networked environments, which also raises some issues such as cyber-security and data privacy [32, 38, 40, 41, 43, 44, 46-48, 50-53, 56-61, 64, 65, 67, 69-71].

1.4.3 Recent innovation trends include the latest innovations such as tools, techniques, and technologies: for example, the intelligence grid, VR and AR [32, 41, 43, 45, 46, 49-52, 58, 60, 61, 70, 71].

2. *Skills*: consists of 5 main categories: communication skills, system thinking skills, inventive thinking skills, learning skills, and technical skills, which can be further divided into 18 items, summarized in Table 1. The details are as follows:

2.1 Communication skills include communicating, exchanging, and presenting information and one's ideas through writing and speaking, at a level of adequate expression. Skills in this category are as follows:

2.1.1 Speaking and listening [32, 40, 41, 43-46, 48-52, 57-67, 69, 71]

2.1.2 Presentation [40, 41, 43-45, 49, 50, 52, 57, 59, 62, 64, 65, 69].

2.2 System thinking skills require a constructive thinking ability to give adequate reasons. Skills in this category are as follows:

2.2.1 Component interaction understanding [32, 38, 40, 43, 45, 48-52, 54, 57, 59, 61-63, 66, 67]

2.2.2 Critical thinking [32, 41, 43-47, 49-51, 53-56, 58, 59, 61-63, 65, 67, 69, 71]

2.2.3 Analytical thinking [32, 38, 41, 43-49, 51, 53, 56-59, 61-63, 65-67, 69, 71]

2.2.4 Problem-solving [32, 38, 40, 41, 43-52, 54, 55, 57-65, 67, 69, 71].

2.3 Creative thinking, adaptation, and decision-making skills are concerned with applying the creative and evaluative aspects of one's ideas to a wide range of challenges involving uncertainty and diversity. Skills in this category are as follows:

2.3.1 Creative thinking [32, 38, 41, 43-49, 51-53, 60-63, 66, 67, 69, 70]

2.3.2 Adaptation [40, 41, 43-50, 52, 54, 57-59, 62, 64, 65, 70]

2.3.3 Decision-making [32, 38, 40, 41, 43-46, 49, 52, 53, 56-59, 61, 63, 65-67, 69, 70].

2.4 Learning skills are the ability to observe and explore, to have curiosity, and to pose relevant questions. Skills in this category are as follows:

2.4.1 Good questioning [32, 40, 43, 45, 49-51, 56, 59, 60, 62-65, 67, 70]

2.4.2 Cross-disciplinary skills [32, 40, 41, 44-45, 48-50, 52-55, 57, 59-64, 67, 70]

2.4.3 Lifelong learning [32, 40, 41, 43-48, 50, 52, 54, 57-60, 62-65, 67, 70]

2.4.4 Research skills [32, 38, 41, 43-45, 49, 52, 57-61, 65, 66].

2.5 Technical skills are a set of abilities that allow the use of tools, basic industrial operations, and fundamental technological capacities to achieve specific results. Skills in this category are as follows:

2.5.1 Operational planning [32, 38, 41, 43-46, 51, 52, 58, 59, 61, 64-66, 70, 72]

2.5.2 Choosing the right tool [32, 43-45, 47, 48, 51, 52, 54, 58, 59, 61-63, 65, 66, 70, 72]

2.5.3 Managing and prioritizing [32, 38, 41, 43-45, 48, 51, 52, 57-59, 61, 63, 65-67, 69, 70, 72]

2.5.4 Skills in using tools [32, 38, 41, 43-49, 51-53, 57-59, 61, 63, 65-67, 69-72]

2.5.5 Supervising the use of tools [32, 38, 41, 43-48, 51-53, 57-59, 61-63, 65-67, 69-72].

A questionnaire to prioritize and identify important IE knowledge and skills for Industry 4.0 from the automotive industry in Thailand's perspective was developed. The questionnaire consists of three parts with the following details:

Part 1 consists of 5 questions asking about the respondent and the company, such as the job position of the respondent, years of experience in the current position of the respondent, area of experience of the respondent, years of experience in the automotive industry of the respondent, and the organization category in the automotive industry, i.e., automobiles, other parts and accessories for automobiles, and bodies for automobiles, including trailers and semitrailers. Descriptive statistics were used in this part of the analysis.

Part 2 consists of 12 questions asking about the company's actions with regard to Industry 4.0. These questions asked about the level of Industry 4.0 adoption in 12 aspects: (1) the company's implementation of the Industry 4.0 strategy, (2) the company's investment in the implementation of Industry 4.0, (3) the company's information technology (IT) equipment infrastructure through the collection, storage, and processing of data, (4) the company's operations via IT systems in its supply chain, (5) the company's usage of cloud technology, (6) the company's status of IT security, (7) the company's autonomous processes for production, (8) the company's status of information sharing, (9) the company's products equipped with information communication technology (ICT) components, (10) the company's data-driven services, (11) the company's data analytics services of its products in the usage phase, and (12) the company's requirements for workforce qualifications of Industry 4.0. This research is a continuation of [73], which developed a model for assessment of the level of Industry 4.0 adoption. In developing such a model, [73] used past research studies as a guideline to develop these 12 questions. Please refer to [73] for more details about the assessment of the phase of Industry 4.0 adoption in the automotive industry in Thailand.

Part 3 consists of 33 questions asking about the level of importance of each knowledge area and skill (as shown in Table 1) for the IE to support Industry 4.0 in the automotive industry in Thailand. All the knowledge and skills studied and researched in 34 previous research works [32, 38, 40, 41, 43-72] were studied, compiled, grouped and adapted to the IE and Industry 4.0 context, resulting in a total of 33 knowledge and skills questions used in this part of the questionnaire. The respondents were asked to rate the level of importance, with 5 being the most important, 4 being very important, 3 being moderately important, 2 being less important, and 1 the least important.

The questionnaire was all in Thai, so that the respondents could fully comprehend it. In addition, the questionnaire also included definitions of all relevant terms, so that the respondents understood their meanings clearly.

2.2 Questionnaire content validity

Before distributing the questionnaire, the index of Item-Objective Congruence (IOC) was used to test the content validity. Three experts in the fields of Industry 4.0 & IE, questionnaire development, and the automotive industry were asked to rate each question on a scale of 1 for clearly measuring the objective, -1 for not clearly measuring, or 0 for somewhat measuring the objective or being unclear whether it measures the objective [74]. The mean IOC score for each question was calculated. If the question had a mean IOC score between 0.5 and 1, that question was considered acceptable [75]. However, if the question had a mean IOC score below 0.5, the question needed to be reviewed or changed according to the experts' advice [75]. The researchers improved those questions by either providing adequate comprehensive descriptions or changing the questions to better reflect the research objectives. The researchers then discussed with the experts again until the IOC met the criteria. For the final results, all questions met the criteria.

2.3 Demographics of respondents

Due to the COVID-19 situation, the questionnaire was distributed online, with the respondents able to choose to answer either in the attached file format or in the web-based format. If in doubt, the respondent could contact the researchers at any time, or could stop answering the questionnaire at any time if desired.

The questionnaires were sent online to 100 of the 168 companies having a registered capital of at least 100 million baht in the automotive industry in Thailand, listed in the 2019 Thailand automobiles, trailers, and semitrailers manufacturers list, including the manufacture of automobiles for the carriage of passengers or freight, the manufacture of other parts and accessories for automobiles, and the manufacture of bodies for automobiles, including trailers and semitrailers. The researchers chose to study only large enterprises, without including small and medium enterprises (SMEs), because when considering information from the Thailand Automotive Institute regarding the structure of entrepreneurs in the Thai automotive industry [76-78], it was found that SMEs have a lower level of investment in research and development of production technology. In addition, most of the SMEs are only suppliers of raw materials and/or producing components, replacement parts or automotive spare parts for large enterprises. Furthermore, in addition to producing genuine parts or components according to specified standards for large automotive companies, SMEs also produce non-genuine parts which are cheaper but of lower quality and aimed at the low-end market. The researchers therefore considered that they may not be at the stage of using various technologies for Industry 4.0.

Thirty-one companies responded, giving a response rate of 31% and accounting for 18.45% of the total population of 168 companies. This sample size from the total population is at the confidence level of 95% and a margin of error of 16%.

The respondents had to be responsible for determining the IE competencies required by the company. They had to have experienced and understood the company and Industry 4.0 in the automotive industry. All of the respondents had the aforementioned qualifications, with the demographic information summarized in Table 2. It was found that the average years of experience of the respondents in the automotive industry was 10 years, while their average years in position was 7.8. Most of the respondents were engineers whose areas of expertise were in production.

In terms of the organizational characteristics that the respondents represented, they are companies manufacturing (1) automobiles, which include personal cars, pickup trucks, motors, and other motors used for passengers or freight, (2) other parts and accessories for automobiles, which include seats and electrical equipment, and (3) bodies for automobiles, trailers and semitrailers, and cargo containers. All 31 companies are located in the central and eastern regions of Thailand. Each company has a total annual revenue of more than 500 million Thai baht, which is considered as a Large Enterprise in Thailand according to the Ministerial Regulations on Designation of the Characteristics of SME Promotion Act B.E. 2562 (2019).

Table 2 Demographics of respondents

	Demographics of respondents	Percentage
Job position of respondent	Engineer	45%
	Manager	36%
	Others: business owner/director/ consultant/specialist	19%
Area of expertise of respondent	Production	42%
	R&D	29%
	Supply chain management & logistics	16%
	Quality control	13%
Category of automotive industry of the organization	Automobiles	45%
	Other parts and accessories for automobiles	45%
	Bodies for automobiles, trailers, and semitrailers	10%

3. Results

3.1 Ranking of important IE knowledge

The data collected for this study consisted of the responses on important IE knowledge obtained from 31 companies as outlined in the previous section. Participants rated the importance of the knowledge items on a Likert scale ranging from 1 (least important) to 5 (most important). Since the ratings represented ordinal data, they were treated as such in the analysis. The IE knowledge subjects were then ranked based on their respective Likert scores, and in cases where multiple subjects shared the same score, their rankings were averaged to determine their final ranking. As an example, when a company provided Likert responses for five subjects as 4, 5, 5, 2, and 3, the rankings among these five subjects were 3, 1.5, 1.5, 5, and 4, respectively. The average ranking of the important IE knowledge subjects across the 31 companies and the final rankings are shown in Table 3 and Figure 1. The subjects 'foreign languages (No. 4)', 'mathematics and statistics fundamentals (1)', 'technology application (13)', and 'engineering fundamentals (10)' rank as the top four, whereas 'civic literacy (15)', 'health literacy (7)', and 'physical and chemical sciences (2)' are positioned as the bottom three in terms of importance.

Table 3 Average ranking and final ranking of 15 IE knowledge subjects

No		Knowledge	Average ranking	Final ranking
1	Core subjects	Mathematics and statistics fundamentals	6.13	2
2		Physical and chemical sciences	9.89	13
3		Economics and business	7.97	8
4		Foreign languages	5.95	1
5		Law and politics	8.97	12
6	Global subjects	Civic literacy	10.55	15
7		Health literacy	9.95	14
8		Environmental literacy	8.60	11
9		Global awareness	8.29	9
10	Engineering subjects	Engineering fundamentals	6.58	4
11		Engineers' laws, regulations, and standards	8.55	10
12		Specialized knowledge in industrial engineering	7.39	6.5
13	Technological fundamentals	Technology application	6.50	3
14		Information literacy	7.39	6.5
15		Recent innovation trends	7.31	5

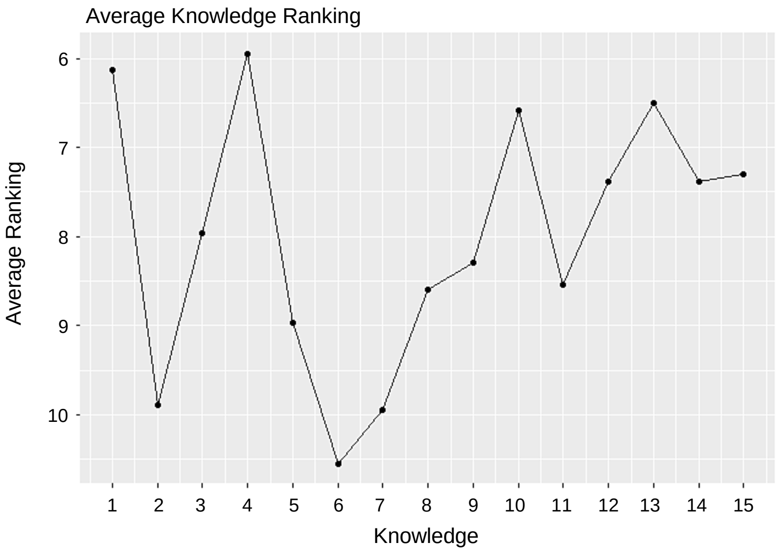


Figure 1 Average importance ranking of 15 IE knowledge subjects

3.2 IE knowledge importance ranking of companies with different Industry 4.0 adoption levels

Building upon the outcomes of the Industry 4.0 adoption questionnaire [73] outlined in the previous section, the average values of responses, ranging from 1 (low) to 5 (high), to questions regarding the various facets of Industry 4.0 adoption were utilized to roughly classify companies into three distinct groups representing different adoption levels: (1) high, (2) medium, and (3) low. The boundaries between the different adoption level groups are obtained by K-means clustering of the average score, where the boundary between the low and medium adoption level groups was 2.58 and the boundary between the medium and high adoption level groups was 3.46. The K-means company clustering results are illustrated in Figure 2 and Table 4.

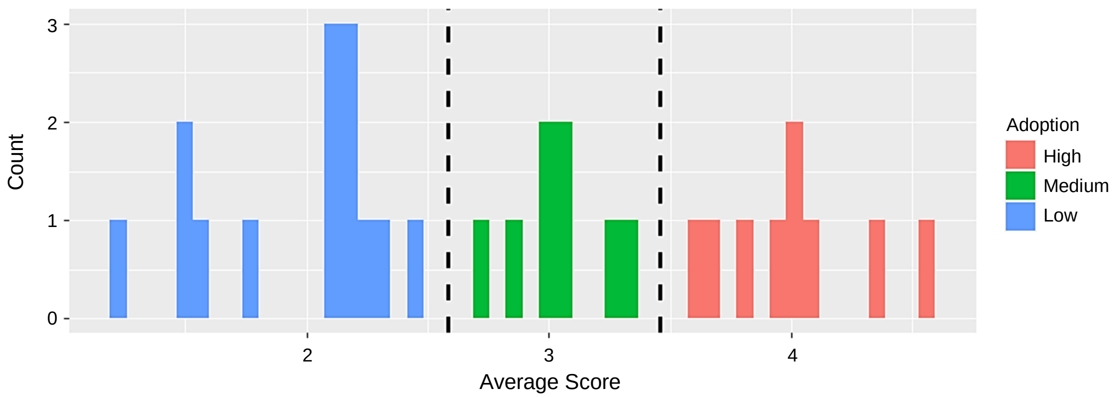


Figure 2 K-means company clustering using average score of the Industry 4.0 adoption level questionnaire results

Table 4 Company classification based on K-means clustering of average score from the Industry 4.0 adoption level questionnaire results

Group	Average score	Companies
1. High adoption level	Over 3.46	1, 3, 4, 8, 10, 20, 22, 23, 25 (9 companies)
2. Medium adoption level	Between 2.58 and 3.46	2, 5, 17, 18, 19, 21, 24, 29 (8 companies)
3. Low adoption level	Below 2.58	6, 7, 9, 11, 12, 13, 14, 15, 16, 26, 27, 28, 30, 31 (14 companies)

The comparison of the average knowledge importance rankings of these three groups is shown in Figure 3, and Table 5 illustrates the final important knowledge rankings for these groups. The high adoption level group (group 1) considers ‘technology application (13)’, ‘mathematics and statistics fundamentals (1)’, ‘foreign languages (4)’, ‘information literacy (14)’, and ‘recent innovation trends (15)’ as having the most importance, and ‘physical and chemical sciences (2)’, ‘civic literacy (6)’, and ‘health literacy (7)’ as having the least importance. The two remaining groups exhibit similar trends to group 1, albeit less extreme, and there is no significant distinction between them.

In Table 5, there is a clear consensus across all three groups that ‘foreign languages (4)’ ranks within the top three, while ‘civic literacy (6)’ and ‘health literacy (7)’ consistently occupy one of the bottom three positions in all three rankings. Furthermore, the rankings of ‘technology application (13)’, ‘information literacy (14)’, and ‘recent innovation trends (15)’ decline in tandem with the level of adoption.

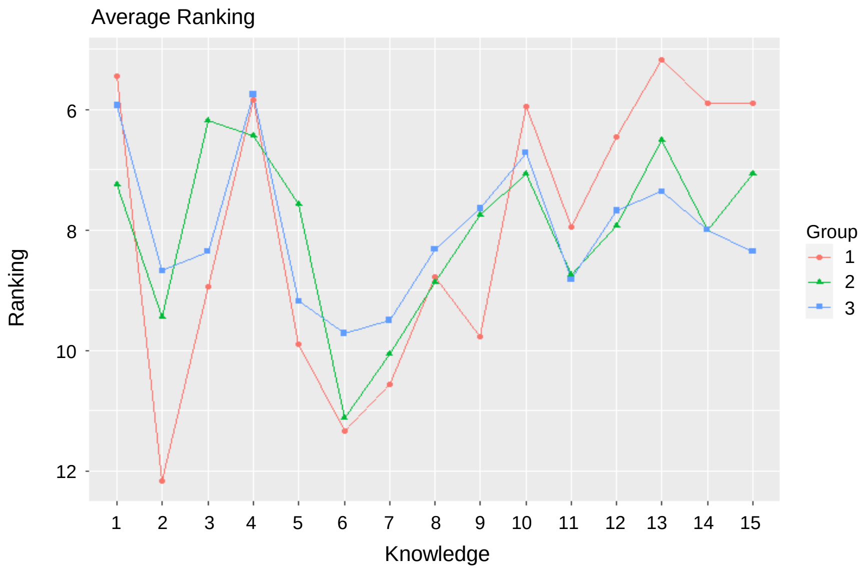


Figure 3 Average knowledge importance ranking for three Industry 4.0 adoption level groups

Table 5 Important IE knowledge rankings of three adoption level groups

High adoption level	Medium adoption level	Low adoption level
Technology application (13)	Economics and business (3)	Foreign languages (4)
Mathematics and statistics fundamentals (1)	Foreign languages (4)	Mathematics and statistics fundamentals (1)
Foreign languages (4)	Technology application (13)	Engineering fundamentals (10)
Information literacy (14)	Engineering fundamentals (10)	Technology application (13)
Recent innovation trends (15)	Recent innovation trends (15)	Global awareness (9)
Engineering fundamentals (10)	Mathematics and statistics fundamentals (1)	Specialized knowledge in industrial engineering (12)
Specialized knowledge in industrial engineering (12)	Law and politics (5)	Information literacy (14)
Engineers' laws, regulations, and standards (11)	Global awareness (9)	Environmental literacy (8)
Environmental literacy (8)	Specialized knowledge in industrial engineering (12)	Economics and business (3)
Economics and business (3)	Information literacy (14)	Recent innovation trends (15)
Global awareness (9)	Engineers' laws, regulations, and standards (11)	Physical and chemical sciences (2)
Law and politics (5)	Environmental literacy (8)	Engineers' laws, regulations, and standards (11)
Health literacy (7)	Physical and chemical sciences (2)	Law and politics (5)
Civic literacy (6)	Health literacy (7)	Health literacy (7)
Physical and chemical sciences (2)	Civic literacy (6)	Civic literacy (6)

Significant distinctions became evident upon contrasting the outcomes of Group 1 and Group 3. Group 1 gives higher priority to the topics of 'technology applications (13)', 'information literacy (14)', and 'recent innovation trends (15)', while less emphasis is placed on the topics of 'physical and chemical sciences (2)' and 'global awareness (9)'. As Industry 4.0 revolves around the integration of cutting-edge innovations, it is vital for companies to remain vigilant and up-to-date with the swiftly evolving technological trends. The utilization of data for analytics is experiencing unprecedented growth, necessitating individuals who grasp the importance of data and information and are proficient in their strategic application – making information literacy of paramount importance. Moreover, keeping up with emerging technologies and innovations, along with the ability to discern when and how to implement them, is equally essential for these companies.

Figure 4 (a)–(c) illustrates the clustered heatmap plot of the ranking of 15 IE knowledge areas from companies in the high, medium, and low adoption levels respectively. The colors in Figure 4 denote the ranking, with dark blue indicating the highest (1) and red indicating the lowest (15). The hierarchical clustering method is utilized to cluster columns and rows with Euclidean distances defined in Eqn (1) and Eqn (2).

Euclidian distance between company a and b for column clustering =

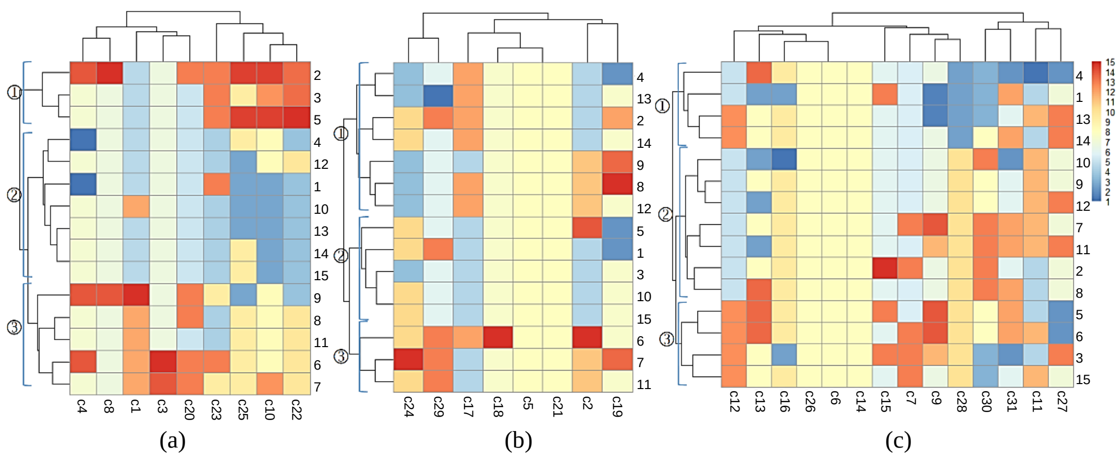
$$\sqrt{\sum_i (r_{i,a} - r_{i,b})^2} \tag{1}$$

Euclidian distance between knowledge a and b for row clustering =

$$\sqrt{\sum_j (r_{a,j} - r_{b,j})^2} \tag{2}$$

where $r_{i,j}$ denotes the knowledge i ranking (1–15) of company j.

The dendrograms on the left of Figure 4 (a)–(c) visually depict the clustering of knowledge areas that received similar ranking patterns from various companies, while the dendrograms at the top depict the clustering of companies that have similar ranking patterns. The objective of these plots is to examine the uniformity of rankings among the companies within each level group.



(a) (b) (c)

Figure 4 Clustered heatmap plot of ranking of 15 knowledge areas (1–15) from 31 companies (c1–c31): (a) high adoption level, (b) medium adoption level, (c) low adoption level

In Figure 4 (a)–(c), when attempting to categorize the 15 knowledge areas into three clusters, it becomes apparent that cluster 2 in both (a) and (b), as well as cluster 1 in (c), display a stronger bluish tint, indicative of higher rankings in contrast to the other two clusters in each respective figure. Specifically, cluster 2 in the high adoption level exhibits the most unanimous ranking pattern in contrast to the medium and low adoption groups. Across all levels, there is a more consistent consensus when it comes to choosing a set of highly important knowledge areas compared to selecting knowledge of medium and low importance. Furthermore, companies with a high level of adoption demonstrate a more effective ability to prioritize crucial knowledge when compared to their counterparts in the medium and low adoption groups.

Given that a more consistent consensus on selecting a set of highly important knowledge exists solely within the high adoption group, all seven knowledge areas in this group; ‘technology application (13)’, ‘mathematics and statistics fundamentals (1)’, ‘foreign languages (4)’, ‘information literacy (14)’, ‘recent innovation trends (15)’, ‘engineering fundamentals (10)’, and ‘specialized knowledge in industrial engineering (12)’, align with the top seven results outlined in Table 5. In contrast, there is less uniformity in ranking opinions within the medium and low adoption level groups.

3.3 Ranking of important IE skills

Table 6 and Figure 5 present the average rankings of important IE skills among the 31 companies, along with their final rankings. The top four skills are ‘managing and prioritizing (No. 31)’, ‘analytical thinking (20)’, ‘problem-solving (21)’, and ‘operational planning (29)’. On the other hand, the three skills ranked at the bottom in terms of importance are ‘cross-disciplinary skills (26)’, ‘research skills (28)’, and ‘supervising the use of tools (33)’.

Table 6 Average ranking and final ranking of 18 skills

No		Skill	Average ranking	Final ranking
16	Communication skills	Speaking and listening	8.31	5
17		Presentation	9.31	9
18	System thinking skills	Component interaction understanding	8.89	6
19		Critical thinking	10.05	13
20		Analytical thinking	7.81	2
21		Problem-solving	8.06	3.5
22	Creative thinking, adaptation, and decision- making skills	Creative thinking	8.90	7
23		Adaptation	9.13	8
24		Decision-making	9.85	11
25	Learning skills	Good questioning	10.52	15
26		Cross-disciplinary skills	11.76	18
27		Lifelong learning	9.81	10
28		Research skills	11.50	17
29	Technical skills	Operational planning	8.06	3.5
30		Choosing the right tool	10.00	12
31		Managing and prioritizing	7.26	1
32		Skills in using tools	10.39	14
33		Supervising the use of tools	11.40	16

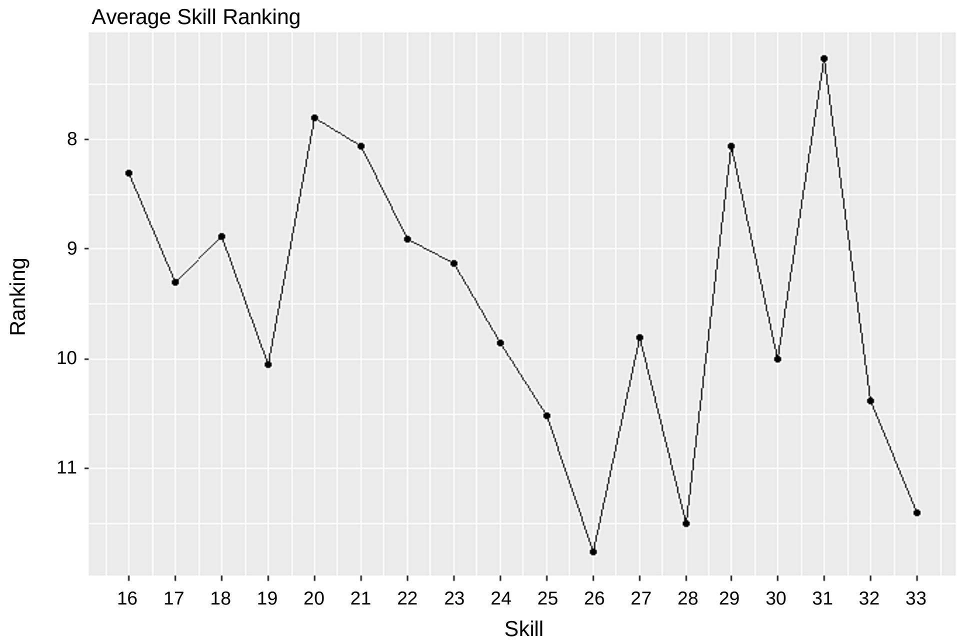


Figure 5 Average importance ranking of 18 skills

3.4 IE skill importance ranking of companies with different Industry 4.0 adoption levels

Based on the company classification using the average scores of the Industry 4.0 adoption level questionnaire results as depicted in Table 4, Figure 6 and Table 7 illustrate the average rankings and the final rankings of IE skill importance for the three identified groups, respectively. In the high adoption level group (group 1), 'analytical thinking (20)' and 'problem-solving (21)' are considered the most crucial skills, while 'research skill (28)' and 'cross-disciplinary skills (26)' rank as the least important. For the medium adoption level group (group 2), the most important skills are 'managing and prioritizing (31)', 'analytical thinking (20)', and 'problem-solving (21)', while 'research skill (28)' is deemed the least important. Lastly, the low adoption level group (group 3) places 'speaking and listening (16)', 'managing and prioritizing (31)', and 'operational planning (29)' as the most important skills, and considers 'supervising the use of tools (33)' and 'cross-disciplinary skills (26)' as comparatively less vital.

It is intriguing to examine if there are any notable disparities in the contrast between Group 1 and Group 3. Group 1 places a higher priority on skills such as 'analytical thinking (20)', 'problem-solving (21)', 'skills in using tools (32)', and 'supervising the use of tools (33)', while putting less emphasis on skills like 'speaking and listening (16)' and 'presentation (17)'. Analytical thinking and problem-solving abilities assume critical importance in more advanced companies, given their greater likelihood of encountering highly complex challenges. Tool usage and the supervision of tool usage are considered vital skills, as advanced companies often rely on cutting-edge technologies and tools to maintain a high level of competitiveness. These advanced tools require expertise in their proper utilization and monitoring, making this knowledge essential for success.

In Table 7, the rankings of 'analytical thinking (20)', 'problem-solving (21)', 'skills in using tools (32)', and 'supervising the use of tools (33)' exhibit a corresponding decline in alignment with the adoption level. In contrast, the rankings of 'presentation (17)' and 'speaking and listening (16)' follow an opposing trend in relation to the adoption level.

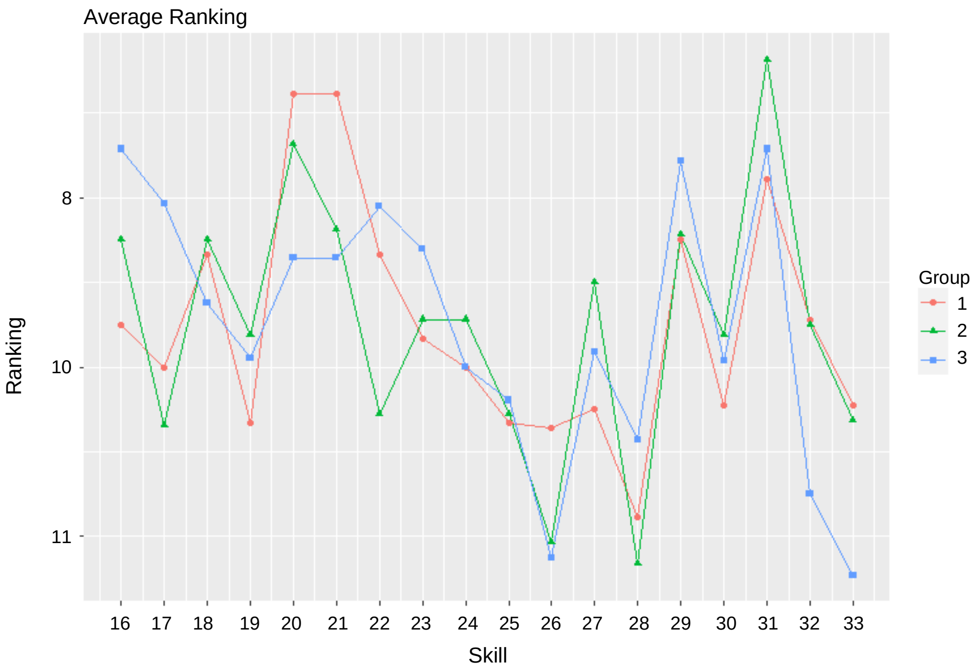


Figure 6 The average skill importance rankings for the three Industry 4.0 adoption level groups

Table 7 Important IE skill rankings of three adoption level groups

High adoption level	Medium adoption level	Low adoption level
Analytical thinking (20)	Managing and prioritizing (31)	Speaking and listening (16)
Problem-solving (21)	Analytical thinking (20)	Managing and prioritizing (31)
Managing and prioritizing (31)	Problem-solving (21)	Operational planning (29)
Operational planning (29)	Operational planning (29)	Presentation (17)
Component interaction understanding (18)	Speaking and listening (16)	Creative thinking (22)
Creative thinking (22)	Component interaction understanding (18)	Adaptation (23)
Skills in using tools (32)	Lifelong learning (27)	Analytical thinking (20)
Speaking and listening (16)	Adaptation (23)	Problem-solving (21)
Adaptation (23)	Decision-making (24)	Component interaction understanding (18)
Presentation (17)	Skills in using tools (32)	Lifelong learning (27)
Decision-making (24)	Critical thinking (19)	Critical thinking (19)
Choosing the right tool (30)	Choosing the right tool (30)	Choosing the right tool (30)
Supervising the use of tools (33)	Creative thinking (22)	Decision-making (24)
Lifelong learning (27)	Good questioning (25)	Good questioning (25)
Critical thinking (19)	Supervising the use of tools (33)	Research skills (28)
Good questioning (25)	Presentation (17)	Skills in using tools (32)
Cross-disciplinary skills (26)	Cross-disciplinary skills (26)	Cross-disciplinary skills (26)
Research skills (28)	Research skills (28)	Supervising the use of tools (33)

Figure 7 (a)–(c) present clustered heatmap plots depicting the ranking of 18 IE skills, categorized by the companies in the high, medium, and low adoption levels, respectively. The colors in Figure 7 illustrate the ranking, spanning from the highest (1) in dark blue to the lowest (18) in red. Hierarchical clustering is employed as the clustering method with the Euclidean distances defined in the previous section. Here, $r_{i,j}$ represents the ranking (1–18) of skill i for company j.

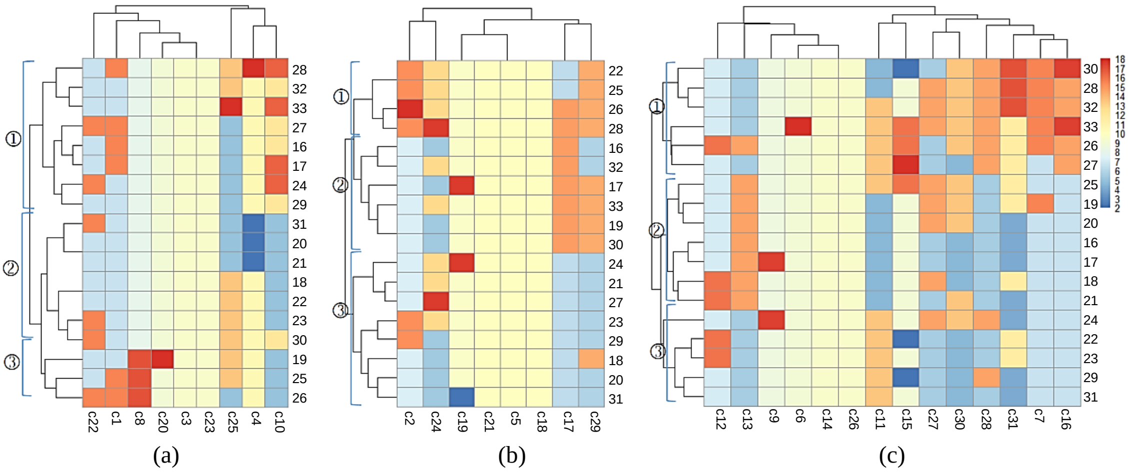


Figure 7 Clustered heatmap plot of ranking of 18 skills (26–33) from 31 companies (c1–c31): (a) high adoption level, (b) medium adoption level, (c) low adoption level

In Figure 7 (a)–(c), upon categorizing the 18 skills into three clusters, it is evident that cluster 2 in both (a) and (c), along with cluster 3 in (b), exhibits a more intense bluish tint, signifying higher rankings when compared to the other two clusters in each respective figure. Observing the most reddish cluster in Figure 7 reveals a more consistent consensus on selecting a set of less important skills, particularly within the low adoption group. All six skills in this group: 'lifelong learning (27)', 'choosing the right tool (30)', 'research skills (28)', 'skills in using tools (32)', 'cross-disciplinary skills (26), and 'supervising the use of tools (33)', closely match the bottom six results detailed in Table 7. Conversely, there is a diminished uniformity in ranking opinions within the high and medium adoption level groups.

4. Discussions and conclusions

The findings present the overall ranking of important industrial engineering knowledge and skills within the Thai automobile industry. Furthermore, the importance ranking based on companies with varying levels of Industry 4.0 adoption is also obtained.

Given that Industry 4.0 hinges on the integration of cutting-edge innovations, it is imperative for companies with high adoption levels to remain vigilant and stay current with the rapidly evolving technological landscape. The increasing use of data for analytics underscores the need for individuals who comprehend the value of data and information and are adept at strategically applying them, underscoring the critical importance of information literacy. Additionally, keeping pace with emerging technologies and innovations, as well as the ability to discern the appropriate timing and methods for their implementation, are equally vital for these companies.

In high adoption level companies, analytical thinking and problem-solving skills take on paramount significance due to their higher likelihood of encountering exceedingly intricate challenges. Skills related to tool usage and the supervision of such tools are regarded as crucial, as advanced companies frequently depend on state-of-the-art technologies and tools to uphold their competitive edge. Proficiency in the proper utilization and monitoring of these advanced tools becomes indispensable for achieving success.

Companies with low adoption levels typically have straightforward operations, employing tools of modest complexity and minimal integration of various components. They generally have limited reliance on data analysis. As a result, these companies prioritize fundamental knowledge and skills, emphasizing essentials like mathematics, statistics, engineering fundamentals, foreign languages, and basic communication skills over advanced competencies.

Furthermore, skills related to management, prioritization, and operational planning are universally regarded as highly significant across all levels of Industry 4.0 adoption.

Drawing from the study's insights into the prioritized ranking of crucial Industrial Engineering knowledge and skills, specifically focusing on the top 9 knowledge areas and top 12 skills, the following recommendations are proposed for universities to tailor Industrial Engineering curricula to meet the demands of the Industry 4.0 era:

Knowledge-focused recommendations

1. Integrate comprehensive technology application courses: Develop courses that provide in-depth insights and hands-on experience in applying advanced technologies relevant to Industry 4.0, such as IoT, AI, and automation.
2. Enhance the mathematics and statistics curriculum: Strengthen the mathematics and statistics curriculum to include advanced topics, emphasizing their application in modeling, data analytics, and decision-making for Industry 4.0 scenarios.
3. Prioritize foreign language proficiency: Offer language programs that focus on practical communication skills, specifically tailored to the global nature of Industry 4.0 collaboration and international business environments.
4. Embed information literacy across the curriculum: Infuse information literacy skills throughout the curriculum, ensuring students can effectively gather, analyze, and leverage information in Industry 4.0 contexts.
5. Integrate recent innovation trends: Create coursework that explores and incorporates the latest trends and innovations in industrial engineering, ensuring students are well-versed in cutting-edge technologies.
6. Strengthen engineering fundamentals: Reinforce core engineering principles, applying them to advanced technologies and Industry 4.0 applications, providing a solid foundation for specialization.

7. Offer specialized Industry 4.0 courses: Develop specialized courses that delve into the intricacies of Industry 4.0 applications within the industrial engineering domain.
8. Include engineers' laws, regulations, and standards: Integrate knowledge of legal and regulatory aspects relevant to industrial engineering, with a focus on Industry 4.0 compliance and ethical considerations.
9. Incorporate environmental literacy: Create coursework focusing on environmental sustainability and awareness, aligning with the increased emphasis on sustainable practices in Industry 4.0.

Skill-focused recommendations

1. Analytical thinking: Integrate advanced analytics coursework, emphasizing data-driven decision-making in industrial engineering contexts.
2. Problem-solving: Design problem-solving courses with a focus on real-world challenges in Industry 4.0, using case studies and simulations.
3. Managing and prioritizing: Enhance project management courses, emphasizing the efficient allocation of resources in Industry 4.0 projects.
4. Operational planning: Develop coursework on advanced operational planning, incorporating optimization techniques for Industry 4.0 processes.
5. Component interaction understanding: Offer specialized courses on systems thinking and the understanding of component interactions within interconnected systems.
6. Creative thinking: Foster creativity through design thinking courses, encouraging innovative problem-solving approaches.
7. Skills in using tools: Integrate training on the use of Industry 4.0 tools and technologies, such as IoT devices and advanced software platforms.
8. Speaking and listening: Include communication skills development courses, emphasizing effective communication within multidisciplinary teams.
9. Adaptation: Emphasize adaptability through coursework that exposes students to rapidly changing technologies and industry dynamics.
10. Presentation: Introduce courses on effective presentation skills, emphasizing the communication of technical solutions to diverse audiences.
11. Decision-making: Develop coursework focused on decision-making in dynamic Industry 4.0 environments, considering uncertainties and complexities.
12. Choosing the right tool: Integrate practical training on selecting and using the right tools and technologies for specific Industry 4.0 tasks.

These adjustments aim to equip industrial engineering students with the knowledge and skills necessary for success in a rapidly evolving Industry 4.0 landscape. Regular curriculum reviews and updates are crucial to staying aligned with industry trends and employer expectations.

5. Future research

Future study directions encompass several key areas of research that can expand our understanding of Industry 4.0 adoption and its implications:

Enhancing data accuracy: To further improve the precision and reliability of our findings, it is advisable to collect additional data specifically within the automotive industry. This will contribute to a more comprehensive and in-depth analysis of the automotive sector's adoption of Industry 4.0, including its distinctive intricacies and subtleties.

Cross-industry comparisons: Beyond the automotive industry, it is valuable to extend data collection to various industries. This approach allows for broader analyses and comparisons, enabling us to identify common trends and variations in Industry 4.0 adoption across diverse sectors.

Advanced prediction models: Developing advanced prediction models is a promising avenue for future research. These models should aim to estimate a company's Industry 4.0 adoption level without relying solely on direct adoption assessment questions. Instead, they can incorporate alternative, readily available information, such as ratings of the importance of knowledge and skills. This innovative approach can enhance the accuracy and efficiency of adoption level predictions.

Incorporating attitudes: It is essential to broaden the analysis to include the study of workforce attitudes, which constitute a vital attribute alongside knowledge and skills. Assessing and understanding attitudes within the context of Industry 4.0 adoption can provide valuable insights into the human factors that influence the successful implementation of Industry 4.0 practices.

By delving into these future study directions, we can gain a more holistic understanding of Industry 4.0 adoption and its multifaceted aspects, ultimately contributing to more informed decision-making and policy development.

6. Research contribution

Although this research only studied the knowledge and skills of industrial engineers in the automobile industry, the research methods can be applied to studies in other kinds of engineers or other industries. In addition, the findings of this research can be used as a guideline for the improvement of the Industrial Engineering curriculum in Thailand, as well as a job requirements roadmap for Industry 4.0. In addition, it can also be used as a guideline for the assessment of competent human resources in the organization, particularly industrial engineers, for Industry 4.0.

7. Acknowledgement

This research is part of the project "A Strategic Roadmap Toward the Next Level of Intelligent, Sustainable, and Human-Centered SME: SME 5.0" from the European Union's Horizon 2021 research and innovation program under the Marie Skłodowska-Curie Grant agreement No. 101086487. The researchers would like to also thank the experts for their assistance in evaluating the questionnaire and thank all respondents and all companies for providing useful information in this research.

8. References

[1] Filos E. Manufacturing innovation and horizon 2020. In: Kovács GL, Kochan D, editors. Digital product and process development systems. Berlin: Springer; 2013. p. 36-40.
[2] Kang HS, Lee JY, Choi S, Kim H, Park JH, Son JY, et al. Smart manufacturing: past research, present findings, and future directions. Int J Precis Eng Manuf – Green Technol. 2016;3:111-28.
[3] Erol S, Jäger A, Hold P, Ott K, Sihn W. Tangible Industry 4.0: a scenario-based approach to learning for the future of production. Procedia CIRP. 2016;54:13-8.
[4] Kagermann H. Change through digitization—value creation in the age of Industry 4.0. In: Albach H, Meffert H, Pinkwart A, Reichwald R, editors. Management of Permanent Change. Wiesbaden: Springer Gabler; 2015. p. 23-45.
[5] Qin J, Liu Y, Grosvenor R. A categorical framework of manufacturing for Industry 4.0 and beyond. Procedia CIRP. 2016;52:173-8.
[6] Sackey SM, Bester A. Industrial engineering curriculum in Industry 4.0 in a South African context. S Afr J Ind Eng. 2016;27(4):101-14.
[7] da Silva ER, Shinohara AC. Nielsen CP, de Lima EP, Angelis J. Operating digital manufacturing in Industry 4.0: The role of advanced manufacturing technologies. Procedia CIRP. 2020;93:174-9.
[8] Hernández-Muñoz GM, Habib-Mireles L, García-Castillo FA, Montemayor-Ibarra F. Industry 4.0 and engineering education: an analysis of nine technological domains inclusion in higher educational curriculum. In: García Alcaraz J, Rivera Cadavid L, González-Ramírez R, Leal Jamil G, Chong Chong M, editors. Best Practices in Manufacturing Processes. Cham: Springer; 2019. p. 525-43.
[9] Jones M, Zarzycki L, Murray G. Does Industry 4.0 pose a challenge for the SME machine builder? a case study and reflection of readiness for a UK SME. In: Ratchev S, editor. Precision Assembly in the Digital Age. IFIP Advances in Information and Communication Technology. Cham: Springer; 2019. p. 183-97.
[10] Khan WZ, Rehman MH, Zangoti HM, Afzal MK, Armi N, Salah K. Industrial internet of things: recent advances, enabling technologies and open challenges. Comput Electr Eng. 2020;81:1-13.
[11] Pacchini APT, Lucato WC, Facchini F, Mummolo G. The degree of readiness for the implementation of Industry 4.0. Comput Ind. 2019;113:1-8.
[12] Saucedo-Martínez JA, Pérez-Lara M, Marmolejo-Saucedo JA, Salais-Fierro TE, Vasant P. Industry 4.0 framework for management and operations: a review. J Ambient Intell Human Comput. 2018;9:789-801.
[13] Vrchota J, Pech M. Readiness of enterprises in Czech Republic to implement Industry 4.0: index of Industry 4.0. Appl Sci. 2019;9(24):1-25.
[14] Castro HF, Carvalho ARF, Leal F, Gouveia H. Assessing Industry 4.0 readiness of Portuguese companies. In: Almeida H, Vasco J, editors. Progress in Digital and Physical Manufacturing (ProDPM 2019). Lecture Notes in Mechanical Engineering. Cham: Springer; 2019. p. 57-64.
[15] Maisiri W, van Dyk L. Industry 4.0 readiness assessment for South African industries. S Afr J Ind Eng. 2019;30(3):134-48.
[16] Rakic S, Pavlovic M, Marjanovic U. A precondition of sustainability: Industry 4.0 readiness. Sustainability. 2021;13(12):1-12.
[17] Todorovic T, Lalic B, Majstorovic V, Marjanovic U, Tasic N. General readiness assessment of Industry 4.0: evidence from Serbian manufacturing industry. In: Lalic B, Majstorovic V, Marjanovic U, von Cieminski G, Romero D, editors. Advances in Production Management Systems. The Path to Digital Transformation and Innovation of Production Management Systems, IFIP Advances in Information and Communication Technology. Cham: Springer; 2020. p. 139-46.
[18] VDMA (Mechanical Engineering Industry Association). IMPULS: Industrie 4.0 readiness [Internet]. 2016 [cited 2021 Apr 11]. Available from: http://sf-eu.net/wp-content/uploads/2016/08/vdma-2015-industrie-4.0-readiness-en.pdf.
[19] Hizam-Hanafiah M, Soomro MA, Abdullah NL. Industry 4.0 readiness models: a systematic literature review of model dimensions. Information. 2020;11(7):1-13.
[20] Rauch E, Vickery AR, Brown CA, Matt DT. SME requirements and guidelines for the design of smart and highly adaptable manufacturing systems. In: Matt D, Modrák V, Zsifkovits H, editors. Industry 4.0 for SMEs. Cham: Palgrave Macmillan; 2020. p. 39-72.
[21] Baygin M, Yetis H, Karakose M, Akin E. An effect analysis of industry 4.0 to higher education. The 15th International Conference on Information Technology Based Higher Education and Training (ITHET); 2016 Sep 8-10; Istanbul, Türkiye. USA: IEEE; 2016. p. 1-4.
[22] Thailand Development Research Institute (TDRI). Challenges of Thai workers in the digital age [Internet]. 2015 [cited 2020 Feb 27]. Available from: https://tdri.or.th/2015/01/thailaborinthedigitalage/. (In Thai)
[23] Trstenjak M, Opetuk T. Industry 4.0 readiness factor calculation and process planning: state-of-the-art review. Trans Famena 2020;44:1-22.
[24] Eastern Economic Corridor (EEC). Next-generation automotive [Internet]. 2019 [cited 2022 Apr 16]. Available from: https://www.eeco.or.th/th/next-generation-automotive-industry. (In Thai)
[25] Thailand’s automotive industry. Opportunities and incentives ASEAN briefing [Internet]. 2018 [cited 2021 May 10]. Available from: https://www.aseanbriefing.com/news/thailands-automotive-industry-opportunities-incentives/.
[26] Thailand Automotive Institute. GWM officially opened the 2nd fully operational factory outside China in Thailand [Internet]. 2022 [cited 2022 Jan 10]. Available from: https://www.thaiauto.or.th/2020/news/?news_subtype=automotive_industry_news.
[27] Department of Business Development (DBD). Thailand standard industrial classification (TSIC) [Internet]. 2019 [cited 2019 Feb 27]. Available from: https://www.dbd.go.th/download/PDF_/book_business_man.pdf. (In Thai)
[28] Thammasat University Research and Consultancy Institute (TURCI). Thailand's MICE industry report robotics [Internet]. 2018 [cited 2020 Aug 26]. Available from: https://elibrary.tceb.or.th/BookList/TCEB-Project-study/MICE-Industry-Reports/MICE-Industry-Report-2018-Robotics.aspx.
[29] Thailand Development Research Institute (TDRI). TDRI offers 4 built to fulfill the potential of Thai students [Internet]. 2013 [cited 2020 Feb 27]. Available from: https://tdri.or.th/2014/05/yearend2013-human-capital-development/. (In Thai)
[30] Summary the Twelfth National Economic and Social Development Plan (2017-2021) [Internet]. 2017 [cited 2020 Feb 27]. Available from: https://www.nesdc.go.th/ewt_dl_link.php?nid=9640.

[31] The Institute of Industrial and Systems Engineers (IISE). Industrial and systems engineering BoK [Internet]. 2021 [cited 2021 Apr 16]. Available from: https://iise.org/Details.aspx?id=43631.
[32] Mingaleva ZA, Vukovic NA. Development of engineering students competencies based on cognitive technologies in conditions of Industry 4.0. Int J Cogn Res Sci Eng Educ. 2020;8:93-101.
[33] Gonçalves MJA, Rocha Á, Cota MP, Pimenta P. Model for identifying competencies and learning outcomes (MICRA). In: Pinheiro MM, Simões D, editors. Handbook of Research on Engaging Digital Natives in Higher Education Settings. USA: IGI Global; 2016. p. 154-70.
[34] Bloom BS, Engelhart MD, Furst, EJ, Hill WH, Krathwohl DR. The taxonomy of educational objectives. Handbook 1, cognitive domain. New York: David McKay Company; 1956.
[35] Simpson EJ. The classification of educational objectives in the psychomotor domain. Washington: Gryphon House; 1972. p. 1-35.
[36] Pattanapairoj S, Nitisiri K, Sethanan K. A gap study between employers' expectations in Thailand and current competence of master's degree students in industrial engineering under Industry 4.0. Prod Eng Arch. 2021;27(1):50-7.
[37] de Souza RG, Quelhas OLG. Model proposal for diagnosis and integration of Industry 4.0 concepts in production engineering courses. Sustainability. 2020;12(8):3471.
[38] Pinzone M, Fantini P, Perini S, Garavaglia S, Taisch M, Miragliotta G. Jobs and skills in Industry 4.0: an exploratory research. In: Lödding H, Riedel R, Thoben KD, von Cieminski G, Kiritsis D, editors. Advances in Production Management Systems. The Path to Intelligent, Collaborative and Sustainable Manufacturing. APM 2017. IFIP Advances in Information and Communication Technology. Cham: Springer; 2017. p. 282-8.
[39] Tan HS, Ivander, Oktarina R, Reynaldo V, Sharina C. Conceptual development of learning factory for industrial engineering education in Indonesia context as an enabler of students' competencies in Industry 4.0 era. IOP Conf Ser: Earth Environ Sci. 2020;426:012123.
[40] Ahadov A, Asgarov ES, El-Thalji I. A summary of adapting Industry 4.0 vision into engineering education in Azerbaijan. IOP Conf Ser: Mater Sci Eng. 2019;700:012063.
[41] Sackey SM, Bester A, Adams D. Industry 4.0 learning factory didactic design parameters for industrial engineering education in South Africa. S Afr J Ind Eng. 2017;28(1):114-24.
[42] Ratnasingam J, Yi LY, Abdul Azim A, Halis R, Choon Liat L, Khoo A, et al. Assessing the awareness and readiness of the Malaysian furniture industry for Industry 4.0. BioRes. 2020;15(3):4866-85.
[43] Bischof-dos-Santos C, de Oliveira E. Production engineering competencies in the Industry 4.0 context: perspectives on the Brazilian labor market. Production. 2020;30:1-10.
[44] Sánchez Carracedo F, Soler A, Martín C, López D, Ageno A, Cabré J, et al. Competency maps: an effective model to integrate professional competencies across a STEM curriculum. J Sci Educ Technol. 2018;27(5):448-68.
[45] Employment and Training Administration (ETA). Engineering competency model clearing house employment and training administration [Internet]. 2020 [cited 2020 Dec 17]. Available from: https://www.careeronestop.org/competencymodel/competency-models/engineering.aspx.
[46] Kuzminov Y, Sorokin P, Froumin ID. Generic and specific skills as components of human capital: new challenges for education theory and practice. Foresight STI Gov. 2019;13(2):19-41.
[47] Brito CR, Ciampi MM, Vasconcelos RM, Amaral LA, Santos HD, Barros VA. Rethinking engineering education. 2017 IEEE Frontiers in Education Conference (FIE); 2017 Oct 18-21; Indianapolis, USA. USA: IEEE; 2017. p. 1-5.
[48] Backa L, Wihersaari M. Future engineering education: what competences are energy companies looking for when recruiting graduates with a master of science (technology) degree?. Eng Educ. 2014;991):2-17.
[49] Lönngren J. Wicked problems in engineering education: preparing future engineers to work for sustainability. Environ Educ Res. 2019;25(12):1808-9.
[50] Rajala SA. Beyond 2020: preparing engineers for the future. Proc IEEE. 2012;100(Special Centennial Issue):1376-83.
[51] Mourtzis D. Development of skills and competences in manufacturing towards education 4.0: a teaching factory approach. In: Ni J, Majstorovic V, Djurdjanovic D, editors. Proceedings of the 3rd International Conference on the Industry 4.0 Model for Advanced Manufacturing (AMP 2018). Lecture Notes in Mechanical Engineering. Cham: Springer; 2018. p. 194-210.
[52] Terkowsky C, Frye S, May D. Online engineering education for manufacturing technology: Is a remote experiment a suitable tool to teach competences for "Working 4.0"?. Eur J Educ. 2019;54(4):577-90.
[53] Monteiro F, Leite C, Rocha C. From the dominant engineering education perspective to the aim of promoting service to humanity and the common good: the importance of rethinking engineering education. Eur J Eng Educ. 2019;44(4):504-18.
[54] Bussey M, Song MM, Hsieh SH. Anticipatory imagination as a tool for rethinking engineering education. J Prof Iss Eng Ed Pr. 2017;143(4):1-5.
[55] Fabregat J. Explicit training in human values and social attitudes of future engineers in Spain: commentary on "preparing to understand and use science in the real world: interdisciplinary study concentrations at the technical University of Darmstadt". Sci Eng Ethics. 2013;19(4):1551-6.
[56] Lönngren J. Exploring the discursive construction of ethics in an introductory engineering course. J Eng Educ. 2021;110(10:44-69.
[57] Jerman A, Pejić Bach M, Bertoncelj A. A bibliometric and topic analysis on future competences at smart factories. Machines. 2018;6(3):1-13.
[58] Liszka K, Klimkiewicz K, Malinowski P. Polish foundry engineer with regard to changes carried by the industry 4.0. Arch Foundry Eng. 2019;19(1):103-8.
[59] Muñoz-La Rivera F, Hermosilla P, Delgadillo J, Echeverría D. The sustainable development goals (SDGs) as a basis for innovation skills for engineers in the Industry 4.0 context. Sustainability. 2020;12(16):1-14.
[60] Lantada AD. Engineering education 5.0: continuously evolving engineering education. Int J Eng Educ. 2020;36(6):1814-32.
[61] Soboleva EV, Karavaev NL. Preparing engineers of the future: the development of environmental thinking as a universal competency in teaching robotics. Eur J Contemp Educ. 2020;9(1):160-76.
[62] King I, Saxena C, Pak C, Lam CM, Cai H. Rethinking engineering education: policy, pedagogy, and assessment during crises. IEEE Signal Process Mag. 2021;38(3):174-84.

[63] Segalàs J, Ferrer-Balas D, Svanström M, Lundqvist U, Mulder KF. What has to be learnt for sustainability? a comparison of bachelor engineering education competences at three European universities. Sustain Sci. 2009;4:17-27.

[64] Hahn L, Sorenson L. Developing engineering students' language and cultural skills for academic and professional success. 2014 IEEE Frontiers in Education Conference (FIE); 2014 Oct 22-25; Madrid, Spain. USA: IEEE; 2014. p. 1-4.

[65] Render DN, Holgate HA, Calahan CA. Facilitating intercultural development: Preparing future engineers for multidisciplinary teams and multicultural environments. 2018 IEEE Frontiers in Education Conference (FIE); 2018 Oct 3-6; San Jose, USA. USA: IEEE; 2018. p. 1-9.

[66] Stefanovic M. The objectives, architectures and effects of distance learning laboratories for industrial engineering education. Comput Educ. 2013;69:250-62.

[67] Behl DV, Ferreira S. Systems thinking: an analysis of key factors and relationships. Procedia Comput Sci. 2004;36:104-9.

[68] Herkert JR. Moral dilemmas in engineering. In: Herkert JR, editor. Social, ethical, and policy implications of engineering. Hoboken: Wiley-IEEE Press; 1999. p. 77-80.

[69] van Laar E, van Deursen AJAM, van Dijk JAGM, de Haan J. 21st-century digital skills instrument aimed at working professionals: Conceptual development and empirical validation. Telemat Inform. 2018;35(8):2184-200.

[70] Xiao J, Sun-Lin HZ, Lin TH, Li M, Pan Z, Cheng HC. What makes learners a good fit for hybrid learning? learning competences as predictors of experience and satisfaction in hybrid learning space. Br. J Educ Technol. 2020;51(4):1203-19.

[71] Wrobel-Lachowska M, Wisniewski Z, Polak-Sopinska A, Lachowski R. ICT in logistics as a challenge for mature workers: knowledge management role in information society. In: Goossens R, editor. Advances in Social & Occupational Ergonomics. AHFE 2017. Advances in Intelligent Systems and Computing. Cham: Springer; 2018. p. 171-8.

[72] Ferris TLJ, Aziz M. A psychomotor skills extension to Bloom's taxonomy of education objectives for engineering education. Exploring Innovation in Education and Research (iCEER-2005); 2005 Mar 1-5; Tainan, Taiwan. p. 1-6.

[73] Wichajaroen W, Chompu-inwai R. Assessment of phase of Industry 4.0 adoption: a pilot study in automotive industry in Thailand. Eng J CMU. 2022;29(2):1-14.

[74] Ismail FKM, Zubairi AMB. Item objective congruence analysis for multidimensional items content validation of a reading test in Sri Lankan university. English Lang Teach. 2022;15(1):106-17.

[75] Brown JD. Testing in language programs: a comprehensive guide to English language assessment. Hawaii: McGraw-Hill; 2005.

[76] Yongpisanphob W. Industry outlook 2019-2021: auto parts industry [Internet]. 2019 [updated 2019 Aug 16; cited 2023 Dec 10]. Available from: https://www.krungsri.com/en/research/industry/industry-outlook/hi-tech-industries/auto-parts/io/auto-parts-19.

[77] Yongpisanphob W. Industry outlook 2020-2022: auto parts industry [Internet]. 2020 [updated 2020 Sep 10; cited 2023 Dec 10]. Available from: https://www.krungsri.com/en/research/industry/industry-outlook/hi-tech-industries/auto-parts/io/auto-parts-2021.

[78] Yongpisanphob W. Industry outlook 2023-2025: auto parts industry [Internet]. 2023 [updated 2023 Mar 1; cited 2023 Dec 10]. Available from: https://www.krungsri.com/en/research/industry/industry-outlook/hi-tech-industries/auto-parts/io/auto-parts-2023-2025.