Assessment of essential competencies of open university students in Thailand for the sustainable smart manufacturing industry

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Abstract

Purpose – This research examines the essential competencies open university students in Thailand require to meet the demands of the sustainable smart manufacturing industry. The study addresses skills gaps in technological, green, 21st-century and future-thinking dimensions, aligning with Thailand's 4.0 strategy and the United Nations Sustainable Development Goals.

Design/methodology/approach – A mixed-methods approach was employed, integrating quantitative data from a survey of 421 undergraduate students, selected through stratified sampling and qualitative insights from 31 industry experts, chosen using purposive sampling. Competency assessments were validated using a four-dimensional model and analysed through descriptive statistics to compare expert expectations with student self-assessments.

Findings – The study identified significant discrepancies between expert expectations and student self-assessments, particularly in advanced technological skills (e.g. robotics and Internet of Things [IoT]) and green competencies (e.g. lifecycle assessment). While students demonstrated moderate proficiency in 21st-century and interpersonal skills, comprehensive curriculum adjustments are required to address these critical gaps.

Practical implications – The findings highlight the need for curriculum reforms integrating blended learning, hands-on practical training and academic–industry collaboration. These measures are critical for equipping students with the skills required for sustainable smart manufacturing.

Originality/value – This study offers a validated, multi-dimensional competency framework tailored to the sustainable smart manufacturing industry. It provides actionable insights for educators and policymakers to bridge educational and industrial gaps and ensure workforce readiness for an evolving technological landscape.

Keywords 21st-century skills, Future-thinking skills, Green competencies, Open university, Sustainable smart manufacturing, Technological skills

Paper type Research paper

Introduction

In 2015, the United Nations (UN) announced the Global Sustainable Development Goals (SDGs) (UN, 2018), which were adopted by 193 UN member countries. It is a development

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direction that requires collaboration among all nations. This covers 15 years, from 2016 AD to 2030 AD. The goal is to end poverty and scarcity, along with strategies that improve health and education, reduce inequality and stimulate economic growth. The United Nations has announced 17 SDGs for development, which cover five dimensions: (1) People development, (2) Environment, (3) Economy and prosperity, (4) Peace and justice and (5) Development partnership. One of the SDGs is Goal 9 (SDG9): Build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation. A part of SDG9 focuses on promoting sustainable industrialisation, which lies specifically in smart manufacturing, an industry integral to the 4th Industrial Revolution, also known as Industry 4.0 (Yang and Gu, 2021). This revolution, announced in 2011, aims to revolutionise industrial processes by leveraging technologies to enhance efficiency, flexibility and speed. This transformation relies heavily on data collection and analysis, creating opportunities for innovation in manufacturing processes. To achieve these goals, developing a skilled workforce is essential to thriving in this evolving landscape. Educating students in sustainable industrialisation and Industry 4.0 equips them to drive innovative practices, ensuring a future-ready workforce that advances SDG9.

In Thailand, under the Office of the Prime Minister, the Office of the National Economic and Social Development Council has drafted the 13th National Economic and Social Development Plan (2023–2027), emphasising the industrial sector as a key economic driver. However, the sector has shown slow growth, with most industries focused on contract manufacturing or low-value-added activities. Total factor productivity has grown at just 2.1% annually, lagging behind other upper-middle-income countries due to challenges in labour productivity, skills, technology adoption and limited investment in innovation (NESDC, 2023). Additionally, industries lack ownership of advanced technologies and raw materials, constraining technological development and innovation (NESDC, 2023). In addition, the Thai Ministry of Industry has established the “Thailand 4.0 Industrial Development Strategy”, a 20-year plan (2017–2036). This strategy aims to drive economic prosperity through innovation, inclusiveness and environmental sustainability to transform Thailand into a high-income nation with equitable wealth distribution and eco-friendliness. Sustainable smart manufacturing is part of Thailand’s vision for future industries, aligning with the 20-year National Strategy framework driven by knowledge and innovation and following the SDGs. In line with this, Thailand has made progress by establishing the Industrial Transformation Centre (ITC) to support businesses in enhancing operational efficiency and transitioning to the digital era (MIND, 2017).

The concept of Society 5.0, introduced by Japan, envisions a future society driven by scientific and technological innovation, emphasising a human-centred, super-smart and efficient society. This concept was outlined in the 5th Science and Technology Basic Plan by the Council for Science, Technology and Innovation and approved by a Cabinet decision in January 2016. Society 5.0 aims to balance economic advancement with addressing social challenges in the country. Its goal is to establish a human-centric, super-smart society where all citizens can access high-quality lives marked by comfort and vitality. This is achieved by delivering personalised goods and services through the integration of cyberspace and physical space, using advanced technologies (Fukuyama, 2018). According to this strategy, achieving mid- and long-term growth hinges on realising Society 5.0, which addresses societal challenges by integrating innovations from the Fourth Industrial Revolution into all industries and aspects of social life. This underscores the central importance of humans as the core of a human-centric, super-smart society (Huang *et al*., 2022).

In Thailand, Sukhothai Thammathirat Open University (STOU) offers distance learning, allowing students from various locations and backgrounds to access education outside of traditional campus settings. This model supports lifelong learning and contributes to advancing educational equity (Laosum, 2024). In this context, STOU, as part of a dynamic educational landscape, must develop a model for evaluating the student competencies required for the sustainable smart manufacturing industry.

This study advances the literature on sustainable smart manufacturing by proposing a four-dimensional competency model – technological skills, green competencies, 21st-century skills and future-thinking skills – tailored to the Thai context and open university education. It addresses a critical gap by linking Industry 4.0 and Society 5.0 demands with student competency development aligned to national strategies and the SDGs (Tait, 2018). The findings offer a framework for assessing and enhancing university curricula to better prepare students for a sustainability-driven industrial future, serving as a model for educators, policymakers and industry stakeholders.

Literature review on sustainable smart manufacturing and student competency needs

(1) Review of the sustainable smart manufacturing industry

The evolution of the industrial world can be categorised into five eras: Industry 1.0 through 5.0. The latest paradigm, Industry 5.0, introduces a human-centric, sustainable and resilient approach to manufacturing, prioritising both technology advancement and social well-being (Huang *et al*., 2022). It extends upon Industry 4.0 technologies – such as artificial intelligence (AI), the Internet of Things (IoT), cyber-physical systems (CPS) and Big Data – by integrating sustainability and ethical responsibility into development (Juasiripukdee, 2017).

Smart manufacturing incorporates technologies such as machine learning (ML), additive manufacturing (AM), simulation, computer-aided technologies in various fields (CAx) and cloud computing, enabling the automation and optimisation of production systems (Mittal *et al*., 2017; Kang *et al*., 2016). These tools support efficiency and competitiveness in both large enterprises and SMEs.

Sustainable manufacturing, on the other hand, has evolved from material substitution to lean practices to a holistic view, encompassing green manufacturing and the six Rs: reduce, reuse, recover, redesign, remanufacture and recycle, promoting resource efficiency and sustainability throughout the manufacturing process (Jayal *et al*., 2010). This transition highlights the growing need for green competencies, such as waste minimisation, energy conservation and circular economies (Akyazi *et al*., 2022).

The integration of these two concepts gives rise to sustainable smart manufacturing (Mohamed *et al*., 2020). Mohamed *et al*. (2020) define this approach as the application of advanced technologies, such as AI, IoT, Big Data, AM and CPS – across all industrial activities while adhering to the principles of the six Rs. This framework seeks to harmonise sustainability with technological innovation to achieve balanced societal and industrial progress. Similarly, Natarajan *et al*. (2021) highlighted the importance of smart manufacturing for Industry 4.0, emphasising its role in enhancing productivity, reducing waste and promoting sustainability. Smart manufacturing optimises resource utilisation, improves efficiency and minimises environmental impact through automation, IoT and AI technologies. These advancements benefit large industries and SMEs, providing a sustainable and competitive framework for the manufacturing sector. However, Gautam *et al*. (2022) have observed that sustainable smart manufacturing remains underutilised, with its adoption shaped by factors such as environmental sustainability practices, market demand, cost considerations and the size and scale of the business.

(2) Review of student competence

The rapid pace of global economic change and the adoption of advanced technologies necessitate a workforce with high levels of competence, knowledge and skills to meet the demands of a highly industrialised world. Industries increasingly seek innovative, adaptable and flexible graduates capable of navigating the evolving workplace landscape (Ferns *et al*., 2019; Debolina Halder *et al*., 2024). In addition, employment remains a significant concern across many sectors of the global economy (Tagulwa *et al*., 2023).

Student competence is a topic of interest in many educational contexts. Efremova (2023) presented the challenges of competency assessment and introduced an algorithm designed to develop competency assessment using modelling and performance in student activities. A rational model assessment tool was designed to validate assessment results, accompanied by an extended model that supported teachers and developers of assessment tools and processes. Rahayu and Rozi (2021) found high overall student competency, with an average of 78.97% in attitude, knowledge and abilities. They recommended that teachers encourage active participation, promote character values and collaborate with students to enhance skill development. Daryono *et al*. (2023) focused on the competency needs of architectural engineering students and emphasised the importance of matching competency with industry needs. The assessment model described the total competency required by this student population, which was 89.75%. Retnaningsih's (2022) reviewed nursing student competency and identified three competency areas: (1) biological, psychological, social, spiritual and cultural competency, (2) knowledge of care and ethics and (3) knowledge and information technology competency. Nelyza *et al*. (2021) examined the results of a guided inquiry format to improve student brain competency and found promising results. Therefore, overall student competency, including assessment, level, needs and improvement strategies, was assessed using the guided inquiry format to improve students' competencies. The average overall score of students' skills was 0.65, which was moderate.

In addition to the student as a primary factor, numerous studies have also emphasised the significance of external factors influencing outcomes. Amsal *et al*. (2023) explored the understanding that students had regarding the personality and social competencies of teachers, identifying six key aspects for strengthening character education in prospective teachers: nationalism and patriotism, appreciation of differences, prioritising appeal, managing stress and authority, discipline and the call of the soul. These aspects aim to enhance the personal and professional development of future educators. Smith *et al*. (2023) identified three categories in their analysis: engaging, measuring and moderating. The interaction between these categories highlights the basic social process of "aligning" and supports the development of the emergent substantive theory of the paramedic assessment process. Thao (2020) examined student teachers' experiences by assessing their teaching competency with the aid of English language teaching competency assessment framework. The study underscores the importance of evaluating students' competencies across various educational contexts. Froese and Hong (2022) found that adolescents from higher socioeconomic backgrounds develop employability skills more quickly, widening the skills gap due to unequal social capital. Onu *et al*. (2023) emphasised the importance of combining technical, social and communication skills, such as teamwork, adaptability and effective collaboration in multicultural environments, to enhance industrial effectiveness. Similarly, González-Pérez and Ramírez-Montoya (2022) and Dumitru and Halpern (2023) highlighted key components of Education 4.0 for Industry 4.0, including active learning strategies to develop critical thinking, problem-solving and collaboration; integrating technologies like AI and big data in education and the importance of social, digital and systemic thinking skills. Their research advocates for educational frameworks that link technology with lifelong learning and sustainable solutions to address future challenges.

This study will focus on the conceptual context of the sustainable smart manufacturing industry and the competencies required for Thailand's sustainable smart manufacturing industry. The researcher's investigation found that research on this issue is still unclear. Therefore, this study is underpinned by a competency-based education (CBE) framework, which aligns educational outcomes with the skills and knowledge demanded by industry. It also draws on systems theory, recognising that the interaction of individual competencies, technological systems and environmental goals shapes performance in sustainable manufacturing contexts. Building on prior studies, a four-dimensional competency model has been proposed to address the skills gap, particularly in the context of sustainable smart manufacturing. The first dimension, technological skills, emphasises proficiency in Industry 4.0 technologies—such as IoT, CPS, Big Data and AI—for industrial applications (Cohen and Macek, 2021; David *et al*., 2024). The second dimension is green competencies, which concerns environmental awareness across multiple domains, encompassing knowledge, skills, awareness, attitudes, abilities and behaviours (Cabral and Lochan Dhar, 2019). The third dimension is 21st-century skills, which refer to advanced competencies beyond foundational literacy, including cognitive, intrapersonal, interpersonal, technical, financial and entrepreneurial competencies essential for addressing contemporary challenges (Geisinger, 2016; Gede *et al.*, 2024). The final dimension is future-thinking skills, which involves the use of foresight, strategic foresight and future studies (DPMC, 2023). Collectively, these competencies promote a creative and exploratory mindset, grounded in divergent thinking that seeks possibility in the face of uncertainty (Buntting and Jones, 2015). These skills include identifying and testing hypotheses, exploring beyond hypothetical futures, generating new insights into possible future developments, recognising both intended and unintended future consequences and reducing risk through development (DPMC, 2023; Jones *et al.*, 2012). This comprehensive model equips individuals with the necessary skills to thrive in a rapidly evolving, sustainability-focused industrial landscape. These competencies are used to assess the preparedness of university students for entering the sustainable smart manufacturing industry. To sum up, the purpose of this research is to examine the concept of sustainable smart manufacturing and assess the competencies required by students in Thailand to enter this sector. Specifically, the study evaluates the preparedness of Thai open university students using the proposed four-dimensional competency model. The findings will provide a benchmark for curriculum development and workforce readiness in the context of Thailand's evolving industrial ecosystem.

Methodology

Research design

A mixed-methods approach was employed, integrating quantitative data from a survey of 421 undergraduate students, selected through stratified sampling and qualitative insights from 31 industry experts, chosen using purposive sampling. This combination aimed to ensure a comprehensive understanding by triangulating numerical analysis with expert perspectives.

Research informants and samples

Regarding the validation of the model's indicators, 31 experts were interviewed as a part of a focus group discussion (FGD). The criteria for inclusion were that each should have a minimum of three years' experience and should also hold at least a managerial position in a leading business related to the sustainable smart manufacturing industry. These experts were arranged into six small groups with five participants each to obtain complete and saturated data. Regarding the appropriateness verification of the model, three senior lecturers, each having a minimum of five years' experience in the sustainable smart manufacturing industry, education and measurement and evaluation, were selected.

In total, 421 undergraduate students from five academic disciplines in the third or fourth year at STOU were sampled to develop the model. The samples were in fields of study directly related to the sustainable smart manufacturing industry, consisting of (1) science and technology, (2) management science, (3) health science, (4) agriculture and cooperatives and (5) economics. The questionnaire data were collected online or through hard copy data collection. Additionally, the 31 experts were asked to scale the model to reflect the expected competencies students should demonstrate as users.

Materials and tools

The researcher employed a questionnaire that was created after a thorough examination of the literature and expert confirmation. The questionnaire was divided into three sections. The first section required the completion of general information. The second section contained questions forming an assessment of student competence towards the sustainable smart manufacturing industry and required responses on a five-point Likert scale. The final section contained an assessment of the importance of the four-dimensional competencies towards the sustainable smart manufacturing industry and also required responses on a five-point Likert scale.

The item-objective congruence (IOC) index was used to evaluate content validity. All questions were suitable within the IOC values range of 0.67–1.00, which agreed with Rovinelli and Hambleton's (1976) criteria.

Data collection procedure

Phase 1: Qualitative data collection was conducted through FGDs with 31 industry experts to validate competency indicators. FGDs were structured around guiding questions and recorded for thematic analysis.

Phase 2: Quantitative data was collected through questionnaires distributed to the 421 student participants. Surveys were administered online and in person, with informed consent obtained beforehand.

Data analysis

The descriptive statistics used to analyse the data were the mean, standard deviation, differences and questions on the competence levels of Thai students regarding their readiness for the sustainable smart manufacturing industry.

The researcher's questionnaire used a five-point Likert scale: highest competence (five), high competence (four), moderate competence (three), low competence (two) and lowest competence (one) for assessing student competence towards the sustainable smart manufacturing industry and a five-point Likert scale: most important (five), highly important (four), moderately important (three), low important (two) and least important (one) for assessing the importance of the four-dimensional competencies towards the sustainable smart manufacturing industry.

The mixed-methods design and triangulated analysis ensured depth and reliability of the findings. The data analysis techniques, combining descriptive statistics and thematic analysis, were appropriate and sufficient to address the study's objectives by providing both breadth and depth of understanding.

Ethical considerations

This study did not require formal ethics committee approval as it involved general questions without personal or sensitive data. Participants were informed about the study's purpose, voluntary participation and confidentiality. Informed consent was obtained, and all responses were anonymised to ensure privacy.

Findings

This section presents the results of the study, focusing on 60 indicators in four dimensions of competency: technological skills (11 indicators), green competencies (13 indicators), 21st-century skills (26 indicators) and future-thinking skills (ten indicators). The model's analysis consisted of two parts.

(1) Descriptive statistics: mean, standard deviation and differences

- Summarising the general information, the responses revealed that of the 421 students, the majority were aged between 30 and 39 years (36.10%), followed by those in the 21 and 29 age group (26.84%) and the 40 and 49 age group (26.60%). A significant proportion of the respondents were female (64.61%) compared to males (34.92%). Regarding academic background, most students were enrolled in science and technology (66.75%), followed by health science (28.03%). Most were in their second year of study (26.84%) and followed by third-year students (22.33%). Regarding prior education, most respondents entered STOU with a vocational certificate, associate degree or equivalent (44.66%), followed by those with a bachelor's degree or higher (41.33%). In terms of employment, the majority were employed full-time (88.84%), followed by freelancers (7.13%). Additionally, most respondents had more than 10 years of work experience (65.32%), followed by those with 7–10 years of experience (17.58%).

- Dimension 1 – Technological skills of students (V1–V11) consist of 11 variables, representing the technological skills expected of students from the sustainable smart manufacturing industry experts. The analysis indicated that the mean scores ($\overline{x}$) for expert expectations ranged from 3.30 to 4.27, with standard deviations (SD) ranging from 0.74 to 1.15. The ranking of variables based on mean scores, from highest to lowest, was V1, V9, V8, V3, V5, V7, V6, V10, V11, V4 and V2. In contrast, students' self-assessments of their competencies yielded mean scores ranging from 2.59 to 3.06, with SD between 1.02 and 1.17. The ranking of these variables, from highest to lowest, was: V9, V1, V2, V5, V6, V8, V3, V11, V10 and V4. A comparison of the expert-expected competency scores and the students' self-assessed scores revealed that the expert means were consistently higher, with differences ranging from 0.44 to 1.31. The overall SD of the students' self-assessed competency were more significant than those of the expert-expected competency scores, indicating higher variability. The most notable gaps in mean scores between expert-expected student competencies and student self-assessment of competencies were observed in V3 and V8, both showing a discrepancy of 1.31, as illustrated in Table 1.
- Dimension 2 – Green competencies of students (V12–V24) encompass 13 variables. The analysis revealed that the mean scores for expert expectations ranged from 3.77 to 4.43, with SD between 0.77 and 1.06. The ranking of variables based on expert mean scores, from highest to lowest, was V14, V13, V16, V18, V20, V12, V19, V15, V22, V24, V23, V17 and V21. In contrast, students' self-assessed competency scores showed mean values ranging from 3.06 to 3.49, with SD ranging from 1.08 to 1.16. The ranking of these variables, from highest to lowest, was V12, V13, V14, V16, V19, V15, V18, V23, V20, V24, V21, V22 and V17. A comparison of expert-expected competency scores and students' self-assessed scores demonstrated that expert means were consistently higher, with differences ranging from 0.44 to 1.00. Furthermore, the SD of students' self-assessed scores were more significant than those of expert-expected scores, indicating higher variability in students' evaluations of their competencies. The most important gaps in mean scores between expert-expected student competencies and student self-assessment of competencies were observed in V20 (1.00) and V14 (0.97), as illustrated in Table 1.
- Dimension 3 – Student skills for the 21st-century (V25–V50) for the sustainable smart manufacturing industry comprise 26 variables representing the skills that experts expect students to possess within the context of the sustainable smart manufacturing industry. The analysis revealed that the mean scores for expert expectations ranged from 3.43 to 4.27, with SD between 1.06 and 1.22. The ranking of variables, based on expert mean scores from highest to lowest, was as follows: V26, V25, V27, V47, V32, V49, V50, V28, V48, V36, V30, V31, V37, V38, V46, V40, V45, V29, V33, V39, V41, V42, V34, V35, V43 and V44. In contrast, students' self-assessed competency scores had mean values ranging from 3.39 to 4.19, with SD between 0.91 and 1.09. The ranking of variables, from highest to lowest, was as follows: V50, V30, V31, V32, V33, V29, V25, V28, V39, V27, V34,

Table 1. Assessment of student competency for the sustainable smart manufacturing industry

Variable	Indicator	Expert-expected student competency score $\bar{x}$	SD	Student competency self-assessment score $\bar{x}$	SD	The gap between the $\bar{x}$ of students' competencies and the experts' expectation score
	Dimension 1 – Technological skills					
V1	To proficiently use AI or ML	4.27	0.74	3.02	1.03	1.25
V2	To proficiently use reality technologies (RT), such as augmented reality (AR) and virtual reality (VR)	3.30	1.15	2.86	1.02	0.44
V3	To proficiently use automation or robotics	4.10	0.92	2.79	1.08	1.31
V4	To proficiently use a 3D printer	3.57	1.07	2.59	1.10	0.97
V5	To proficiently use Big Data	4.03	1.03	2.85	1.05	1.18
V6	To proficiently use cloud computing technology	3.83	0.95	2.84	1.07	0.99
V7	To proficiently use computer-aided design (CAD), computer-aided manufacturing (CAM) or CAx software	3.93	1.05	2.84	1.17	1.10
V8	To proficiently apply the design for manufacturing (DFM) concept	4.13	0.90	2.82	1.11	1.31
V9	To proficiently use the IoT or IIoT	4.20	0.81	3.06	1.13	1.14
V10	To proficiently utilise simulation or digital twin technology	3.73	1.05	2.72	1.07	1.01
V11	To proficiently apply the cybersecurity concept	3.67	1.15	2.79	1.02	0.88
	Dimension 2 – Green competencies					
V12	To sustainably manage manufacturing work through reuse and recycling	4.10	1.06	3.66	1.11	0.44
V13	To proficiently make manufacturing processes use less energy	4.27	0.87	3.49	1.09	0.77
V14	To reduce and handle waste in factories	4.43	0.77	3.46	1.16	0.97
V15	To apply the principles of sustainable supply chain management	4.00	0.95	3.29	1.08	0.71
V16	To assess the environmental impact of manufacturing processes	4.23	0.90	3.46	1.12	0.77
V17	To apply the principles of green chemistry to manufacturing processes effectively	3.80	0.96	3.06	1.11	0.74
V18	To use renewable energy technologies in manufacturing	4.20	1.00	3.25	1.12	0.95
V19	To apply the water conservation practices in manufacturing	4.03	1.00	3.38	1.16	0.65
V20	To apply the lifecycle assessment (LCA) techniques to products	4.17	0.95	3.17	1.13	1.00
V21	To integrate eco-design principles into product development	3.77	1.01	3.10	1.08	0.67
V22	To proficiently assess the carbon credit	3.97	1.03	3.09	1.08	0.87
V23	To explain regulations related to the environment, such as ISO14001	3.87	1.04	3.24	1.13	0.63
V24	To explain the SDGs related to the environment	3.93	1.05	3.16	1.09	0.77
	Dimension 3 – 21st-century skills					
V25	To evaluate multiple sources before completing a task	4.20	1.21	3.82	0.91	0.38

(*continued*)

Table 1. Continued

Variable	Indicator	Expert-expected student competency score		Student competency self-assessment score		The gap between the $\bar{x}$ of students' competencies and the experts' expectation score
		$\bar{x}$	SD	$\bar{x}$	SD	
V26	To proficiently make conclusions by analysing various data, such as numbers, facts or pertinent information	4.27	1.14	3.69	0.93	0.58
V27	To proficiently interpret knowledge gained through readings and lectures	4.17	1.09	3.76	0.92	0.4
V28	To proficiently apply knowledge gained from independent study to offer solutions to the discussed problem	4.03	1.22	3.80	0.93	0.23
V29	To be comfortable working in a group to complete a task together	3.80	1.21	3.84	0.97	−0.04
V30	To be willing to include others' perspectives when making decisions	3.97	1.10	4.09	0.90	−0.13
V31	To enjoy collaborating with other students to complete tasks while leveraging their contributions	3.93	1.17	3.99	0.95	−0.06
V32	To effectively collaborate with individuals from diverse backgrounds	4.10	1.18	3.99	0.92	0.11
V33	To be comfortable answering questions in front of an audience	3.80	1.10	3.87	0.96	−0.07
V34	To proficiently communicate ideas using various media formats, such as posters, videos or blogs	3.73	1.05	3.75	0.98	−0.02
V35	To proficiently employ an appropriate organisational pattern to present work or demonstrate learning effectively	3.70	1.06	3.70	0.94	0.00
V36	To proficiently structure data for use in written products or oral presentations, utilising tools such as charts or tables	4.00	1.20	3.64	0.98	0.36
V37	To employ idea-creation techniques such as brainstorming or concept mapping	3.93	1.11	3.67	0.93	0.26
V38	To independently generate innovative ideas to address problems or questions	3.93	1.08	3.69	0.94	0.24
V39	To enjoy exploring and refining various ideas	3.80	1.06	3.80	0.96	0.00
V40	To be capable of inventing solutions to complex, open-ended questions or problems	3.90	1.06	3.64	0.92	0.26
V41	To enjoy learning about other countries or cultures	3.80	1.16	3.68	0.91	0.12
V42	To proficiently incorporate information or ideas from individuals in other countries or cultures	3.77	1.07	3.67	0.97	0.10
V43	To understand and discuss issues of global interdependency, such as environmental trends and the global economy	3.57	1.07	3.54	1.00	0.02
V44	To understand the life experiences of people from other cultures	3.43	1.01	3.52	1.05	−0.08
V45	To motivate and persuade others effectively	3.87	1.14	3.55	1.01	0.31
V46	To negotiate and reason on important matters with others	3.93	1.08	3.64	0.93	0.30

(*continued*)

Table 1. Continued

Variable	Indicator	Expert-expected student competency score $\bar{x}$	SD	Student competency self-assessment score $\bar{x}$	SD	The gap between the $\bar{x}$ of students' competencies and the experts' expectation score
V47	To proficiently communicate using foreign languages such as English or Chinese	4.17	1.09	3.39	1.09	0.77
V48	To possess problem-solving skills and the ability to manage interpersonal conflicts within and/or outside the organisation	4.03	1.07	3.56	0.97	0.48
V49	To be capable of withstanding organisational pressure, accepting challenges and embracing change	4.10	1.16	3.64	0.98	0.46
V50	To demonstrate self-respect and respect for others	4.07	1.20	4.19	0.98	−0.12
	Dimension 4 – Future-thinking skills					
V51	To proficiently connect the current situation in the manufacturing industry with the future trends	4.03	0.93	3.43	0.97	0.61
V52	To identify the key drivers responsible for significant changes in the future of manufacturing	3.97	0.85	3.36	0.98	0.60
V53	To anticipate the future skills required in manufacturing and undertake upskilling or reskilling initiatives accordingly	3.80	0.85	3.44	0.98	0.36
V54	To analyse and adapt manufacturing to global trends	3.93	0.87	3.37	0.99	0.56
V55	To interpret signals of change, including potential risks that may affect manufacturing in the future	4.00	0.74	3.34	1.01	0.66
V56	To forecast future trends in manufacturing based on current issues and challenges	4.03	0.76	3.32	1.02	0.71
V57	To apply foresight tools and methodologies to achieve desired results related to manufacturing	3.93	0.83	3.31	1.04	0.62
V58	To evaluate the long-term impacts of decisions and explore alternative future scenarios in manufacturing	4.13	0.82	3.50	1.01	0.63
V59	To seek diverse perspectives and expertise in manufacturing when exploring future possibilities	4.10	0.80	3.53	0.98	0.57
V60	To look for alternative framings and not just conventional ways of thinking related to manufacturing	4.13	0.78	3.58	0.99	0.55

Note(s): The titles of the indicators were adjusted so that readers could understand their content. However, each sample group received slightly different descriptions. Taking V1 as an example, for experts the question translates as, "I expect that students can be proficient in using AI or ML". Meanwhile, on the student questionnaire V1 translates as, "I am proficient in using AI or ML"
Source(s): The authors

V35, V38, V26, V41, V37, V42, V40, V49, V36, V46, V48, V45, V43, V44 and V47. A comparison between the expert-expected competency scores and students' self-assessed scores indicated that expert mean scores were higher for 17 variables, while nine had equal or lower expert scores. The differences ranged from −0.13 to

0.77. Additionally, the SD of the students' self-assessed competency scores were lower than those of the expert-expected competency scores, indicating reduced variability in the students' assessments. The most substantial gaps in mean scores between expert-expected student competencies and student self-assessment of competencies were observed in V47 (0.77) and V48 (0.48), as presented in Table 1.

- Dimension 4 – Future-thinking skills of students (V51–V60) comprise ten variables. The analysis revealed that the mean scores for expert expectations ranged from 3.80 to 4.13, with SD between 0.74 and 0.93. The ranking of variables based on mean scores, from highest to lowest, was V58, V60, V59, V51, V56, V55, V52, V54, V57 and V53. In contrast, students' self-assessed competencies yielded mean scores between 3.31 and 3.58, with SD ranging from 0.97 to 1.04. The ranking of these variables, from highest to lowest, was V60, V59, V58, V53, V51, V54, V52, V55, V56 and V57. Upon comparing the expert-expected competency scores with the students' self-assessed scores, it was evident that the expert means consistently exceeded those of the students, with differences ranging from 0.36 to 0.71. Furthermore, the SD of the students' self-assessed scores were substantially more significant than those of the expert-expected scores, indicating more considerable variability in the students' evaluations. Notably, the most pronounced gaps in mean scores between expert-expected student competencies and student self-assessment of competencies were observed in V56 (0.71) and V55 (0.55), as detailed in Table 1.

(2) The assessment of the priority of various competencies for the sustainable smart manufacturing industry, as evaluated by experts, revealed that experts ranked the competencies in the following order, from highest to lowest: D1, D3, D2 and D4, as shown in Table 2. In contrast, the assessment of competency priorities by the 421 student respondents indicated that students ranked the competencies as follows, from highest to lowest: D1, D4, D2 and D3. Experts placed the most significant importance on D1 and the least on D4. However, the expert participants in this study generally assigned higher importance to all competencies than students did. D4 showed the smallest gap between the experts' and students' scores, with a mean difference of only 0.09, indicating a closer alignment between the two groups on this particular competency.

Discussion

Both quantitative and qualitative methods were employed to address the research objectives of this study. The findings are discussed as follows: (1) to examine the competence of Thai

Table 2. Assessment of competency prioritisation for the sustainable smart manufacturing industry

Variable	Indicator	Expert-expected student competency score		Student competency self-assessment score		The gap between the $\bar{x}$ of students' competencies and the experts' expectation score
		$\bar{x}$	SD	$\bar{x}$	SD	
D1	Technological skills	4.63	0.49	4.17	1.05	0.46
D2	Green competencies	4.33	0.76	4.16	1.13	0.17
D3	21st-century skills	4.43	0.57	4.03	1.05	0.40
D4	Future-thinking skills	4.27	0.69	4.17	1.07	0.09

Source(s): The authors

students concerning the sustainable smart manufacturing industry and (2) to assess the competence and readiness of Thai students for the sustainable smart manufacturing industry.

The model developed for the study

The model, which was developed for the current study, was constructed of four-dimensional components which were agreed upon by the 31 experts who participated in the research. The results associated with each of these dimensions are now discussed in turn.

(1) Dimension 1 – Technological skills

Technological skills agreed upon by the experts, as shown in Table 1, cover the knowledge of AI/ML, reality technologies (RT) (augmented reality [AR], virtual reality [VR], mixed reality [MR] and extended reality [ER]), automation/robotics, AM (3D printing)/hybrid manufacturing (between AM and subtractive manufacturing, e.g. drilling, cutting and milling), big data analysis, cloud computing, computer-aided design (CAD)/computer-aided manufacturing (CAM)/Cax, design for manufacturing (DFM), IoT/edge computing/IIoT, simulation/digital twin and cybersecurity. These are essential elements to drive the sustainable smart manufacturing industry in terms of technological skills. Similarly, the skills were mentioned in several previous studies (Mittal *et al*., 2017; Kang *et al*., 2016; Natarajan *et al*., 2021; Goutham *et al*., 2022). Key technological skills essential for a sustainable smart manufacturing industry include AI and ML for decision-making, AR/VR for training, automation and robotics for efficiency, 3D printing for customisation, cloud computing for data management, CAD/CAM for product design, DFM for process simplification, IoT/IIoT for connectivity, digital twins and cybersecurity for protection. Additionally, Natarajan *et al*. (2021) emphasised that integrating Industry 4.0 technologies can boost productivity, reduce waste and support sustainability while maintaining market competitiveness.

(2) Dimension 2 – Green competencies

Green competencies, as shown in Table 1 (Dimension 2: V12–V24), cover green knowledge, green skills, green awareness, green attitudes, green abilities and green behaviour, including carbon credit, environmental regulations and SDGs. This was similar to Braun *et al*. (2022), who found that there was a need for green skills in Industry 4.0 in order to achieve sustainable growth. Akyazi *et al*. (2022) also mentioned that green skills, energy conservation, waste reduction and efficient resource use will be essential in the future. Indeed, skills in sustainable resource management, such as the circular economy and recycling, will be crucial in creating sustainable industries. The green competencies of sustainable smart manufacturing reflect a shift towards sustainability-focused practices. Key strategies include eco-friendly manufacturing through material reuse and recycling to conserve resources and minimise waste, energy-efficient technologies like automation and renewable energy to cut costs and emissions, and effective waste management using green chemistry to reduce hazardous substances. Environmental impact assessment (EIA) and lifecycle assessment (LCA) offer insights into product impacts, while eco-design principles prioritise resource efficiency and recyclability. Compliance with standards like ISO 14001 and carbon credit systems and alignment with SDGs ensures holistic environmental consideration with regard to products and processes.

(3) Dimension 3 – 21st-century skills

21st-century skills, as shown in Table 1 (Dimension 3: V25–V50), skills cover communication, technical, thinking, problem-solving, interpersonal, financial and entrepreneurial skills, aligning with findings by Onu *et al*. (2023) and González-Pérez and Ramírez-Montoya. (2022), who emphasise key competencies such as data analysis, teamwork, communication and creativity, as noted in the literature. Effective collaboration requires openness and support, while clear presentations using visuals like charts or videos enhance idea sharing. Brainstorming and concept mapping foster innovative problem-solving and cross-cultural communication, including the use of foreign languages and global cooperation. Indeed, Onu *et al*. (2023) highlight the importance of social and communication skills, while González-Pérez and Ramírez-Montoya (2022) emphasise the integration of technical and social skills through active learning. Furthermore, critical thinking, adaptability and teamwork are all vital for success in a dynamic environment.

(4) Dimension 4 – Future-thinking skills

Future-thinking skills, as shown in Table 1 (Dimension 4: V51–V60), cover identifying and testing hypotheses, exploring beyond fictitious futures, generating new insights into possible future development, recognising both intended and unintended future consequences and risk reduction skills. This is consistent with several studies, such as those by Braun *et al*. (2022), Akyazi *et al*. (2022) and Dumitru and Halpern (2023), which emphasise skills-matching systems and lifelong learning to address Industry 4.0 demands, particularly in AI, robotics and automation. As European manufacturing embraces digitalisation and sustainability, an automated skills database aids training, highlighting critical thinking, teamwork and strategic decision-making – skills essential for solving problems and navigating uncertainties that remain irreplaceable by technology.

Assessment students competences

The discussion now turns to what has been revealed by the student responses to the assessment and, particularly, what it suggests concerning the importance of the four-dimensional competencies towards the sustainable smart manufacturing industry.

(1) Dimension 1 – Technological skills: the highest mean scores for both expert-expected student competencies and student self-assessments were AI/ML and IoT/edge computing/IIoT, reflecting their perceived importance in the sustainable smart manufacturing industry from both perspectives. However, the most significant gaps between expert expectations and student self-assessments were observed in automation/robotics and DFM, likely due to these skills being more specialised and commonly applied in advanced settings like sustainable smart factories.

(2) Dimension 2 – Green competencies: the highest mean scores for both expert-expected student competencies and student self-assessments were in reducing and handling factory waste and improving energy efficiency in manufacturing processes, indicating alignment between both perspectives. However, the most significant gaps between expert expectations and student self-assessments were observed in reducing and handling factory waste and applying the LCA techniques for products, likely due to these skills requiring expertise and knowledge to understand the broader contexts.

(3) Dimension 3 – 21st-century skills: the top three variables ranked by expert mean scores were "making conclusions by analysing various data", "reviewing information from multiple sources before concluding or finalising a task or assignment" and "interpreting the knowledge gained through readings and lectures". In contrast, the top three variables ranked by student self-assessment mean scores were "demonstrated self-respect and respect for others", "being willing to include others' perspectives when making decisions" and "enjoying collaborating with other students to complete tasks while leveraging their contributions". The overall mean scores between expert expectations and student self-assessments exhibited a high degree of similarity, which may be attributed to the demographic profile of the surveyed STOU students, with over 70% being 30 or older, actively employed and possessing more than a decade of professional experience. Notably, experts and students emphasised communication in foreign languages as a critical area for skill development.

(4) Dimension 4 – Future-thinking skills: the highest mean scores for both expert-expected student competencies and student self-assessments were observed in "reflecting on the pros and cons of the decisions over time and their effect in creating various alternative scenarios in the future related to manufacturing", "looking for alternative framings and not just conventional ways of thinking related to manufacturing", and "seeking diverse perspectives and expertise in manufacturing when exploring future possibilities". These results suggest a significant alignment between the two perspectives. However, the most considerable discrepancies between expert expectations and student self-assessments were found in "forecasting future trends in manufacturing based on current issues" and "challenges and in interpreting signals of change, including potential risks that may affect manufacturing in the future".

(5) The prioritisation of competencies for the sustainable smart manufacturing industry, as assessed by both experts and students, revealed a consensus that technological skills were the most critical dimension. Both groups assigned similar priority to future-thinking skills. However, experts consistently attributed greater importance to all competencies than students, suggesting that experts have higher expectations regarding student competencies.

Conclusion and recommendations

This study has focused on the conceptual context of the sustainable smart manufacturing industry and the competencies required for Thailand's sustainable smart manufacturing industry. The four-dimensional competency model has been proposed to address the skills gap, particularly in the context of sustainable smart manufacturing. These dimensions include technological skills, green competencies, 21st-century skills and future-thinking skills, as agreed upon by the 31 experts in the industry who participated in the study.

The competencies and readiness of Thai students at STOU for the sustainable smart manufacturing industry require enhancement to meet expert expectations. Notable gaps between expert expectations and student self-assessments were observed in technological skills, particularly in automation/robotics and DFM, likely due to the specialised nature of these skills, which are more commonly applied in advanced settings such as sustainable smart factories. Regarding green competencies, the most pronounced gaps were found in waste reduction and management and applying LCA techniques to products. This suggests that these skills require a high level of expertise and the ability to assess holistic environmental impacts. For 21st-century skills, the mean scores between expert expectations and student self-assessments were closely aligned, likely due to the demographic profile of the STOU students, with over 70% being aged 30 or older, actively employed and possessing extensive professional experience. Both experts and students identified foreign language communication as a critical skill area for development. Lastly, the most significant discrepancies in future-thinking skills were observed in forecasting manufacturing trends based on current issues and challenges and in interpreting signals of change and potential risks that may impact future manufacturing.

As assessed by experts and students, the prioritisation of competencies for the sustainable smart manufacturing industry revealed a consensus that technological skills were the most critical dimension. Both groups assigned similar priority to future-thinking skills. However, experts consistently attributed greater importance to all competencies than students, suggesting that experts have higher expectations regarding student competencies.

To bridge the gap between expert expectations and student self-assessments, the following strategic recommendations are proposed:

(1) Policy recommendations for enhancing competencies for the sustainable smart manufacturing industry: Develop policies to strengthen STOU student competencies. Key strategies include:

- Curriculum development: The curriculum should align with fields relevant to the industry, such as science, technology, health science management, agriculture and economics, emphasising technological competencies and current employment trends.
- Blended learning models: A blended approach combining face-to-face and online learning is essential, with practical training, suitable venues, and material adaptable to multiple devices

(2) Reducing the gap through collaboration: Collaboration among academics, researchers and industry stakeholders is key to narrowing the gap between academic training and industry needs. Distance learning should incorporate innovation, energy efficiency and sustainability to develop skilled professionals and support the nation's leadership in sustainable manufacturing.

Moreover, the researcher recommends that future research concentrate on three key areas: (1) comparing ability levels with skill mapping to evaluate how effectively student competencies align with industry requirements, (2) developing a curriculum specifically designed for the sustainable smart manufacturing industry to ensure students are equipped for emerging technological challenges and (3) designing and optimising distance learning media to meet the industry's needs, enhancing remote education with practical, industry-relevant content.

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