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Guidelines for the creative integration of workforce competency development with intelligent automation in industrial businesses

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Abstract: Rapid integration of intelligent automation and digital technologies under Industry 4.0 is transforming industrial production systems and workforce requirements. While previous research has examined automation adoption and digital skill development in advanced economies, limited empirical evidence exists on how workforce competency development can be strategically structured in emerging economies, particularly in Southeast Asia. Addressing this gap, this study investigates organisational mechanisms that support workforce readiness for intelligent automation in Thailand's manufacturing and heavy industry sectors. A mixed-methods research design was employed, combining expert interviews and focus group discussions with quantitative surveys of industrial executives. Structural equation modelling was used to test the proposed conceptual framework. Results identified four key organisational components influencing workforce competency development: skill transformation, collaboration network, SMART organisation, and competency database. Findings show that skill transformation plays a central role in strengthening organisational collaboration, enabling smart organisational systems, and supporting competency management infrastructures for intelligent automation environments.

Keywords: workforce competency development; intelligent automation systems; digital transformation; skill transformation; SMART organisation; structural equation model.

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1 Introduction

The rapid advancement of digital technologies and intelligent automation has significantly transformed the nature of work across industries worldwide. The emergence of Industry 4.0 has accelerated the integration of artificial intelligence (AI), robotics, big data analytics, and cyber-physical systems into industrial production and organisational processes. While these developments have been widely studied in advanced industrial economies, their implications for emerging industrial regions, particularly Southeast Asia, remain comparatively under-explored, despite the region's growing role in global manufacturing and supply chains. Southeast Asian economies, including Thailand, have experienced rapid industrial expansion and technological adoption in recent years, yet the extent to which workforce competencies are evolving in parallel with these technological shifts is still not well understood. As intelligent automation becomes increasingly embedded in industrial systems, workers are required to develop new competencies that enable effective interaction with automated technologies and digital platforms (Acerbi et al., 2022; Kolade and Owoseni, 2022).

Recent global reports highlight the magnitude of this transformation. According to the World Economic Forum (2023), technological disruption is expected to reshape labour markets significantly, with many traditional job roles declining while new roles requiring digital, analytical, and technological skills emerge. Studies on artificial intelligence adoption have similarly emphasised that organisations must prioritise workforce upskilling and reskilling in order to successfully integrate AI technologies into their operational processes (Morandini et al., 2023). However, much of this evidence is derived from developed economies, where institutional support systems, workforce structures, and technological maturity differ from those of emerging regions. In contrast, Southeast Asian industrial economies are undergoing accelerated technological transition without always having equivalent workforce development frameworks in place, which may create structural imbalances between technological capability and human capital readiness.

Developing workforce competencies has therefore become a strategic priority for industrial organisations undergoing digital transformation, particularly within manufacturing-intensive economies. Previous studies have identified several important dimensions of workforce readiness for Industry 4.0 environments. For example, Kipper et al. (2021) highlighted the importance of interdisciplinary competencies, including technical knowledge, teamwork, problem-solving ability, and digital literacy. Santana and Diaz-Fernandez (2021) further emphasised the growing importance of analytical and

data-driven skills in AI-enabled workplaces. In addition to individual competencies, scholars have also emphasised the importance of organisational structures and collaborative ecosystems that support knowledge sharing and innovation. Research by Ivanov (2023) and Bettiol et al. (2023) suggests that collaboration networks and organisational transformation play a crucial role in enabling firms to adopt advanced technologies and maintain competitive advantage in Industry 4.0 environments.

Despite the growing body of research on workforce development and digital transformation, several limitations remain within the existing literature. Much of the prior work has focused on identifying the technical skills required in digital workplaces or examining the organisational impacts of specific technologies such as artificial intelligence or robotics. However, relatively limited research has proposed empirically validated frameworks that integrate multiple organisational dimensions, including workforce skill transformation, collaborative networks, intelligent organisational systems, and data-driven competency management, into a comprehensive model for workforce competency development in intelligent automation environments. This limitation is particularly evident in studies focusing on emerging economies, where organisational structures, labour market conditions, and institutional support systems differ significantly from those in developed countries. As a result, organisations in these contexts often lack clear strategic guidance on how these elements interact to support workforce readiness and long-term competitiveness.

This gap is especially relevant in the context of Thailand, which represents one of Southeast Asia's key manufacturing hubs, with strong participation in global value chains across industries such as automotive, electronics, and heavy manufacturing. As Thailand continues to pursue national strategies such as Thailand 4.0, industrial organisations are increasingly adopting intelligent automation technologies to enhance productivity and competitiveness. However, workforce capability development has not always progressed at the same pace as technological adoption. Labour productivity trends illustrate this challenge clearly. Recent international assessments (OECD, 2024; World Bank, 2022) indicate that Thailand's labour productivity growth has slowed considerably in recent years. Average productivity growth declined from approximately 3.7% per year during 1990–2010 and 4.8% during 2010–2015 to only about 2.1% between 2015 and 2023, indicating a substantial reduction in efficiency gains across the economy. In addition, recent productivity indicators show that Thailand's productivity index declined from 119.82 in the second quarter of 2025 to 116.51 in the third quarter of 2025, suggesting continuing challenges in maintaining productivity growth despite increasing technological adoption. These trends point to a growing misalignment between technological advancement and workforce capability, highlighting the need for more structured and context-specific workforce development strategies.

To address this gap, the present study investigates strategic approaches for developing workforce competencies in industrial organisations operating in intelligent automation environments, with a particular focus on Thailand's manufacturing and heavy industry sectors. Existing studies have largely examined individual skill requirements or the impact of specific technologies on organisational performance. However, fewer studies have proposed empirically validated models that integrate multiple organisational dimensions influencing workforce readiness. In particular, there remains limited empirical evidence explaining how skill transformation, collaborative networks, intelligent organisational systems, and competency data infrastructures interact to support

workforce competency development in industrial automation contexts, especially within emerging Southeast Asian economies.

Accordingly, this study aims to advance existing knowledge by examining the structural relationships among these organisational dimensions and their role in enabling workforce readiness for intelligent automation systems. Specifically, the research seeks to:

1 examine the organisational structures and operational characteristics of industrial businesses in relation to workforce competency development

2 identify and analyse the key components that constitute effective strategies for developing workforce competencies to work creatively with intelligent automation systems

3 develop a structural equation model (SEM) that conceptualises and empirically validates a framework for workforce competency development tailored to intelligent automation environments.

By addressing these objectives, this study contributes to the theoretical development of workforce transformation research while also providing practical insights for policymakers, educators, and industrial leaders seeking to strengthen workforce capability and organisational competitiveness in the era of Industry 4.0 and digital transformation.

2 Theoretical background and literature review

The rapid transformation of industrial production systems driven by digital technologies has intensified scholarly interest in workforce capability development within the context of Industry 4.0 and intelligent automation. Understanding how organisations develop competencies that enable employees to collaborate effectively with automated technologies requires an integrated theoretical perspective. Several theoretical frameworks provide important foundations for examining this issue, including human capital theory, socio-technical systems theory, dynamic capability theory and the knowledge-based view of the firm.

Human capital theory suggests that investments in employee knowledge, skills, and training enhance organisational productivity and economic performance. In the context of Industry 4.0, these investments increasingly involve digital literacy, interdisciplinary technical capabilities, and analytical competencies required for operating advanced manufacturing technologies. Complementing this perspective, socio-technical systems theory emphasises that organisational effectiveness depends on the alignment between technological systems and human capabilities. Intelligent automation environments require human workers and automated technologies to function as interdependent components within a broader socio-technical system.

Dynamic capability theory further explains how organisations adapt to rapidly evolving technological environments by developing and reconfiguring internal capabilities that support innovation and competitive advantage. Workforce competency development therefore becomes a critical mechanism through which organisations respond to technological disruption. Finally, the knowledge-based view highlights the strategic role of organisational knowledge systems in capturing, storing, and utilising

workforce competencies. Together, these theoretical perspectives suggest that workforce competency development should be examined not only at the individual level but also as part of an integrated organisational system involving workforce skills, collaborative networks, organisational structures, and knowledge management mechanisms.

Building upon these theoretical foundations, the present study examines four key dimensions that influence workforce competency development in intelligent automation environments: skill transformation, collaboration network, SMART organisation and competency database. These constructs represent organisational mechanisms through which workforce competencies are developed, coordinated, and integrated with intelligent technologies.

2.1 Skill transformation

Skill transformation represents a fundamental component of workforce adaptation in Industry 4.0 environments. According to human capital theory, organisations must continuously invest in workforce skill development in order to maintain productivity and competitiveness in technologically evolving industries. The rapid introduction of automation technologies has altered the nature of industrial work, creating demand for hybrid competencies that combine technical expertise with cognitive, digital, and collaborative capabilities.

Several studies have examined the implications of digital transformation for workforce skills. Acerbi et al. (2022) emphasised that Industry 4.0 environments require workers to develop interdisciplinary competencies that integrate engineering knowledge, digital literacy, and problem-solving abilities. Similarly, Kolade and Owoseni (2022) observed that technological disruption is reshaping labour markets and employment structures, creating new job roles that demand continuous workforce reskilling and lifelong learning. Morandini et al. (2023) further highlighted that the integration of artificial intelligence within organisational operations requires employees to develop competencies related to data interpretation, technological decision making and human-machine collaboration.

These studies collectively suggest that skill transformation is a critical factor influencing workforce readiness in digitally enabled industries. However, existing research primarily focuses on identifying future skill requirements rather than examining how organisations systematically manage skill transformation processes. Furthermore, most empirical studies have been conducted in advanced industrial economies, leaving limited evidence regarding how workforce skill transformation strategies operate in emerging industrial contexts. Consequently, a contextual gap remains in understanding how organisations in emerging economies develop workforce competencies that enable effective interaction with intelligent automation technologies.

2.2 Collaboration network

Collaboration networks represent an important organisational mechanism through which firms access knowledge, technological expertise, and innovation capabilities. From the perspective of social capital theory and network theory, collaborative relationships facilitate knowledge exchange, trust-building, and collective learning, which are critical for organisational adaptation to technological change.

In Industry 4.0 environments, collaboration networks frequently extend beyond organisational boundaries to include partnerships between firms, research institutions, technology providers, and government agencies. Scherngell (2021) highlighted the importance of research and development collaboration networks in enabling organisations to share specialised knowledge and reduce technological uncertainty. Similarly, Bettiol et al. (2023) found that both internal and external collaboration networks facilitate knowledge creation and innovation within Industry 4.0 ecosystems.

The emergence of Industry 5.0 further reinforces the importance of collaborative ecosystems that integrate technological innovation with human-centred development. Ivanov (2023) argued that future industrial systems will depend on cooperative interactions between human workers, intelligent technologies, and institutional stakeholders. Through such networks, organisations are able to accelerate technological learning and strengthen workforce capabilities.

Despite these insights, existing studies primarily examine collaboration networks in relation to technological innovation or supply chain coordination rather than workforce competency development. As a result, limited empirical evidence exists regarding how collaboration networks directly support workforce skill development in intelligent automation environments. Understanding this relationship is therefore important for identifying how collaborative systems contribute to workforce readiness for Industry 4.0.

2.3 SMART organisation

The concept of the SMART organisation has emerged as a key framework for understanding how organisations integrate advanced technologies with adaptive management practices. From the perspective of dynamic capability theory, organisations must continuously develop and reconfigure internal capabilities to respond effectively to rapidly evolving technological environments.

Adamik and Sikora-Fernandez (2021) describe SMART organisations as entities capable of integrating technological innovation, digital infrastructure, and organisational learning processes to enhance competitiveness. Such organisations utilise intelligent technologies and digital management systems to improve operational efficiency while fostering innovation and strategic decision making. Similarly, Li et al. (2023) introduced the concept of decentralised autonomous organisations (DAO), where digital systems facilitate collaborative decision making between human workers and intelligent agents.

Industry 5.0 perspectives further emphasise the importance of balancing technological advancement with human-centred organisational design. Zizic et al. (2022) argued that future industrial systems must integrate technological efficiency with workforce well-being and sustainability considerations. Within this context, SMART organisations represent an organisational structure capable of coordinating technological capabilities with workforce competencies.

However, existing research on SMART organisational systems has largely focused on technological infrastructure, innovation management, and organisational performance. Relatively limited studies have examined how SMART organisational structures support workforce competency development in intelligent automation environments. This limitation suggests the need for empirical research examining how organisational transformation influences workforce readiness for digital manufacturing systems.

2.4 Competency database

Competency databases represent a critical organisational tool for managing workforce capabilities in knowledge-intensive environments. From the perspective of the knowledge-based view of the firm, organisational knowledge constitutes a key strategic resource that enables firms to maintain competitive advantage. Competency databases support this process by capturing, organising, and analysing workforce skills, training needs, and knowledge resources.

Studies on Industry 4.0 workforce development highlight the increasing importance of structured competency management systems. Kipper et al. (2021) emphasised that organisations must establish competency frameworks that integrate technical, analytical, and social skills required in digital manufacturing environments. Santana and Diaz-Fernandez (2021) similarly highlighted the growing importance of data-driven competency management systems for organisations adopting artificial intelligence technologies.

Furthermore, Hamdan et al. (2021) demonstrated that advanced analytics and digital knowledge systems enable organisations to improve workforce planning and decision making by providing real-time insights into employee competencies and skill gaps. By integrating competency databases with organisational information systems, firms can design targeted training programmes and support continuous workforce development.

Despite these developments, existing research has largely examined competency databases from technological or human resource management perspectives. Limited research has explored how competency databases interact with organisational mechanisms such as skill transformation strategies, collaboration networks, and organisational capability development to support workforce competency development in intelligent automation environments.

2.5 Research gaps

Collectively, the literature demonstrates that workforce competency development in intelligent automation environments is influenced by multiple organisational dimensions, including skill transformation, collaborative networks, smart organisational systems, and knowledge management infrastructures. However, several important gaps remain in the current body of research.

First, a relational gap exists in that many studies examine these constructs independently rather than analysing how they interact within a broader organisational system supporting workforce competency development. Much of the existing literature focuses either on workforce skills, technological adoption, or organisational innovation in isolation, with limited attention given to the structural relationships among these organisational mechanisms.

Second, a significant contextual gap exists in the geographical focus of existing research. Most empirical studies examining Industry 4.0 workforce transformation have been conducted in advanced industrial economies, particularly in Europe and North America. Comparatively limited research has examined workforce competency development in emerging industrial economies, where institutional structures, labour markets, and organisational capabilities differ significantly. In particular, empirical studies examining intelligent automation and workforce development within Southeast Asian industrial contexts remain scarce.

This issue is especially relevant in the case of Thailand, which possesses one of the largest manufacturing-based economies in Southeast Asia and plays a significant role in global supply chains across sectors such as automotive, electronics, and industrial production. As Thailand continues to pursue national strategies related to Industry 4.0 and digital transformation, industrial organisations are increasingly adopting intelligent automation technologies to enhance productivity and competitiveness. However, despite the economic importance of Thailand's manufacturing sector, relatively few empirical studies have examined how organisations within this context develop workforce competencies that enable effective collaboration between human workers and intelligent automation systems.

Finally, a methodological gap exists in that relatively few studies have proposed empirically validated models explaining the structural relationships among workforce skill transformation, collaboration networks, SMART organisational systems, and competency databases. Addressing these contextual, relational, and methodological gaps therefore provides the motivation for the present study, which develops and empirically validates a structural equation model linking these organisational dimensions within the context of intelligent automation environments in Thailand's industrial sector.

3 Research hypotheses

The increasing integration of intelligent automation technologies in industrial production systems has intensified the need to understand how workforce competencies evolve in response to technological change. As discussed in the preceding literature review, several organisational mechanisms play important roles in shaping workforce readiness for Industry 4.0 environments. Drawing upon human capital theory, socio-technical systems theory, dynamic capability theory, and the knowledge-based view of the firm, this study conceptualises workforce competency development as a multidimensional organisational process influenced by interconnected factors including skill transformation, collaboration networks, smart organisational systems, and competency data infrastructures.

Although previous studies have explored these constructs individually, relatively limited empirical research has examined their structural relationships within a comprehensive framework, particularly in emerging industrial economies. To address this gap, the present study proposes a structural equation model that examines how these organisational dimensions interact to influence workforce competency development in intelligent automation environments. Based on the theoretical foundations and empirical findings discussed in Section 3, the following hypotheses are proposed.

3.1 Skill transformation and collaboration network

Skill transformation plays a fundamental role in enabling employees to adapt to technological change. According to human capital theory, organisations that invest in developing employee competencies create a workforce capable of responding to new technological and organisational demands. In digital production environments, skill transformation often requires employees to engage in collaborative learning processes that facilitate knowledge exchange and collective problem-solving.

Previous research highlights the importance of collaborative environments in supporting workforce capability development. Tohani and Aulia (2022) examined the

role of 21st-century learning approaches in strengthening competencies related to critical thinking, creativity, communication, and collaboration. Their findings demonstrated that structured learning environments encourage the development of collaborative capabilities, which in turn support broader skill development processes. As workers develop new technological and cognitive skills, they increasingly rely on collaboration networks to share knowledge, exchange expertise, and adapt to evolving workplace requirements.

From an organisational perspective, collaboration networks also provide opportunities for employees to engage with external stakeholders such as educational institutions, technology vendors, and professional training organisations. These interactions facilitate knowledge transfer and enable organisations to strengthen workforce competencies more effectively. Based on these theoretical and empirical insights, it is expected that workforce skill transformation will contribute positively to the development of collaboration networks within industrial organisations.

H1 Skill transformation has a direct influence on collaboration network.

3.2 Skill transformation and SMART organisation

Organisational transformation represents an essential component of successful technology adoption in Industry 4.0 environments. Dynamic capability theory suggests that organisations must continuously adapt their internal structures and processes to accommodate technological change. Workforce skill transformation is therefore closely linked to organisational capability development, as employees must possess the competencies required to operate within digitally enabled systems.

Research examining artificial intelligence integration within organisations has emphasised the need for continuous reskilling and organisational learning. Morandini et al. (2023) highlighted that the introduction of AI technologies not only improves operational efficiency but also requires organisations to redesign workforce development strategies. Employees must acquire new competencies related to digital systems, data analysis, and interdisciplinary collaboration in order to effectively engage with intelligent technologies.

The development of SMART organisations further reinforces this relationship. Smart organisational systems rely on technologically skilled employees capable of interacting with advanced digital infrastructure. As workforce competencies evolve through skill transformation processes, organisations become better positioned to implement intelligent systems and digital management practices. Consequently, workforce skill development can act as a catalyst for broader organisational transformation toward SMART organisational models.

H2 Skill transformation has a direct influence on SMART organisation.

3.3 Skill transformation and competency database

In addition to influencing organisational transformation, workforce skill development also contributes to the creation and utilisation of organisational knowledge systems. From the perspective of the knowledge-based view, organisational competitiveness depends

heavily on the effective management of knowledge resources, including employee competencies and expertise.

Research on digital transformation highlights the importance of structured competency management systems that enable organisations to monitor and develop workforce capabilities. Chin (2024) emphasised that organisations adopting advanced technologies such as artificial intelligence, big data, and robotics must establish competency frameworks that align workforce capabilities with technological requirements. These systems often rely on competency databases that store and analyse workforce skill information to support training and development initiatives.

As organisations implement skill transformation programmes, competency data becomes increasingly valuable for monitoring workforce capabilities and identifying skill gaps. The systematic documentation of workforce competencies allows organisations to design targeted training programmes and align employee skills with evolving technological demands. Consequently, workforce skill transformation is expected to contribute directly to the development and utilisation of competency databases within organisations.

H3 Skill transformation has a direct influence on competency database.

3.4 Collaboration network and SMART organisation

Collaboration networks also play an important role in supporting organisational transformation. According to social capital theory, collaborative relationships enable organisations to access external knowledge, resources, and expertise that facilitate innovation and organisational learning. These networks are particularly important in Industry 4.0 environments, where technological complexity often requires cooperation among multiple stakeholders.

Treviño-Elizondo et al. (2023) proposed a maturity model that integrates Lean management principles with Industry 4.0 technologies to guide organisational transformation. Their study emphasised that collaboration among stakeholders – including industry partners, technology providers, and research institutions – can significantly accelerate organisational readiness for digital transformation. Collaborative ecosystems enable organisations to acquire technological knowledge, implement digital infrastructure, and strengthen organisational capabilities required for SMART organisational systems.

Through these collaborative mechanisms, organisations are able to integrate new technologies more effectively while simultaneously strengthening internal organisational structures. As collaboration networks expand, organisations gain access to external expertise and innovative practices that support the development of smart organisational systems. Therefore, collaboration networks are expected to positively influence the development of SMART organisations within industrial contexts.

H4 Collaboration network has a direct influence on SMART organisation.

3.5 SMART organisation and competency database

SMART organisational systems often rely on digital technologies and data-driven management processes to support organisational decision making. From the perspective of organisational capability development, the adoption of smart organisational systems

frequently requires the implementation of integrated information systems that manage workforce knowledge and competencies.

Adamik and Sikora-Fernandez (2021) highlighted that SMART organisations utilise digital infrastructure and knowledge management systems to enhance organisational performance and competitiveness. These organisations integrate technological capabilities with workforce development strategies, enabling them to systematically monitor and improve employee competencies.

Within such environments, competency databases serve as a key organisational tool for managing workforce knowledge resources. These systems allow organisations to collect, analyse, and utilise workforce competency information to support training programmes, performance evaluation, and workforce planning. As organisations transition toward SMART organisational systems, the development of competency databases becomes increasingly important for aligning workforce capabilities with technological and organisational objectives.

Accordingly, the development of SMART organisational systems is expected to contribute directly to the establishment and utilisation of competency databases.

H5 SMART organisation has a direct influence on competency database.

3.6 Differences in workforce competency development priorities based on enterprise size

In addition to examining structural relationships among organisational dimensions, this study also considers whether organisational size influences how industrial firms prioritise workforce competency development strategies. Previous studies have suggested that the adoption of Industry 4.0 technologies may vary depending on organisational characteristics such as firm size, technological capability, and resource availability.

Yu and Khan (2021) examined the relationship between Industry 4.0 technologies and circular economy practices within the automotive industry. Their findings suggested that technological adoption can enhance operational performance across organisations of different sizes, although resource availability and organisational capacity may influence implementation strategies. These findings raise the question of whether small and medium-sized enterprises (SMEs) and large enterprises prioritise workforce competency development strategies differently.

Given the increasing importance of workforce readiness in intelligent automation environments, it is important to examine whether organisational size influences the perceived importance of competency development initiatives. Accordingly, the present study investigates whether differences exist in the prioritisation of workforce competency development components across enterprises of different sizes.

H6 The level of importance assigned to workforce competency development for creative engagement with intelligent automation systems does not differ significantly by enterprise size.

4 Methods

This study adopts a mixed-methods research design to investigate strategic approaches to workforce competency development in industrial organisations operating in intelligent automation environments. The integration of qualitative and quantitative methods allows for a more comprehensive understanding of complex organisational phenomena by combining exploratory insights with empirical validation. Mixed-methods approaches are particularly appropriate when examining emerging research topics – such as workforce competency development for intelligent automation – where both conceptual exploration and statistical testing are necessary to develop robust theoretical frameworks.

The rationale for adopting a mixed-methods design in this study is twofold. First, the qualitative phase enables the identification and refinement of the key organisational dimensions influencing workforce competency development in intelligent automation contexts. Second, the quantitative phase allows these relationships to be empirically tested using structural equation modelling (SEM). By integrating both approaches, the study ensures that the proposed conceptual framework is grounded in both expert knowledge and empirical evidence.

The research was conducted within the manufacturing and heavy industrial sector of Thailand, which represents one of the largest manufacturing-based economies in Southeast Asia. Thailand plays a significant role in global supply chains across industries such as automotive production, electronics manufacturing, machinery, and heavy industrial processing. As part of the National Thailand 4.0 development strategy, many industrial organisations have begun integrating intelligent automation technologies into their production systems. This transition has created increasing demand for workforce competencies that enable effective collaboration between human workers and advanced technological systems.

The study focuses specifically on manufacturing and heavy industry sectors, where automation technologies are widely implemented in production processes. These sectors include industries such as automotive manufacturing, electronics production, metal fabrication, machinery manufacturing, and other industrial production activities that involve advanced manufacturing systems. These industries were selected because they represent key contributors to Thailand's industrial economy and are among the most affected by the adoption of intelligent automation technologies.

The research design consists of three sequential stages:

1 exploratory qualitative research through in-depth interviews

2 quantitative data collection through survey research

3 qualitative validation through focus group discussions to confirm the proposed conceptual model.

4.1 Population and sample selection

4.1.1 Qualitative phase: in-depth interviews

The first phase of the study employed qualitative research methods to explore the organisational mechanisms that influence workforce competency development in intelligent automation environments. Purposive sampling was used to select participants

with relevant expertise in industrial workforce development, automation technologies, and organisational management.

A total of nine experts participated in the in-depth interview stage. These experts were drawn from three stakeholder groups:

1 industrial sector executives involved in manufacturing and heavy industry operations

2 government representatives responsible for labour development and industrial policy

3 academic scholars with expertise in workforce development, industrial transformation, and automation technologies

Each group contributed three participants, ensuring representation across policy, industry, and academic perspectives. The interviews focused on identifying the key organisational factors that influence workforce competency development in intelligent automation environments.

4.1.2 Quantitative phase: survey research

The second phase involved quantitative data collection through a structured survey. The target population consisted of industrial enterprises in Thailand's manufacturing and heavy industry sectors that had received investment promotion from the board of investment (BOI). These firms represent technologically active industrial organisations that are likely to adopt intelligent automation systems as part of their production strategies.

According to BOI records, the total population consisted of 7,311 industrial establishments operating within these sectors. The respondents included individuals directly involved in workforce development and production management, such as engineers, production managers, operations managers, and human resource executives responsible for employee training and technological integration.

Sample size determination was guided by Yamane's (1967) formula for sample size calculation and the recommendations of Comrey and Lee (1992), who suggest that a sample size of 500 respondents is considered 'very good' for structural equation modelling studies. Accordingly, a total of 500 responses were collected.

A multi-stage sampling procedure was employed. First, cluster sampling was used to classify firms according to organisational size, dividing the sample into small and medium-sized enterprises (SMEs) and large industrial firms. Second, systematic sampling was applied to select firms within each cluster. The final sample consisted of 250 respondents from SMEs and 250 respondents from large enterprises, allowing for comparison between different organisational scales.

4.1.3 Qualitative phase: focus group discussions

Following the quantitative analysis, a focus group discussion was conducted to validate the conceptual model and interpret the empirical findings. A total of 11 experts participated in the focus group session. These experts were selected based on their experience in industrial workforce development, automation technologies, and organisational management. The focus group discussion provided additional insights regarding the practical applicability and strategic relevance of the proposed workforce competency development framework.

4.2 Research tools

Two primary research instruments were developed to support the qualitative and quantitative phases of the study.

4.2.1 Qualitative: structured interview guide

For the qualitative phase, a structured interview guide was developed based on the conceptual framework identified in the literature review. The interview questions were designed to explore four key organisational dimensions:

1 skill transformation

2 collaboration network

3 SMART organisation

4 competency database.

The interview process enabled the researchers to gather expert insights regarding the challenges and strategies associated with workforce competency development in intelligent automation environments.

4.2.2 Quantitative: questionnaire design

For the quantitative phase, a structured questionnaire was developed to measure organisational practices related to workforce competency development in intelligent automation contexts. The questionnaire consisted of 100 items measured using a five-point Likert scale, ranging from 'very low importance' to 'very high importance'.

To ensure content validity, the questionnaire was reviewed by five subject-matter experts, and the item objective congruence (IOC) method was applied to evaluate the relevance of each item. A pilot test was subsequently conducted with 30 respondents from industrial organisations similar to the target population.

Item analysis indicated that standard deviation values ranged from 0.51 to 3.61, while corrected item-total correlation values ranged from 0.58 to 0.93, indicating satisfactory discrimination among questionnaire items. Reliability testing using Cronbach's alpha produced a value of 0.99, demonstrating very high internal consistency.

4.3 Data analysis

The collected data were analysed using both qualitative and quantitative analytical techniques in order to ensure comprehensive evaluation of the proposed conceptual framework.

4.3.1 Qualitative analysis

Qualitative data obtained from the in-depth interviews and focus group discussions were analysed using content analysis. This analytical approach allows researchers to systematically identify recurring themes, conceptual patterns, and relationships among organisational dimensions influencing workforce competency development in intelligent

automation environments. The insights obtained from the qualitative phase were used to refine the conceptual framework and to support interpretation of the quantitative results.

4.3.2 Quantitative analysis

Quantitative data obtained from the survey were analysed using descriptive statistics, inferential statistics, and multivariate analysis techniques. Descriptive statistics were first applied to summarise the demographic characteristics of respondents, including organisational size, industrial sector, managerial position, and years of professional experience. Presenting the demographic profile of respondents helps establish the representativeness of the sample and provides contextual information regarding the industrial organisations participating in the study.

Following the descriptive analysis, structural equation modelling (SEM) was employed to examine the relationships among the constructs proposed in the conceptual framework. SEM was selected because it enables the simultaneous analysis of multiple relationships among latent variables while accounting for measurement error. The analysis was conducted using SPSS and AMOS software.

4.3.3 Measurement model assessment

Prior to testing the structural model, the measurement model was evaluated to assess the reliability and validity of the constructs. Several statistical criteria were applied to ensure the adequacy of the measurement model.

Reliability assessment was conducted using Cronbach's alpha and composite reliability (CR) values. Cronbach's alpha values greater than 0.70 indicate acceptable internal consistency of measurement items. Composite reliability values above 0.70 similarly demonstrate satisfactory reliability of the latent constructs.

Convergent validity was evaluated using standardised factor loadings and average variance extracted (AVE) values. Standardised factor loadings greater than 0.50 indicate that observed variables adequately represent their corresponding latent constructs. The AVE value should exceed 0.50, indicating that the construct explains more than half of the variance of its indicators.

Discriminant validity was assessed by comparing the square root of the AVE for each construct with the correlations among constructs. Discriminant validity is considered acceptable when the square root of the AVE is greater than the inter-construct correlations, indicating that each construct is empirically distinct from the others.

Additionally, variance inflation factor (VIF) values were calculated to evaluate potential multicollinearity among indicators. VIF values below 5.00 indicate that multicollinearity is not a significant concern in the measurement model.

4.3.4 Structural model evaluation

Once the measurement model demonstrated satisfactory reliability and validity, the structural model was evaluated to test the hypothesised relationships among constructs. Model fit was assessed using several commonly accepted goodness-of-fit indices (Arbuckle, 2016).

The chi-square statistic (χ^2) evaluates the discrepancy between the observed covariance matrix and the model-implied covariance matrix, and is expressed as:

$$\chi^2 = (N-1)F_{ML}$$

where N represents the sample size and F_{ML} is the maximum likelihood fitting function. The associated probability value (CMIN-p) should be greater than 0.05, indicating an acceptable fit between the model and the data.

The relative chi-square (CMIN/DF), also referred to as the normed chi-square, adjusts the chi-square statistic for model complexity and is calculated as:

$$\frac{\chi^2}{df}$$

where *df* denotes the degrees of freedom. Values less than 2.00 indicate a good model fit.

The goodness-of-fit index (GFI) measures the proportion of variance accounted for by the estimated population covariance and is defined as:

$$GFI = 1 - \frac{\sum (s_{ij} - \hat{\sigma}_{ij})}{\sum (s_{ij})^2}$$

where s_{ij} represents elements of the observed covariance matrix and $\hat{\sigma}_{ij}$ represents elements of the model-implied covariance matrix. A value greater than 0.90 indicates acceptable fit.

The root mean square error of approximation (RMSEA) evaluates the lack of fit per degree of freedom and is calculated as:

$$RMSEA = \sqrt{\left[\frac{\chi^2 - df}{df(N-1)}\right]}$$

Values less than 0.08 indicate reasonable model fit, while values below 0.05 suggest a close fit.

These indices collectively provide a comprehensive assessment of model adequacy, ensuring that both absolute and relative fit criteria are satisfied.

In addition to model fit indices, standardised path coefficients were examined to determine the strength and significance of the hypothesised relationships among the constructs. Statistical significance was evaluated at the 0.05 level.

The integration of measurement model assessment and structural model analysis ensures the robustness and validity of the proposed conceptual framework. By combining qualitative insights with rigorous quantitative analysis, the study provides a comprehensive evaluation of workforce competency development strategies in intelligent automation environments within Thailand's manufacturing and heavy industry sectors.

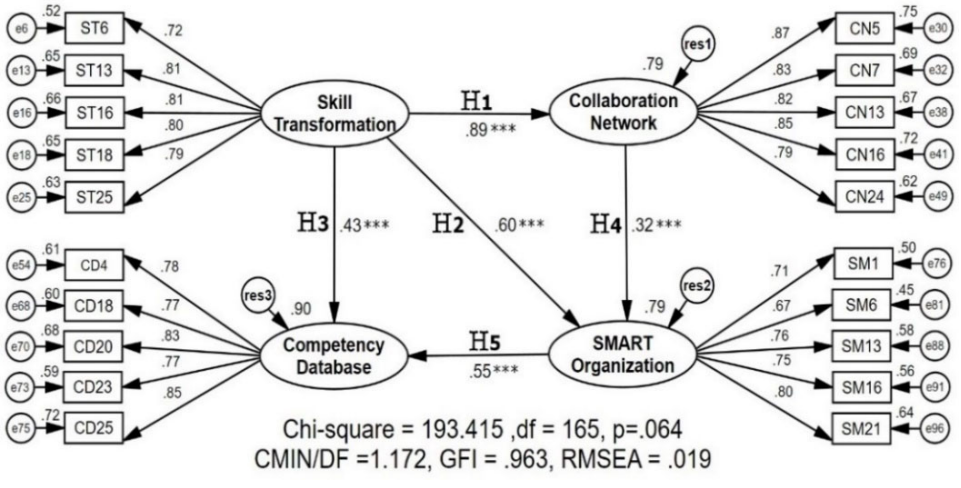
5 Results

The analysis of the perceived importance levels of strategic approaches to workforce competency development in industrial businesses, specifically in relation to integration with intelligent automation systems and categorised by business size, is summarised in Table 1.

Table 1 Mean and standard deviation of the perceived importance of workforce competency development components for intelligent automation systems, categorised by business size

Competency development components	*Small- and medium-size enterprises (SMEs)*			*Large enterprises*		
	Mean	*S.D.*	*Sig. level*	*Mean*	*S.D.*	*Sig. level*
Overall	4.06	0.52	High	4.09	0.66	High
Skill transformation	4.08	0.54	High	4.15	0.67	High
Collaboration network	4.10	0.57	High	4.09	0.77	High
SMART organisation	4.05	0.53	High	4.07	0.63	High
Competency database	4.00	0.60	High	4.06	0.7	High

Figure 1 Structural equation model, post-refinements, for the creative integration of workforce competency development with intelligent automation systems in industrial businesses



Based on Table 1, the analysis of competency development strategies for enabling industrial workforce engagement with intelligent automation systems shows high importance across all components, regardless of business size. For small and medium-sized enterprises (SMEs), the overall mean was 4.06. Ranking of the components in order of importance revealed the following:

1 collaboration network ($\bar{X} = 4.10$)

2 skill transformation ($\bar{X} = 4.08$)

3 SMART organisation ($\bar{X} = 4.05$)

4 competency database ($\bar{X} = 4.00$).

For large enterprises, the overall mean was 4.09. The ranking of component importance was as follows:

1 skill transformation ($\bar{X} = 4.15$)

2 collaboration network ($\bar{X} = 4.09$)

3 SMART organisation ($\bar{X} = 4.07$)

4 competency database ($\bar{X} = 4.06$).

These findings confirm that across both business sizes, all four dimensions are regarded as highly important in fostering effective workforce integration with advanced automation technologies.

Figure 1 illustrates the structural equation model (SEM) for strategic workforce competency development within industrial organisations, presented in the standardised solution after model refinement. Table 2 summarises the model fit indices before and after the modification process.

Table 2 Model fit indices for the structural equation model, before and after model refinements

Model fit indices	*Acceptable threshold*	*Before refinement*	*After refinement*
CMIN-P (chi-square probability)	>0.05	0.000	0.064
CMIN/DF (relative chi-square)	<2.00	2.858	1.172
Goodness-of-fit index (GFI)	>0.90	0.626	0.963
Root mean square error of approximation (RMSEA)	<0.08	0.061	0.019

Table 2 presents the model fit statistics, showing that prior to modification, the model failed to meet several key fit criteria: the chi-square probability (CMIN-P) was 0.000 (<0.05), and the relative chi-square (CMIN/DF) was 2.858 (>2.00). The goodness-of-fit index (GFI) was 0.626 (<0.90), and the root mean square error of approximation (RMSEA) was 0.061 (<0.08), suggesting partial fit with the empirical data. Following the refinement process, guided by modification indices and theoretical justification in accordance with Arbuckle (2016), the model was improved by sequentially removing underperforming observed variables and re-evaluating the structural parameters. The final model met all four fit criteria: CMIN-P = 0.064 (>0.05), CMIN/DF = 1.172 (<2.00), GFI = 0.963 (>0.90), and RMSEA = 0.019 (<0.08). These results confirm that the revised structural equation model for developing workforce competencies in intelligent automation environments demonstrates an excellent fit with the empirical data and is therefore validated as a robust analytical framework.

Table 4 presents the standardised estimates of direct, indirect, and overall influence among the components of the structural equation model for the integration of workforce competency development in industrial businesses with intelligent automation systems, following model refinement. The results show that the strongest direct influence was found in Hypothesis H1, with a standardised regression weight of 0.89. In terms of overall influence, the component of *skill transformation* exerted the highest total effect on the *competency database*, with a cumulative weight of 0.92 (comprising direct and indirect effects of 0.43, 0.33, and 0.16, respectively).

Table 3 Standardised regression weights of observed variables from the structural equation model, after model refinement

Standardised regression weights of observed variables after model refinement		*Standardised regression weight*
	Skill transformation	
ST6	Develop new work models to enhance competency and improve performance in automation systems	0.72
ST13	Clearly analyse workforce competency efficiency and development strategies	0.81
ST16	Continuously establish workforce competency standards for intelligent automation and emerging technologies	0.81
ST18	Develop standards and conduct skills testing for working with intelligent automation systems	0.80
ST25	Design and integrate new skills into existing ones (hybrid skill) to ensure sustainability	0.79
	Collaboration network	
CN5	Formulate workforce competency development plans in collaboration with the Department of Skill Development and leading training institutions	0.87
CN7	Promote shared value principles in workforce competency development, focusing on collaborative problem-solving between executives and staff	0.83
CN13	Jointly adopt and adapt knowledge based on local contexts to strengthen capabilities of the education sector and automation system vendors	0.82
CN16	Organise joint team-building activities with automation vendors to enhance collaborative problem-solving skills	0.85
CN24	Implement joint measures between executives and personnel to establish feedback mechanisms for improving competency development processes	0.79
	SMART organisation	
SM1	Develop strategic plans to transform the organisation into a SMART entity for workforce development	0.71
SM6	Recruit talent with creative thinking skills	0.67
SM13	Strategically invest in modern technologies or automation systems to create SMART classrooms and enhance knowledge management	0.76
SM16	Use digital tools and systems to communicate organisational vision and policies consistently across the workforce	0.75
SM21	Encourage employees to produce technological outputs in intelligent automation to establish organisational recognition among public and private sectors	0.80

Table 3 Standardised regression weights of observed variables from the structural equation model, after model refinement (continued)

Standardised regression weights of observed variables after model refinement		*Standardised regression weight*
	Competency database	
CD4	Integrate the competency database with other organisational network systems	0.78
CD18	Develop cybersecurity systems to manage access rights and protect data	0.77
CD20	Provide real-time reporting on workforce competency development outcomes across departments	0.83
CD23	Install tools such as big data and data analytics to enable efficient use of data from various sources	0.77
CD25	Develop workforce performance standards for automation systems using competency-based data	0.85

Table 4 Standardised estimates of direct, indirect, and overall influence on competency development components based on the refined structural equation model for integrating workforce competencies with intelligent automation systems

Latent variables	*Skill transformation*	*Collaboration network*	*SMART organisation*	*Competency database*
Collaboration network	0.89	0.00	0.00	0.00
SMART organisation	0.88	0.32	0.00	0.00
Competency database	0.92	0.18	0.55	0.00

6 Discussion

This study aimed to examine organisational mechanisms that support workforce competency development for creative engagement with intelligent automation systems in industrial organisations. Using a mixed-method approach and structural equation modelling, the study investigated the relationships among skill transformation, collaboration networks, SMART organisational systems, and competency databases within the context of Thailand's manufacturing and heavy industry sectors.

The results indicate that workforce competency development in intelligent automation environments is shaped by an interconnected organisational system involving workforce capability development, collaborative knowledge exchange, organisational transformation, and digital knowledge management infrastructures. These findings reinforce the view that workforce transformation in Industry 4.0 is not solely a matter of individual skill acquisition but rather a broader organisational capability-building process.

6.1 Skill transformation and collaboration network

The findings indicate that skill transformation has a significant positive influence on collaboration networks, supporting Hypothesis 1. This result suggests that as organisations invest in developing workforce competencies – particularly digital and

interdisciplinary skills – employees become more capable of participating in collaborative learning environments and knowledge-sharing networks.

From a theoretical perspective, this finding aligns with human capital theory, which posits that investments in employee skills enhance organisational productivity and adaptability. When workers acquire advanced competencies related to digital technologies and automation systems, they are better positioned to engage in collaborative problem-solving and knowledge exchange activities. In Industry 4.0 environments, technological complexity often requires cooperation among workers, engineers, and external experts, making collaboration an essential mechanism for skill development.

The findings also support the arguments of Tohani and Aulia (2022), who emphasised that modern workforce competencies increasingly involve collaborative learning, communication, and interdisciplinary interaction. As employees acquire new technological competencies, they rely on collaboration networks to exchange knowledge, interpret technological data, and collectively address operational challenges.

In the context of Thailand's manufacturing sector, collaboration networks are particularly important because many industrial organisations operate within global production networks. Collaboration with technology providers, research institutions, and training organisations enables firms to access specialised knowledge required for implementing intelligent automation systems. Therefore, skill transformation not only improves individual capabilities but also encourages organisational collaboration that strengthens workforce readiness for technological change.

6.2 Skill transformation and SMART organisation

The results further demonstrate that skill transformation significantly influences the development of SMART organisational systems, supporting Hypothesis 2. This finding indicates that workforce capability development plays a central role in enabling organisations to implement advanced digital systems and intelligent production technologies.

This result is consistent with dynamic capability theory, which suggests that organisations must continuously develop and reconfigure internal capabilities in order to adapt to rapidly changing technological environments. Workforce competencies represent one of the most critical internal capabilities required for organisational transformation. Without employees who possess the necessary digital and analytical skills, organisations may struggle to implement intelligent technologies effectively.

The findings are also consistent with the work of Morandini et al. (2023), who observed that artificial intelligence adoption requires organisations to redesign workforce development strategies. Employees must develop new competencies in areas such as data interpretation, system monitoring, and digital decision making in order to interact effectively with intelligent technologies.

In Thailand's industrial context, the transition toward Thailand 4.0 has accelerated the adoption of automation technologies across sectors such as automotive manufacturing, electronics production, and heavy industry. The present findings suggest that organisational transformation toward SMART systems depends heavily on workforce skill development initiatives. Organisations that actively invest in workforce training and

skill transformation are better positioned to integrate advanced technologies into their operational systems.

6.3 Skill transformation and competency database

The analysis also reveals that skill transformation has a significant influence on the development of competency databases, supporting Hypothesis 3. This finding highlights the important relationship between workforce capability development and organisational knowledge management systems.

From the perspective of the knowledge-based view of the firm, organisational knowledge constitutes a strategic resource that supports competitive advantage. Competency databases allow organisations to capture and organise knowledge related to workforce skills, training requirements, and technological capabilities. As workforce skill transformation programmes expand, organisations require structured systems to monitor and manage workforce competencies effectively.

The findings support previous research by Chin (2024) and Kipper et al. (2021), which emphasised the importance of digital competency management systems in Industry 4.0 environments. These systems allow organisations to identify skill gaps, track employee development, and align workforce capabilities with technological requirements.

Within manufacturing and heavy industry sectors, competency databases are particularly valuable because production systems increasingly involve complex interactions between human operators and automated technologies. By maintaining comprehensive competency databases, organisations can ensure that employees possess the necessary skills to operate advanced equipment and respond to technological changes.

6.4 Collaboration network and SMART organisation

The results indicate that collaboration networks significantly influence the development of SMART organisational systems, supporting Hypothesis 4. This finding highlights the role of collaborative ecosystems in facilitating organisational transformation.

From a theoretical standpoint, this relationship can be explained through social capital theory, which emphasises the role of networks and relationships in enabling knowledge exchange and organisational learning. Collaboration networks allow organisations to access external expertise, technological knowledge, and innovation resources that support digital transformation initiatives.

The findings align with research by Treviño-Elizondo et al. (2023), who demonstrated that collaboration among industrial partners, research institutions, and technology providers accelerates organisational readiness for Industry 4.0 adoption. Such collaborations allow organisations to learn from external stakeholders and adopt best practices for implementing advanced technologies.

For Thai industrial organisations, collaboration networks are particularly important because technological expertise is often distributed across multiple actors within the industrial ecosystem. Partnerships with universities, research institutes, and technology suppliers enable firms to access specialised knowledge required for implementing intelligent automation systems and developing smart organisational structures.

6.5 SMART organisation and competency database

The findings also demonstrate that SMART organisational systems significantly influence the development of competency databases, supporting Hypothesis 5. This result indicates that organisational transformation toward digital and intelligent management systems encourages the adoption of structured knowledge management infrastructures.

SMART organisations typically rely on integrated digital systems to support decision making, performance monitoring, and workforce development. These systems generate large volumes of operational data that can be used to evaluate workforce competencies and identify training needs. Consequently, organisations implementing SMART management systems are more likely to establish competency databases that support workforce planning and development.

This finding supports the work of Adamik and Sikora-Fernandez (2021), who emphasised the importance of digital knowledge management systems within smart organisational environments. By integrating competency databases with organisational information systems, firms can improve workforce planning, enhance employee training programmes, and strengthen organisational learning capabilities.

In Thailand's manufacturing sector, where many organisations are transitioning toward digitally integrated production systems, competency databases provide a valuable tool for managing workforce transformation. These systems enable organisations to align employee capabilities with technological requirements and ensure that workforce development strategies support long-term technological competitiveness.

6.6 Differences in workforce competency development priorities by enterprise size

Finally, the analysis examined whether organisational size influences the prioritisation of workforce competency development strategies. The results indicate that no significant differences were observed between SMEs and large enterprises, supporting Hypothesis 6.

This finding suggests that the importance of workforce competency development for intelligent automation environments is recognised across organisations of different sizes. Regardless of organisational scale, industrial firms must invest in workforce capability development in order to effectively implement advanced technologies.

The result is consistent with the findings of Yu and Khan (2021), who observed that Industry 4.0 technologies can enhance operational performance across firms of varying sizes. Although SMEs and large organisations may differ in their resource capacity, both types of firms recognise the strategic importance of workforce competency development for technological competitiveness.

Within Thailand's industrial ecosystem, SMEs often serve as suppliers within global manufacturing value chains. As a result, these firms must maintain technological capabilities comparable to those of larger enterprises in order to remain competitive. Consequently, workforce competency development becomes a critical priority for both SMEs and large industrial organisations.

Overall, the findings of this study reinforce the view that workforce transformation in intelligent automation environments is shaped by interconnected organisational mechanisms involving workforce skill development, collaborative networks, smart organisational systems, and knowledge management infrastructures. These results

contribute to the growing body of research examining how organisations can prepare their workforce for the technological challenges associated with Industry 4.0 and digital manufacturing systems.

7 Conclusions and implications

This study investigated organisational mechanisms that support workforce competency development for creative engagement with intelligent automation systems within industrial organisations. The research was conducted in the context of Thailand's manufacturing and heavy industry sectors, which represent a major component of Southeast Asia's industrial economy and play a significant role in global manufacturing supply chains. As industrial organisations increasingly adopt intelligent automation technologies, the development of workforce competencies capable of interacting effectively with advanced technological systems has become a critical organisational priority.

Using a mixed-method research design, the study integrated qualitative insights from industry experts with quantitative analysis through structural equation modelling. The results demonstrate that workforce competency development in intelligent automation environments is influenced by an interconnected organisational system involving skill transformation, collaboration networks, SMART organisational systems, and competency databases. In particular, the findings show that skill transformation plays a central role in enabling organisations to strengthen collaboration networks, develop smart organisational structures, and establish competency management systems that support workforce capability development.

The results also confirm that collaboration networks contribute to the development of SMART organisational systems, while smart organisational structures facilitate the implementation of competency databases that allow organisations to monitor and manage workforce capabilities more effectively. These findings reinforce the importance of adopting an integrated organisational approach to workforce transformation in Industry 4.0 environments.

More importantly, this study addresses several important gaps in the existing literature. First, previous research has largely examined workforce skills, organisational transformation, and technological adoption as separate phenomena. This study contributes to the literature by developing and empirically validating an integrated structural framework that explains the relationships among workforce capability development, organisational collaboration, technological transformation, and knowledge management systems. By analysing these constructs simultaneously, the study provides a more comprehensive understanding of how organisations can support workforce readiness for intelligent automation environments.

Second, this research addresses a significant contextual gap in the literature. Much of the existing research on Industry 4.0 workforce transformation has been conducted in advanced industrial economies, particularly in Europe and North America. Comparatively limited empirical research has examined these issues within emerging industrial economies. By focusing on Thailand's manufacturing and heavy industry sectors, this study contributes empirical evidence from a Southeast Asian context, thereby expanding the geographical scope of research on workforce transformation in digital manufacturing environments.

Third, the study addresses a methodological gap by applying a mixed-method approach combined with structural equation modelling to empirically validate the proposed conceptual framework. This methodological integration strengthens the robustness of the findings and provides a systematic framework for analysing workforce competency development strategies in intelligent automation environments.

Overall, the findings of this study highlight that successful workforce transformation in Industry 4.0 environments requires coordinated organisational efforts that integrate workforce skill development, collaborative learning networks, organisational transformation, and knowledge management infrastructures. These results provide valuable insights for industrial organisations seeking to strengthen workforce capabilities in response to rapid technological change.

7.1 Theoretical contributions

This study makes several significant theoretical contributions to the growing body of literature on workforce transformation in Industry 4.0 environments.

First, the study advances existing knowledge by proposing and empirically validating an integrated conceptual framework that explains how multiple organisational mechanisms jointly influence workforce competency development in intelligent automation environments. Whereas prior studies have frequently examined digital skills, organisational innovation, technological adoption, or human resource development as separate issues, the present research demonstrates that workforce transformation is shaped by a broader organisational ecosystem involving skill development processes, collaboration networks, smart organisational structures, and competency management systems. In doing so, the study addresses an important relational gap in the literature by clarifying how these constructs interact rather than merely coexist.

Second, the study contributes to the theoretical integration of several relevant perspectives, including human capital theory, socio-technical systems theory, dynamic capability theory, and the knowledge-based view of the firm. By bringing these perspectives together within a single empirical model, the study offers a stronger theoretical basis for understanding how organisations prepare their workforce for intelligent automation environments. This contribution is important because earlier studies have often relied on single-perspective explanations, which are insufficient for capturing the complexity of organisational transformation under Industry 4.0.

Third, the research extends the geographical scope of Industry 4.0 workforce studies by providing empirical evidence from Thailand's manufacturing and heavy industry sectors, which represent an important industrial hub within Southeast Asia. Since much of the existing research has concentrated on advanced industrial economies, this study helps address the limited availability of empirical evidence from emerging economies, thereby improving the broader relevance and transferability of workforce transformation theory.

8 Recommendations

Based on the findings of this study, recommendations can be proposed at both the policy level and the operational level. These recommendations are grounded in the empirical

relationships identified in the model and are intended to support the development of workforce competencies for intelligent automation within Thailand's industrial sector. Importantly, the recommendations also respond directly to the gaps identified in the literature, particularly the lack of integrated, context-specific, and practically applicable guidance for emerging manufacturing economies in Southeast Asia.

8.1 Policy-level recommendations

At the policy level, the findings indicate that workforce competency development for intelligent automation cannot be achieved through isolated training initiatives alone. Instead, it requires coordinated support across labour policy, higher education, digital infrastructure, industrial investment, and financial systems. The following recommendations are therefore proposed:

1 The Department of Skill Development (Ministry of Labour) should promote new training curricula in areas such as Collaborative robots, human-centric design, mass personalisation, and digital twin technologies. It is also recommended that advanced competency development centres be established and that international collaboration be strengthened with countries such as Japan, Germany and Singapore, where industrial automation and workforce development systems are more mature. In addition, mobile training units and e-learning platforms should be expanded to improve access in remote areas. A dedicated skills development fund should also be launched to support labour market transformation more effectively.

   This recommendation addresses a major practical gap identified in the literature, namely that many studies recognise the need for future-oriented skills but provide limited guidance on how national skill ecosystems should be structured to deliver them systematically.

2 The Office of the National Higher Education, Science, Research and Innovation Policy Council (NXPO), under the Ministry of Higher Education, Science, Research and Innovation, should revise tertiary education curricula so that greater emphasis is placed on AI, robotics, big data, and human-machine interaction. Such revisions should be accompanied by stronger industry-academic collaboration, the establishment of centres of excellence, expanded support for automation-related research, startup incubation programmes, international partnerships, and scholarship schemes aimed at strengthening future workforce and innovation capacity.

   This recommendation addresses the contextual gap between industrial technological advancement and the current preparedness of higher education systems in emerging economies such as Thailand.

3 The Eastern Economic Corridor (EEC) Policy Committee should invest more strategically in smart infrastructure and digital automation ecosystems. This includes establishing advanced skills training centres, promoting research and development in robotics, biotechnology, and clean energy, offering targeted tax incentives, and developing smart cities, sandbox zones, and Industry 4.0 network platforms. Such efforts may further position the EEC as a regional hub for industrial innovation and economic growth.

This recommendation responds to the study's finding that workforce readiness depends not only on training, but also on broader organisational and regional ecosystems that support intelligent automation adoption.

4 The Department of Skill Development should also expand training programmes in human-collaborative robotics, AI, IIoT, and COBOTs. Establishing simulation centres and hybrid training models that combine online learning with practical exercises is strongly recommended. Other useful measures include hackathons, the development of international competency standards, wider e-learning access, rural training programmes, and support for robotics startups.

   This recommendation addresses the methodological-to-practice gap identified in the literature, where competency development is often discussed conceptually but not translated into scalable delivery mechanisms for industrial workers.

5 The Ministry of Digital Economy and Society (MDES) should formulate policies that strengthen workforce capability in relation to AI and intelligent automation systems. Particular emphasis should be placed on human capabilities that remain difficult to automate, such as creativity, adaptive reasoning, and problem-solving. Long-term learning centres should be developed alongside support for AI and robotics startups and investment in digital infrastructure to promote sustainable workforce preparedness.

   This recommendation addresses the study's finding that intelligent automation should not be interpreted as replacing human capability, but rather as increasing the strategic value of uniquely human competencies within socio-technical systems.

6 The Bank of Thailand should support financial policies that enable workforce development in industrial sectors. This includes creating funding mechanisms for skill development programmes in advanced technologies such as AI and robotics, as well as offering low-interest loans to private firms and SMEs investing in workforce training. These measures may strengthen organisations' ability to adapt to technological change and promote more inclusive entrepreneurial development across the industrial sector.

   This recommendation addresses an often overlooked institutional gap in the literature, namely the limited attention given to financial mechanisms that support long-term workforce transformation in emerging economies.

8.2 Operational-level recommendations for industrial businesses

At the operational level, the findings suggest that industrial firms must treat workforce development as a strategic organisational priority linked directly to competitiveness, adaptability, and technological integration. The following recommendations are proposed for manufacturing and heavy industry organisations.

1 Skill transformation: industrial business operators should promote inclusive access to upskilling and reskilling opportunities, align employee competencies with changing industrial requirements, and adopt recognised labour skill standards for competency assessment. Workforce development programmes should be designed to strengthen

not only technical capability but also adaptive, analytical, and collaborative competencies required in intelligent automation environments.

This recommendation addresses the skills implementation gap in the literature, where future skills are often identified but insufficiently operationalised within organisational systems.

2 Collaboration network: greater effort should be made to foster social trust, responsibility, and cooperative engagement among investors, shareholders, executives, and employees. Joint mechanisms for workforce competency development should be established through regular dialogue, while partnerships with the Department of Skill Development, leading educational institutions, and automation vendors should be expanded to accelerate learning and improve operational efficiency.

This recommendation addresses the relational gap identified in the study, highlighting that workforce transformation is strengthened when collaboration networks are institutionalised rather than informal or incidental.

3 SMART organisation: businesses should continuously monitor and adopt emerging technologies that enhance creativity, competitiveness, and adaptive performance. Strategic plans should be explicitly oriented toward becoming a SMART organisation for workforce development. In addition, integrated electronic data management systems should be implemented to store diverse forms of information, including text, numerical records, images, videos, and digital files, so that workforce development can be coordinated more effectively across departments.

This recommendation addresses the organisational gap in the literature, where technological adoption is often discussed without sufficient attention to the internal systems required to support workforce adaptation.

4 Competency database: clear organisational responsibility should be assigned for managing competency development databases. A standardised data collection framework should be adopted throughout the organisation, and tailored learning platforms should be created for each unit to provide services that reflect the specific development needs of workers.

This recommendation addresses the knowledge management gap identified by the study, reinforcing the importance of competency data infrastructures in supporting evidence-based workforce planning.

5 Strategic direction: industrial businesses should establish clear policies and long-term strategic direction aimed at becoming SMART organisations, with particular emphasis on developing a workforce capable of working effectively alongside intelligent automation systems. Such strategies should align technological investment with workforce planning, organisational learning, and continuous competency renewal.

This recommendation addresses the broader strategic integration gap in the literature, where workforce readiness is often treated as a secondary issue rather than as a central part of organisational transformation.

Overall, these recommendations provide a multi-level roadmap integrating labour policy, education, digital infrastructure, finance, and business operations. By responding directly to the contextual, relational, and practical gaps identified in this study, the recommendations contribute to the transformation of industrial labour systems and support stronger alignment between workforce development and technological evolution. In this sense, the study not only advances academic understanding but also offers actionable guidance for strengthening industrial competitiveness and long-term workforce resilience in Thailand and comparable emerging manufacturing economies.

Declarations

The authors report there are no competing interests to declare.

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