



Prioritization of Industry 5.0 Engineering Competencies Using the Analytic Hierarchy Process (AHP)

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ABSTRACT

BACKGROUND & CONTEXT

The transition to Industry 5.0 demands a paradigm shift in engineering education to cultivate competencies aligned with its human-centric, sustainable, and resilient vision. While traditional models prioritize technical expertise, Industry 5.0 requires holistic competencies. This study contributes to developing a Holistic Engineering Competency Model using the Delphi method to determine the relative importance of 30 identified future engineering competencies.

PURPOSE OR GOAL

This study prioritizes future engineering competencies by assessing their relative importance. The goal is to determine the most critical competencies for Industry 5.0-ready engineers, providing insights into how educational curricula and workforce development should evolve.

APPROACH OR METHODOLOGY

This Delphi round used the Analytic Hierarchy Process (AHP) to compare the relative importance of 30 competencies, with judgments from 40 Triple Helix-aligned engineering experts. Aggregated responses produced group results and consensus, while Goepel's Algorithm and K-means clustering identified expert subgroups and optimized prioritization levels.

OUTCOMES

The 30 competencies were grouped into three clusters: "Innovative & Incisive" (high-priority cognitive skills), "Empathetic & Ethical" (medium-priority social skills), and "Adept & Adaptable" (low-priority functional and meta-competencies). These findings highlight the importance of human-centric, ethical, and adaptable skills complementing emerging technologies in Industry 5.0.

CONCLUSIONS

The study affirms the growing value of human-centric competencies in Industry 5.0. It provides evidence to refine the competency model, offering clear direction for aligning engineering education and practice with future workforce demands.

KEYWORDS

Holistic Competency Model, Engineering Competency, Industry 5.0, Delphi, AHP.

Introduction

Industry 5.0 Engineering Competencies

Industry 5.0 represents a transformative shift toward human-centricity, sustainability, and resilience in industrial systems (European Commission: Directorate-General for Research and Innovation et al., 2021). Unlike Industry 4.0's focus on automation, Industry 5.0 emphasizes the symbiotic integration of human creativity and advanced technologies to address societal challenges (Breque et al., 2021; Xu et al., 2021). This paradigm necessitates redefining engineering competencies beyond technical mastery to include cognitive flexibility, ethical judgment, and adaptive problem-solving (Leng et al., 2022; UNESCO & International Centre for Engineering Education, 2021) as well as navigating interdisciplinary complexities while upholding sustainable and socially responsible innovation (Adel, 2022).

Prioritization of Competencies

Prioritization of competencies is critical to aligning with industry demands, not only in engineering but also in other fields. For instance, McGunagle & Zizka (2020) confirmed being a team player, having self-motivation, verbal communication, problem-solving, and being proactive are most important in manufacturing industries. Hidayati et al. (2020) found that programming, interpersonal, and communication skills are the key skills for effective Scrum implementation in global software development. Jhaiyanuntana & Nomnian (2020) found out that critical cultural awareness, attitudes, knowledge, skills to interpret and relate, and abilities to discover and interact are the top 5 intercultural communicative strategies in hospitality industries. These studies underscore the importance of involving field experts or stakeholders to ensure that the prioritization process reflects real-world needs and is valid and reliable.

The Analytic Hierarchy Process (AHP)

AHP, developed by Saaty (1990), is a multi-criteria decision-making method performed through pairwise comparisons. AHP is widely used in the industry in areas such as framework development (Foroozesh et al., 2022), factor analysis (Awan et al., 2022), ranking, and prioritization (Verma et al., 2022). Because of its robustness, it has also been used in competency modelling in many fields, such as maritime operations (Kim & Mallam, 2020), defense industry (Nebati et al., 2023), and engineering (Pattanapairoj et al., 2021). Thus, the use of AHP in the prioritization of future engineering competencies is valid.

Building upon this systematic prioritization process, the present study seeks to address three critical research questions:

1. To what extent do experts demonstrate consensus in the prioritization of Industry 5.0 engineering competencies?
2. How are Industry 5.0 engineering competencies ranked based on priority?
3. What key characteristics of engineers are prioritized for the Industry 5.0 era?

Methodology

This study is part of a larger research initiative to develop a Holistic Engineering Competency Model and Engineering Education 5.0 Framework for Industry 5.0. A systematic review initially identified 30 engineering competencies (Fernando, Ghazali, Phang, & Abdul Rahman, 2025), followed by a 3-round Delphi study to validate and refine them. Round 1 confirmed their relevance and classification as shown in Figure 1 (Fernando, Ghazali, Phang, & Abdul Rahman, 2025), while this round (Round 2) prioritizes their relative importance. Round 3 will establish relationships among competencies to complete the model.

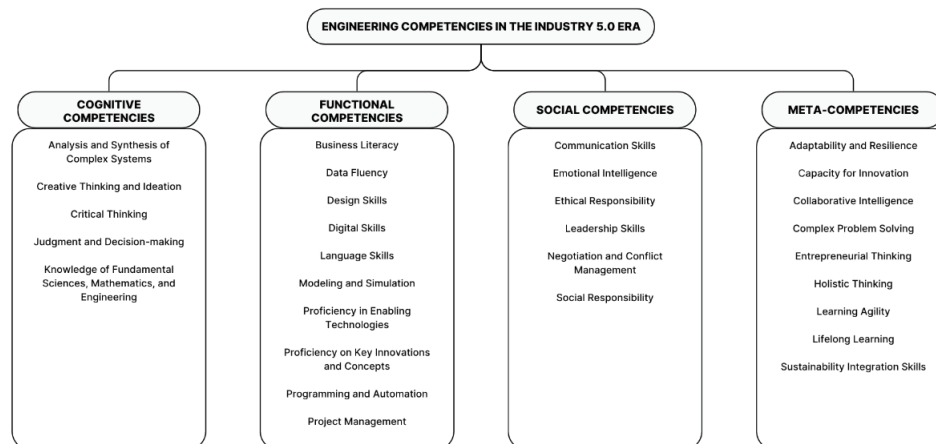


Figure 1: Engineering Competencies in the Industry 5.0 Era

Research Approach

In this round, AHP was primarily employed to prioritize future engineering competencies, with additional procedures implemented to enhance the reliability of the results. Figure 2 presents the research approach organized around the three research questions. The first segment follows the AHP methodology as outlined by Saaty (2008). This is followed by a posteriori analysis and group consensus techniques using Goepel's AHP scale and methods (Goepel, 2019, 2022). The final segment involves clustering (Hartigan, 1975). Each component is discussed in detail in the succeeding sections.

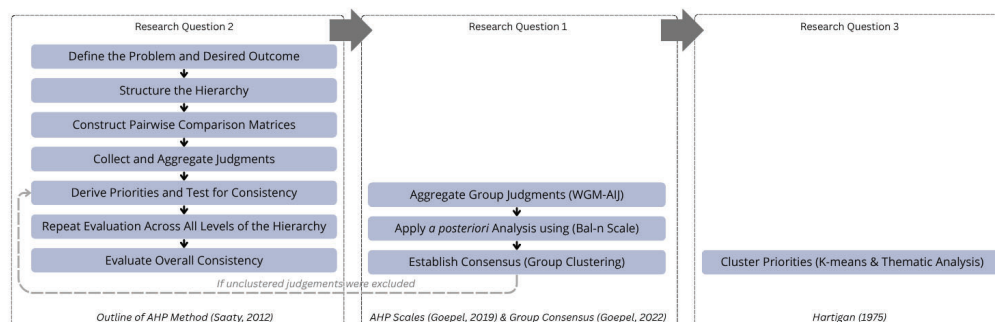


Figure 2: Enhanced AHP Method for the Prioritization of Competencies

Development of the AHP Instrument

The AHP instrument was developed using the AHP-OS (Online System) platform (Goepel, 2018). It was structured to allow experts to conduct pairwise comparisons of competency dimensions and constructs using Saaty's (1990) fundamental 1–9 scale (Table 1).

Table 1: Scale of Relative Importance

Scale	Definition	Description
1	Equal importance	Two competencies contribute equally to the objective.
3	Moderate importance	Experience and judgment slightly favor one competency over another.
5	Strong Importance	Experience and judgment strongly favor one competency over another.
7	Very strong importance	One competency is favored very strongly over another; its dominance is demonstrated in practice.
9	Extreme importance	The evidence favoring one competency over another is of the highest possible order of affirmation.
2, 4, 6, 8 can be used to express intermediate values		

Pairwise comparisons were made across the four competency dimensions (Node 1) and within each of the four dimensions (Nodes 2, 3, 4, and 5).

Data Collection Procedure

Delphi experts in Round 1 were invited to participate in this second round. The AHP-OS link was disseminated electronically, allowing experts to complete the instrument remotely. Experts were instructed to complete pairwise comparisons in a single session to maintain consistency. The tool also automatically computed consistency ratios (CR%) for experts' awareness and improvement of judgments.

Data Analysis Procedure

Responses with a CR% ≤ 0.10 were retained for analysis, while those exceeding the threshold were either returned to the expert for reassessment or excluded. To synthesize group judgments, Goepel's (2018) Weighted Geometric Mean Aggregation of Individual Judgments (WGM-AIJ) was applied.

While the Saaty scale is the most widely used AHP judgment scale, Goepel (2019), in his comparative analysis of AHP judgment scales, proposed the Generalized Balanced Scale (Bal-n), which overcomes key limitations of traditional approaches. The Bal-n scale offered two critical advantages for this study: (1) it automatically adjusted weight dispersion based on the number of criteria (n), preventing underweighting of priorities in larger hierarchies, and (2) it maintained equal weight intervals across all judgment levels, accurately distinguishing Industry 5.0 competencies. A posteriori analysis was applied using the Bal-n scale through AHP-OS.

The group consensus is calculated as the weighted arithmetic mean of the consensus of all nodes. The level of expert agreement was evaluated using Goepel's (2018) interpretation shown in Table 2.

Table 2: Expert Consensus Scale

Agreement Range	Consensus Indicator
87.5% – 100%	Very High
75% – 87.5%	High
62.5% – 75%	Moderate
50% – 62.5%	Low
Below 50%	Very Low

As in Round 1, a high group consensus (at least 75%) is desired. Nodes with moderate consensus and below underwent cluster analysis to group decision makers into smaller subgroups with higher consensus (Goepel, 2022). Experts who belonged to the majority subgroup with high consensus were retained for analysis, while experts who consistently belonged to the minority subgroups and unclustered subgroups were excluded. The experts retained were characterized based on the Triple Helix Systems framework (Ranga & Etzkowitz, 2013), which provides a fine-grained view of innovation actors, both institutional and individual, and the relationships between them.

The prioritization results were presented in terms of local and global priority weights and rankings. Judgments collected within and across competency dimensions are called Local Priorities, while the aggregated judgment, which is the overall result of prioritization, is called Global Priorities. Further, the global priority weights were subjected to k-means clustering to classify the level of priority based on natural groupings of competencies (Hartigan, 1975). Priority clusters were discussed based on their thematic convergence. Visual aids such as tables, a similarity matrix, a priority cluster, and an annotated bar chart were used for clarity.

Validity and Reliability Measures

Validity was ensured through strict expert selection, pre-testing of the AHP tool, and clarity in competency descriptions. Reliability was assessed using the Consistency Ratio and confirmed by cluster analysis to check for coherence in expert perspectives. Group aggregation further ensured that results reflected shared expert judgments rather than individual biases. K-means ensured that priority clustering is valid.

Results and Discussion

AHP Group Consensus

Forty experts from Round 1 were invited to participate. Thirty responded, but five were excluded from analysis. One response (Expert 30) was considered invalid due to incomplete AHP rating, while the other four (Experts 1, 2, 3, 6) were deemed unreliable due to a very high CR% of >10%.

As shown in Table 3, only the Social Competencies node achieved a high consensus level (76.1%). All other nodes, including the Global Priorities, recorded moderate consensus only, ranging from 68.8% to 74.7%.

Table 3: AHP Consensus with and without Group Clustering

Group (Node)	Consensus (Without Group Clustering)	Consensus (With Group Clustering)
Global Priorities	73.2% (moderate)	78.8% (high)
<i>Local Priorities:</i>		
Across Competency Dimensions (1)	74.7% (moderate)	79.8% (high)
<i>Within Competency Dimensions:</i>		
Cognitive Competencies (2)	73.3% (moderate)	79.7% (high)
Functional Competencies (3)	68.8% (moderate)	76.5% (high)
Social Competencies (4)	76.1% (high)	79.0% (high)
Meta-competencies (5)	69.0% (moderate)	75.9% (high)

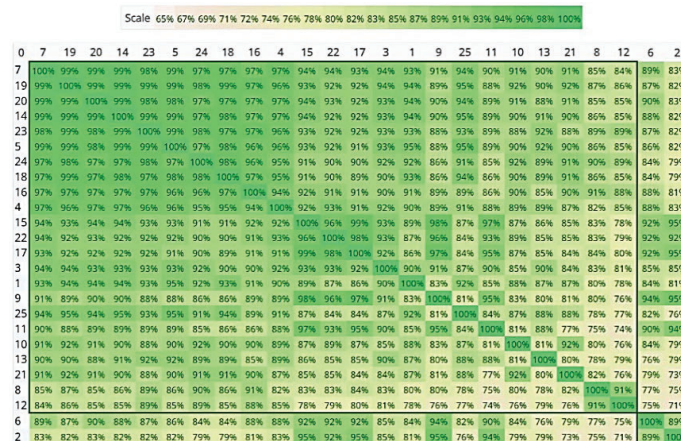


Figure 3: Similarity Matrix for Global Priorities

To further strengthen the validity of the findings, cluster analysis was performed on nodes with moderate consensus. This analysis identified subgroups of experts who shared more internally consistent judgments, thus allowing the refinement of the dataset by excluding outliers (Goepel, 2022). For instance, Figure 3 presents the similarity matrix for the Global Priorities, where experts are numerically labeled along both the rows and columns. The first subgroup, which achieved high consensus, represents the majority of experts, while the remaining experts form minority or unclustered subgroups. Experts who were consistently not part of the high-consensus subgroup were treated as outliers and excluded from the final analysis (i.e., Experts 5, 10, 14, and 16).

The cluster analysis yielded a final expert subgroup of 21 experts, whose judgments were used for priority ranking. As a result of this refined grouping, all nodes attained high consensus post-clustering, as reflected in Table 3. Consensus levels increased across all areas, including Social Competencies, which was already high.

The 21 experts span nine engineering disciplines, predominantly Electronics (8), Chemical (3), and Industrial Engineering (3), with geographic representation across Philippine innovation hubs (Manila, Baguio, Iloilo, Davao). Their hybrid institutional roles, primarily in *Business and Technology Incubators* (13) and *Technology Transfer Offices* (11), reflect deep involvement in the Triple Helix Systems model's knowledge-innovation-consensus spaces (Ranga & Etzkowitz, 2013). Their collective expertise in *technology transfer* (3.24/5) and *global networking* (3.76/5) enriched the prioritization with practical insights. As the involvement of more diverse stakeholders increases the likelihood of innovation (Hernández-Trasobares & Murillo-Lu, 2020), the profile of this panel offers contextually rich and meaningful insights

AHP Group Results

1. Future Engineering Competency Priorities

Table 4 shows the aggregated AHP group result from the experts. The cognitive dimension overwhelmingly led the prioritization, occupying the top four spots by *Analysis and Synthesis of Complex Systems*, *Creative Thinking and Ideation*, *Critical Thinking*, and *Judgment and Decision-making*. The substantial weighting suggests that future engineers must excel in abstraction, problem-framing, and strategic decision-making to navigate complex, interdisciplinary challenges. Notably, *Knowledge of Fundamental Sciences* ranked lower than these cognitive skills, reinforcing that how engineers think matters more than what they know in isolation. Giving cognitive competencies top priority meets Industry 5.0 demand, as it is characterized by a shift from mass automation to enhancing the capabilities of human workers (Breque et al., 2021). This is consistent with the recent reports that analytical thinking is consistently identified as the most sought-after core skill among employers (World Economic Forum, 2025) and creative thinking, systems thinking, and problem-solving are increasingly critical cognitive skills for engineers (UNESCO & International Centre for Engineering Education, 2021). Humans bring cognitive capabilities that machines lack, such as intuition, creativity, versatile problem-solving, and critical thinking (Leng et al., 2022).

The social dimension came second, led by *Ethical Responsibility*, immediately followed by *Communication Skills*, *Leadership Skills*, and *Emotional Intelligence*. This cluster underscores that technical excellence alone is insufficient; engineers must lead teams, navigate ethical dilemmas, and communicate effectively in socially complex environments (e.g., stakeholder negotiations, public policy impacts). The highlight on ethical responsibility fits well with Industry 5.0, as it shifts from being purely technology-driven to being value-driven (Xu et al., 2021). Further, a broad ethical approach and responsibility are highlighted as necessary regarding the development and communication of engineering solutions (UNESCO & International Centre for Engineering Education, 2021). Embedding human-centric values in technology is seen as fundamental for technology to enhance productivity and realize human value, rather than replacing humans (Leng et al., 2022). Effective communication is foundational for the kind of collaboration that defines Industry 5.0, which requires proper interaction with machines (human-AI) as well as operators (human-human) (Adel, 2022). This prioritization suggests that organizations should value integrity and interpersonal effectiveness as critical for collaborative and ethical work environments. However, the lower weightings of *Negotiation and Conflict Management* and *Social Responsibility* may indicate that these are viewed as specialized rather than universal social skills, reserved for leadership or client-facing roles (World Economic Forum, 2025).

Table 4: Aggregated Priorities of Industry 5.0 Engineering Competencies

Competency Construct	Global Priority	Rank
Analysis and Synthesis of Complex Systems	5.90%	1
Creative Thinking and Ideation	5.54%	2
Critical Thinking	5.51%	3
Judgment and Decision-making	5.25%	4
Ethical Responsibility	4.33%	5
Knowledge of Fundamental Sciences, Mathematics, and Engineering	4.26%	6

Communication Skills	3.94%	7
Leadership Skills	3.85%	8
Emotional Intelligence	3.82%	9
Adaptability and Resilience	3.35%	10
Negotiation and Conflict Management	3.26%	11
Design Skills	3.25%	12
Social Responsibility	3.18%	13
Complex Problem Solving	2.90%	14
Data Fluency	2.84%	15
Collaborative Intelligence	2.84%	16
Business Literacy	2.82%	17
Digital Skills	2.81%	18
Project Management	2.80%	19
Capacity for Innovation	2.76%	20
Entrepreneurial Thinking	2.63%	21
Holistic Thinking	2.59%	22
Modeling and Simulation	2.56%	23
Proficiency in Key Innovations and Concepts	2.52%	24
Sustainability Integration Skills	2.51%	25
Proficiency in Enabling Technologies	2.49%	26
Language Skills	2.44%	27
Learning Agility	2.43%	28
Lifelong Learning	2.40%	29
Programming and Automation	2.20%	30

Functional competencies, such as *Design Skills*, *Data Fluency*, and *Business Literacy*, were dispersed mid-ranking, indicating they are contextually vital but not universally dominant. Design skills support the need for engineers to provide innovative and technology-based solutions for pressing challenges (UNESCO & International Centre for Engineering Education, 2021). Industry 5.0 is built upon advanced technologies, such as AI, robots, big data, and mixed realities, which are crucial (World Economic Forum, 2025). The lower rankings of *Programming and Automation* and *Language Skills* may reflect that they are not universally prioritized, have contextual importance, or are potentially replaceable by technologies, especially AI (World Economic Forum, 2025).

Meta-competencies like *Adaptability* and *Complex Problem Solving* were moderately weighted, suggesting they are valued but secondary to cognitive and social skills. Their lower priority may imply they are prerequisites rather than differentiators. However, in the context of Industry 5.0, adaptability is not merely a required competency but a strategic enabler that allows engineers to effectively adapt emerging technologies to human diversity, needs, and contexts. This aligns with global reports and studies that consistently list adaptability and complex problem-solving among the top in-demand skills and key differentiators between growing and declining job roles (Breque et al., 2021; Fernando, 2025; World Economic Forum, 2025). The close prioritization of innovation-related competencies suggests these skills are viewed as interconnected capabilities for future readiness, while the lower rankings of *Learning Agility* and *Lifelong Learning* may indicate they are perceived as fundamental requirements rather than competitive advantages for future engineers, such as the need for continuous professional development (CPD) (Engineering Council, 2020).

2. Clustering of Priorities

To provide a more robust and data-driven classification of the global AHP priorities for engineering competencies, k-means clustering was employed as an unsupervised machine learning approach to group the 30 competencies based on their priority values objectively. The elbow method determined k=3 to be the optimal number of clusters, explaining a substantial 92.43% of the variance in the data, indicating that three clusters effectively captured the inherent grouping structure while avoiding overfitting, as illustrated in Figure 4.

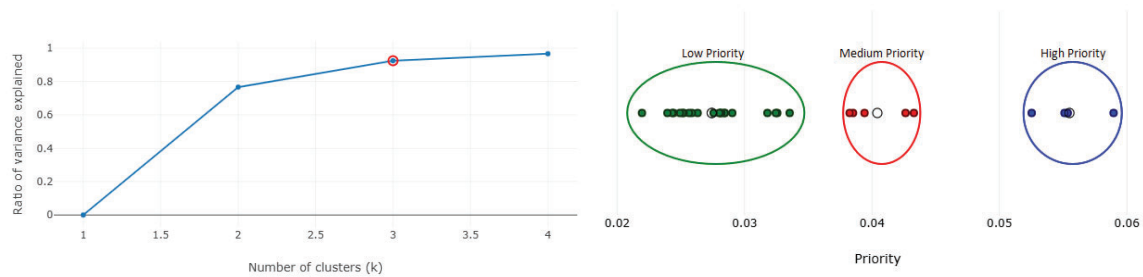


Figure 4: Elbow Method and K-means Clustering

The clustering results revealed three distinct tiers: **a high-priority cluster** (centroid at 0.05549), **a medium-priority cluster** (centroid at 0.04042), and **a low-priority cluster** (centroid at 0.02743). The exceptionally high between-cluster variance ($SSG=0.002947$) compared to minimal within-cluster variance ($SSE=0.0002414$) statistically validates these groupings, with the tight clustering around the high and medium centroids ($SSE<0.000023$) particularly reinforcing the dominance of cognitive and social competencies in the global priorities. These quantitative results align with and substantiate the AHP findings, providing confirmatory evidence that cognitive and social competencies are unequivocally prioritized over technical proficiencies in the evolving engineering landscape.

Engineers in the Industry 5.0 Era

The three priority clusters were deliberately named to embody the competencies engineers need to actualize the human-centric, sustainable, and resilient vision of Industry 5.0 (Figure 5). The **“Innovative & Incisive”** cluster captures the highest-priority competencies, focused on creativity with the ability to connect complex systems, emphasizing their strategic role in driving breakthrough innovation. The **“Empathetic & Ethical”** cluster reflects the medium-priority competencies that promote human-centeredness, social responsibility, and ethical leadership – the core pillars of Industry 5.0. Lastly, the **“Adept & Adaptable”** includes 21 foundational but lower-priority competencies, highlighting essential technical skills and the flexibility required to navigate evolving technologies and cross-disciplinary work environments.

These clusters are more than semantic groupings. They offer actionable direction for curriculum design and workforce development. Their alliterative, dual-adjective format improves recall while capturing the multidimensionality of each competency group. Practically, they can guide engineering institutions in prioritizing learning outcomes, focusing first on cognitive and social competencies that distinguish future-ready engineers, while ensuring foundational technical capabilities are not neglected. This layered prioritization supports a shift in engineering education towards producing systems thinkers, ethical decision-makers, and resilient professionals capable of thriving in dynamic socio-technical ecosystems.

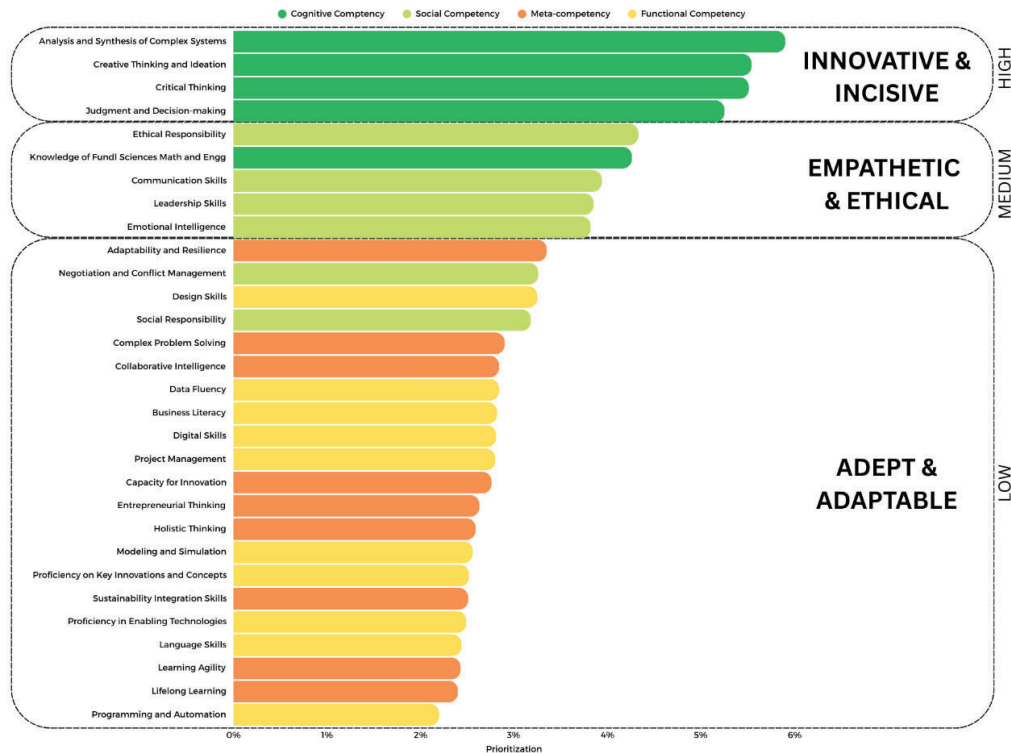


Figure 5: Prioritization of Industry 5.0 Engineering Competencies

While the study employed a rigorous AHP-Delphi approach, its generalizability is limited by a relatively homogeneous, metro-centric expert pool and moderate initial consensus on some competencies. Future research should involve more diverse panels, triangulate with industry data, and use mixed methods to strengthen real-world alignment.

Conclusion

This study prioritized key engineering competencies for Industry 5.0 using a rigorous AHP-Delphi approach, resulting in three validated clusters: Innovative & Incisive (cognitive), Empathetic & Ethical (social), and Adept & Adaptable (functional/meta-competencies). The findings underscore Industry 5.0's shift toward human-centric, sustainable, and resilient systems, emphasizing the need for engineers to master systems thinking, ethical leadership, and technical agility. While the expert-derived priorities provide a validated framework, geographic and disciplinary representation limitations highlight opportunities for broader stakeholder inclusion in future research. The next Delphi round will advance this work by determining the structural relationships among these competencies to provide a systems-level understanding of how they interact within the model.

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Acknowledgements

The authors would like to express their sincere gratitude to the UTM Department of Deputy Vice Chancellor (Research & Innovation) for their financial support. This work was funded under UTM Fundamental Research Grant (Grant No. Q.J130000.3809.23H23). This support has been invaluable in the successful completion of the work presented in this study. The first author also acknowledges the support provided by the National University, Philippines in completing his PhD study.

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