Competency Framework Package for Educating Emerging Construction Technologies

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This study addresses the challenges of human resource development in the architecture, engineering, and construction (AEC) sectors, particularly focusing on the integration of emerging technologies such as robotics, human-machine collaboration, and human augmentation. We propose the Fundamental Competency Package (FCP), a novel framework that systematically organizes essential skills and competencies in a visually accessible format. The framework was developed by extracting and classifying 840 competency nodes from relevant literature, organizing them into a hierarchical structure, and implementing an interactive 3D visualization system.
Semi-structured interviews with three industry experts evaluated the FCP's practical utility. While the framework received generally positive feedback, the evaluation revealed three key areas for improvement: regular data updates, regional adaptability, and enhanced user interface. The study suggests that the FCP shows promise as a foundation for systematic skill development and transfer, though challenges remain, including maintaining currency in rapidly evolving technologies and establishing validation mechanisms. Future development should focus on collaborative enhancement through practitioner-researcher partnerships and potential open-source implementation.

Keywords: *Robotics, Human-machine Collaboration (HMC), Human Augmentation (HA), Skill Development, Education, Fundamental Competency Package (FCP).*

INTRODUCTION

The construction industry currently faces a chronic labor shortage. The situation becomes even more challenging by the increasing difficulty in transferring expertise, stemming from the growing diversity and complexity of project-specific requirements. Several digital technologies and methodologies, including robotics, human-machine collaboration (HMC), human-computer interaction (HCI), and human augmentation (HA), collectively referred to as emerging construction assistance (ECA), have been proposed as potential solutions to address this problem. However, their implementation to the actual project has been hampered by multiple obstacles. Despite the obvious demand for practical use in the years to come, the industry has been experiencing underdeveloped educational infrastructure, high deployment costs, and a shortage of qualified trainers. The adoption of HMC and HA technologies in the construction sector lags notably behind that of other industries. The earlier study demonstrated that the number of academic publications in this

domain has been slightly decreasing over the past decade (Natsuki and Ishizawa, 2024).

This stagnation can be attributed to several factors. University and vocational training curricula in the architectural faculty are already overloaded, leaving little room to incorporate new technological content (Zakharova, 2022; Papavasiliou, 2022). Moreover, there is a scarcity of educators capable of providing specialized instruction in ECA-related fields, as well as a lack of adequate teaching materials and practical training environments. The lack of sufficient and specific needs from the practices also complicates the development of a concrete pedagogical program.

To address these issues, this study proposes a novel framework, termed the Fundamental Competency Package (FCP), which identifies and organizes essential skills and competencies in a systematic and visually appealing format. FCP aims to comprehensively classify cross-disciplinary capabilities of ECA, facilitating efficient human resource development and skill transfer in both educational and industrial contexts.

RESEARCH QUESTION

The research object of this paper is to investigate the underlying factors that hinder the advancement of human resource development for ECA in the architecture, engineering and construction (AEC) sectors. In response to this issue, it is hypothesized that a structured framework is necessary for designing effective training programs and curricula, which is expected to increase the likelihood of incorporating the principles for the technologies into existing curricula. To test this, FCP was developed to systematize skill sets. Semi-structured interviews with experienced practitioners evaluated its utility.

LITERATURE REVIEW

Robotics, HMC, HCI, and HA technologies have been actively researched and implemented across various industries, including manufacturing and healthcare, with the aim of enhancing productivity and ensuring worker safety. Recent reviews have highlighted the advancements in human-machine interface (HMI) technologies, their integration with IoT, and their applicability in various industrial and healthcare settings (Singh and Kumar, 2021; Gupta and Akanksha, 2024). *Human Augmentation: The Dawn of a New Paradigm* (UK Ministry of Defense, 2021) outlines the social and industrial implications of HA technologies, stressing the importance of ethical considerations, feasibility, and integrated strategies. Additionally, The edited volume *Augmented Human* (Rekimoto, ed., 2018) presents diverse perspectives and practical examples of HA applications, contributing to a multifaceted understanding of the field. Keywords from the table of contents and index of such literature have been referenced to aid in the systematic extraction of competencies relevant to robotics and HA.

In contrast, the application of these technologies within architecture and construction remains fragmented and lacks a cohesive, systematic implementation strategy. Efforts have been made to uncover their potential to resolve the paramount issues in the industry. Emaminejad and Akhavian (2022) conducted a systematic review, which examines two decades of literature focusing on trust in AI and AI-driven robotics, and applications of these technologies in the AEC industry.

METHODOLOGY

This research consisted of two main phases. First, FCP was developed as a structured set of competencies designed to support human resource development and curriculum expansion for problem-solving.

Second, semi-structured interviews were conducted to evaluate the FCP's practical usefulness.

Development of the FCP. The findings from these preceding studies benefit the configuration of the field of research. A long list of 840 competency nodes was compiled through an objective extraction of skills and abilities referenced in academic literature and technical documents, namely *Springer Handbook of Robotics* (Siciliano and Khatib, 2016) and *Augmented Human* (Rekimoto, ed., 2018). These competencies are considered as the ones that reflect capabilities required in contemporary society. Selected items of the competencies extracted from reference materials are shown in table 1. This excerpt illustrates how specific concepts were identified and organized during the initial long-list construction process. An attribute was needed to classify the competencies into the educational context.

Table 1
Representative concepts used in the initial construction of the competency list

Source	Representative Concepts
Springer Handbook of Robotics (Siciliano and Khatib, 2016)	Fabrication, Motion Control, Calibration, Fault Tolerance, Robot Arm, Biomimetic Robots, Mobility of Wheeled Robots, etc.
Augmented Human (Rekimoto, ed., 2018)	Electronics, Virtual Reality, Mechatronics, Wearable Devices, Motion Capture, Multimodal Interaction, Power Assist, Brain-Machine Interface (BMI), Projection Mapping, Feedback, Head-Mounted Display, Nanofibers, Telexistence, Prosthetic Hand, Orthosis, etc.
Manually Added by Author	Vocabulary Acquisition, Digital Literacy, Problem Solving, Team Building, Documentation, BIM, 3D Printing, Haptic Feedback, Cybernetics, etc.

In addition to categorization, contextual connections between items were also considered. To achieve this, semantic relationships among nodes were initially defined by the authors based on domain relevance and expected proficiency levels. These relationships were subsequently expanded semi-automatically using a Python-based process that applied natural language processing to build a knowledge graph representing the interconnectedness of competencies.

The resulting classification further supports usability through dynamic visualization. An interactive 3D knowledge graph was implemented using Python scripts.

Verification of the utility. To assess the validity and practicality of the developed FCP, semi-structured interviews were conducted with three individuals who possess both educational backgrounds and professional experience in the AEC industry. The interviewees were selected for their familiarity with both technical and pedagogical aspects of emerging technologies in the AEC domain.

Semi-structured interviews are designed to elicit open-ended opinions and in-depth insights from participants while focusing on predetermined themes. This approach allows for both structured evaluation and flexible, respondent-driven feedback. The primary objectives of the interviews were twofold: to assess the perceived usefulness and workplace applicability of the FCP based on expert insights, and to gather feedback regarding areas for improvement, the appropriateness of the classification method, and its practical relevance in real-world settings.

Although the sample size was limited to three participants, they were selected for their diverse professional roles and expertise, ensuring a variety of perspectives that enrich the qualitative assessment. The methodology was adopted based on the qualitative research guidelines outlined by Terashita (2011).

As an ethical consideration, respondents participated in the interviews on a completely voluntary basis. The interviews were conducted in an environment conducive to the respondents' comfort, and they were permitted to decline answering questions that might be disadvantageous to them and to terminate their participation at any time. Interviews were conducted with respondents who provided prior consent under these conditions.

DEVELOPMENT

This section provides the details of the procedures for the development and evaluation processes of FCP.

Development Process. A comprehensive list of competencies (referred to as "nodes") was generated by extracting keywords from indices and tables of contents in relevant reference materials mentioned above. In addition, several universal skills were manually included by the author to complement the coverage of relevant terms. Based on existing classification schemes commonly used in organizing technical and academic knowledge, the extracted competencies were categorized into the following four dimensions: Field, Sub-classification, Type, and Level. These dimensions, along with their definitions and representative examples, are summarized in table 2.

The categorized nodes were then arranged into a hierarchical structure composed of three conceptual layers. This three-layered structure—core, intermediate, and outer—should be distinguished from the four attribute-based dimensions mentioned above. While the conceptual layers represent the relative positioning of competencies in terms of generality and specialization, the dimensions describe the categorical characteristics of each competency. The core layer includes universal basic skills, surrounded by field-specific foundational skills in the intermediate layer, and highly specialized competencies in the outer layer. Furthermore, relationships between nodes were encoded as "edges," with each edge annotated by type (e.g., hierarchical, subordinate, related), weight, and direction.

Representative examples of the categorized nodes, including their Top-domain, Sub-domain, and Type classifications, are presented in table 3.

The initial set of 65 edges was defined manually as a reference, after which approximately 800 additional edges were generated semi-automatically using a Python script developed to perform rule-based edge generation, applying predefined domain logic such as hierarchical relationships, domain overlap, and classification similarity. The final dataset, consisting of node and edge information, was exported in comma-separated value (CSV) format and visualized using the open-source Python framework named *Streamlit* (Snowflake Inc., 2025).

Table 2
Dimensions for classifying extracted competencies

Dimension	Definition	Examples
1. Field	Top-level domain related to the skill or concept	Universal, Robotics, AEC, HCI/HA, etc.
2. Sub-classification	Thematic or functional grouping within a domain	Software Operation, Hardware Operation, Documentation, etc.
3. Type	Nature or form of the competencies	Knowledge, Operational Skill, Behavioral Characteristics, etc.
4. Level	Relative difficulty or complexity	Beginner, Intermediate, Advanced, etc.

This enabled the creation of an interactive 3D web-based visualization of the FCP network, providing a holistic and intuitive understanding of the specificity and generality of a skillset to be adopted as an educational program.

Figure 1 illustrates an example of the FCP network diagram as displayed in the web application. Each node (dot) represents an individual competency and is color-coded according to the "Field" (top-domain) classification. Competencies located along the outer circumference and at the fan-shaped branches of the diagram indicate skills that are categorized as highly specialized or advanced within their respective fields.

Table 3
Examples of categorized competencies

Node ID	Name	Top-domain	Sub-domain	Type	Level
N02	Vocabulary Acquisition	Universal	Vocabulary	Knowledge	Beginner
N16	Digital Literacy	Universal	Digital Literacy	Skill	Beginner
N47	Material Science	Engineering	Material Science	Knowledge	Intermediate
N49	Sensor Calibration	Robotics	Sensor Calibration	Skill	Advanced
N340	Telerobotics	HCI/HA	Remote Operation	Ability	Intermediate
N643	avatar robot	HCI/HA	Telepresence	Knowledge	Intermediate
N649	building information modeling (BIM)	Architecture & Construction	Information Modeling	Knowledge	Foundational
N775	point cloud	Architecture & Construction	Digital Modeling	Skill	Foundational
N839	virtual reality (VR)	HCI/HA	Immersive Technology	Knowledge	Foundational

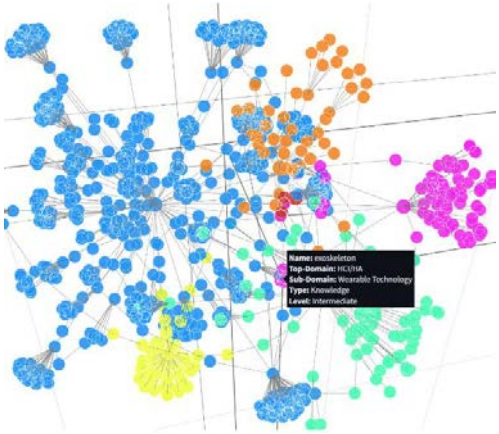

Figure 1
An FCP network diagram on the developed web application

Verification of the Usefulness of FCP. The semi-structured interviews were conducted either face-to-face or online, each lasting approximately 40 minutes. After a brief explanation of the FCP, participants responded to seven questions, comprising five items evaluated using a 5-point Likert scale and two open-ended questions.

The interview procedure consisted of three phases: a 10-minute introduction and explanation of the FCP, followed by a 25-minute question response session, and concluded with a 5-minute period for additional comments and free discussion. The questionnaire comprised two items addressing the participant's professional background and five items evaluating the FCP's utility.

The sessions were conducted with three experts in the fields of architecture and construction. Each participant brought a unique combination of expertise and professional experience:

- **Case 01:** A university faculty member specializing in architectural informatics (Building Information Modeling, Extended Reality, Digital Fabrication) with over 25 years of experience.
- **Case 02:** A researcher at an architectural research institute, specializing in digital communication with over three years of professional experience.
- **Case 03:** A system developer at a general contractor, specializing in architectural design and computational methods (structural engineering, parametric design) with over 15 years of industry experience.

Table 4 summarizes the results of the sessions, presenting the five-point scale ratings regarding the frequency and degree of involvement in human resource development, the perceived usefulness of the FCP, and key suggestions for improvement.

Table 4
The following evaluation scales and free opinions were collected in the interview

Case	Frequency of involvement in skill acquisition (1-5)	Level of involvement in skill acquisition (1-5)	Perceived FCP usefulness (1-5)	Main improvement proposals and reasons
Case 01	4 (a lot)	5 (very much)	4 (useful)	Recommend regular data updates, improved visualization of outputs, and enhanced operability. While effective for training young professionals, rapid technological advancements necessitate short-term or periodic updates of competencies. Additionally, adapting to regional and sector-specific characteristics is desirable.
Case 02	3 (average)	4 (many)	4 (useful)	Propose a flexible classification system responsive to regional characteristics and specific needs of individual construction sites. It would be beneficial if the outputs could directly link to educational materials and training support. Given that skill requirements vary significantly across construction sites, a more adaptable framework is necessary.
Case 03	2 (few)	2 (few)	4 (useful)	Suggest enhancing practicality, including clarifying the relationships among competency elements and improving evaluation methods. Emphasize the need for a user-friendly interface and practical functionality improvements suitable for immediate field use. Frequent data updates are not particularly prioritized.

The perceived usefulness of FCP was rated positively with scores of 4 out of 5. The positiveness potentially varied depending on the participants' job roles and professional responsibilities. Case 01, in particular, who had the longest tenure and direct involvement in education and training, provided concrete suggestions for enhancing educational program design.

Comments were provided from various perspectives on issues such as the system's adaptability to regional contexts and the need for data renewability. Notably, Case 02 highlighted the distinction between users who actively contribute to the FCP database and those who mainly consume the packaged outputs. This observation was echoed by Case 03, although they noted that regular updates and regional responsiveness were not high priorities. These findings suggest that there may be a future need to implement features that support regional adaptation, cultural contextualization, and comparative analysis of output results. Furthermore, several recurring themes emerged across the interviews as common challenges and areas for improvement.

The expert interviews revealed three key areas for improvement. First, regarding data updates, Case 01 emphasized the critical importance of regular maintenance to reflect rapidly evolving technologies and industry trends. Second, Case 02 highlighted the necessity of a flexible classification system that can adapt to regional characteristics, including local project conditions and skill requirements. Third, Case 03 identified the need for an enhanced user interface and a framework structure that facilitates immediate implementation in practical work environments.

DISCUSSION AND FUTURE PERSPECTIVE

The FCP was developed as a foundational competency framework primarily for the AEC sectors, with potential applications in other interdisciplinary fields. Based on diverse practitioner expertise, it systematically organizes domain-specific skills, particularly emphasizing emerging areas such as HCI and HA. The three-dimensional visualization of competency networks enables the identification of adjacent domains and latent relationships, potentially facilitating both educational development and technological innovation.

While traditional vocational aptitude assessments and competency charts have been utilized for career planning and transitions, comprehensive frameworks for domain-specific and cross-domain professional competencies remain limited. The FCP addresses this gap by offering potential solutions for workforce mobility, recruitment optimization, and labor shortage mitigation. Furthermore, it could evolve into a unified technical certification system or "skill passport," enhancing labor market fluidity and talent development efficiency.

The implementation of this framework requires continuous improvement in data accuracy, domain coverage expansion, and regular updates of competency information. Although the current FCP version has limitations due to its relatively narrow data scope and potential biases, its reliability is expected to improve through progressive data accumulation. To facilitate this development, consideration is being given to making the FCP database open-source, thereby promoting collaborative enhancement and system transparency.

The semi-structured interviews yielded generally positive feedback regarding the FCP's utility, although evaluations and suggestions for improvement varied based on participants' professional backgrounds and contexts. Cases 02 and 03 emphasized the need for standardized skill sets, while Case 01 stressed the importance of flexibility in addressing regional and disciplinary requirements. This divergence suggests that the primary challenge lies in presenting framework outputs, indicating a need for customizable comparison mechanisms that are adaptable to specific use cases.

Given the cross-disciplinary nature of emerging technologies like HCI and HA, while complete specialization in single domains may be impractical, the FCP dataset requires continuous expansion and refinement based on practical feedback. The framework faces two fundamental challenges: maintaining both comprehensiveness and currency in the rapidly evolving technological landscape, necessitating periodic updates and archival reviews at three to five-year intervals, and addressing the complexity of relationship weighting and directionality between competency nodes. The latter is particularly crucial for curriculum development, despite the inherent difficulty in establishing uniform evaluation criteria.

Implementation of the FCP requires addressing additional challenges, including the development of operational infrastructure and learning outcome validation mechanisms. Future development should proceed through collaborative efforts between practitioners and researchers, incorporating diverse perspectives to enhance the framework's practical utility and theoretical foundation.

CONCLUSION

This study developed the FCP as a framework to promote the integration of emerging technologies in the construction industry, and its practical usefulness was assessed through expert interviews. The findings revealed several areas for improvement, including adaptation to regional characteristics, enhancements to operability, and the necessity of regular data updates. Nonetheless, the results suggest that the FCP holds significant potential for facilitating skill transfer and supporting human resource development within the industry.

Although the FCP was generally perceived as useful, several issues remain before it can be applied at scale. These include the development of infrastructure to support continuous evaluation and operation, the establishment of mechanisms to assess and validate learner progress, and the capacity to flexibly respond to the diverse needs of stakeholders. Additionally, alignment with existing educational systems and industry standards is essential to ensure the framework's broader applicability and long-term impact.

Moving forward, the continued development of the FCP should be collaboratively pursued by practitioners and researchers, both of whom recognize its necessity and potential. By incorporating ongoing feedback from the field and adapting to evolving technological and societal contexts, the FCP can evolve into a robust framework that bridges the gap between advanced technologies and human labor in the construction sector.

APPENDIX

Interview Protocol and Materials. This interview was conducted as part of a research project that aims to organize interdisciplinary skills in the AEC fields, particularly focusing on Robotics, HMC and HA. The objective was to develop a structured framework called the FCP to support workforce development.

The interview lasted approximately 40 minutes and was conducted either online or in person. After a brief explanation of the FCP, participants answered a series of questions in a semi-structured format. A short reference document was provided in advance, but reviewing it was optional.

Participation was voluntary, and interviewees were allowed to withdraw at any time. Personal information was anonymized according to individual preferences and securely stored in compliance with university data protection guidelines. Responses were used exclusively for this study.

Interview Questions (7 total). Professional Background:

Q1. Please describe your current work or research area.

Q2. Do you engage in HR development related to skill acquisition in AEC?

Evaluation of the FCP:

Q3. What was your first impression of the FCP after the overview presentation?

Q4. Do you think the skillsets proposed in the FCP are useful for human resource development in your field of expertise?

Q5. Compared to existing educational programs (e.g., syllabi, credit/certification systems, corporate training), what strengths or weaknesses do you see in the FCP?

Q6. What challenges might arise in implementing the FCP?

Q7. What modifications or improvements do you think are necessary to make the FCP more practical and effective?

REFERENCES

Emaminejad, M. and Akhavian, R. (2022) 'Trustworthy AI and robotics: Implications for the AEC industry', *Automation in Construction,* 139, 104298, pp. 1-15. Available at: https://doi.org/10.1016/j.autcon.2022.104298 (Accessed: 14 June 2025).

Gupta, J. and Akanksha, E. (2024) 'Human Machine Interface IoT Based System', in *Proceedings of the 2024 International Conference on Electronics, Computing, Communication and Control Technology (ICECCC) Conference,* 2-3 May 2024, Bengaluru, India, pp. 1-5. Available at: https://doi.org/10.1109/iceccc61767.2024.10593899 (Accessed: 14 June 2025).

Natsuki, R. and Ishizawa, T. (2024) 'Exploring the frontier of construction robotics by the cyborg matrix: Transformation in Construction by Unleashing the Potential of Human Augmentation', in *Proceedings of the 14th ISAIA Conference,* Kyoto, Japan, A-6-5, pp. 1-6. Available at: https://confit.atlas.jp/guide/event/isaia2024/subject/21507-11-05/advanced (Accessed: 14 June 2025).

Papavasiliou, M. (2022) 'Comprehensive Characterization of an Open Source Approach to Design in Architectural Education: The integration of the "Do It Yourself" process in architectural design education', in *Proceedings of the 40th eCAADe Conference,* 13-16 September 2022, Ghent, Belgium, pp. 253-260. Available at: https://doi.org/10.52842/conf.ecaade.2022.1.253 (Accessed: 14 June 2025).

Rekimoto, J. (ed.) (2018) *Augmented Human.* Tokyo: NTS Publishing.

Siciliano, B. and Khatib, O. (eds.) (2016) *Springer Handbook of Robotics.* 2nd edn. Cham: Springer Cham. Available at: https://doi.org/10.1007/978-3-319-32552-1 (Accessed: 14 June 2025).

Singh, H.P. and Kumar, P. (2021) 'Developments in the human machine interface technologies and their applications: a review', *Journal of Medical Engineering and Technology,* 45(7), pp. 552-573. Available at: https://doi.org/10.1080/03091902.2021.1936237 (Accessed: 14 June 2025).

Snowflake Inc. (2025) *Streamlit.* An open-source Python library. Snowflake Inc. [Online]. Available at: https://docs.snowflake.com/en/developer-guide/streamlit/about-streamlit (Accessed: 14 June 2025).

Terashita, T. (2011) 'Educational Lecture: Research Methodology - 7. Qualitative Research Methodology', *Japanese Journal of Radiological Technology,* 67(4), pp. 413-417. Available at: https://doi.org/10.6009/jjrt.67.413 (Accessed: 14 June 2025).

UK Ministry of Defence (2021) 'Human Augmentation – The Dawn of a New Paradigm: A strategic implications project', UK Ministry of Defence [Online]. Available at: https://www.gov.uk/government/publications/human-augmentation-the-dawn-of-a-new-paradigm (Accessed: 14 June 2025)

Zakharova, G. (2022) 'Integration of emerging technologies in architectural education' in *AIP Conference Proceedings of the IV International Scientific and Practical Conference "New Information Technologies in the Architecture*

and Construction" (NITAC 2021), 2-3 November 2021, Ekaterinburg, Russia, 2657(1), p. 020008. Available at: https://doi.org/10.1063/5.0107192 (Accessed: 14 June 2025)