An adaptive Framework for Modeling Human-Robot Collaboration Training in Construction Robotics Education

Ebenezer Olukanni[1], Abiola Akanmu[1] and Houtan Jebelli[2]

[1]Myers-Lawson School of Construction, Virginia Tech, Blacksburg, VA, USA | [2]Department of Civil and Environmental Engineering, University of Illinois Urbana-Champaign, IL, USA

Introduction

- Construction robotics is expanding across inspection, monitoring, layout, material handling, fabrication, and other project operations
- These applications increasingly require humans and robots to work together, creating new demands for effective human–robot collaboration (HRC).
- As robots become embedded in dynamic construction workflows, workers must select, supervise, coordinate with, operate, maintain, and evaluate robotic systems.

Research Gap

Previous construction robotics research focus:
- Robotic applications in construction
- Automation and autonomy
- Sensing and control
- System performance
- Task planning

What remains limited:
- What should the construction workforce learn?
- How should the learning be structured?
- How should the learning progress?

Theoretical Framework and Research Questions

Cognitive Apprenticeship Theory
Guided participation • Scaffolding • Authentic practice • Increasing learner independence

Competency-Based Education
Defines explicit knowledge, skills, and abilities as instructional targets.

Revised Bloom's Taxonomy
Provides cognitive classification and progression for learning objectives.

Main Research Question
How can competencies required for HRC be identified, structured, and modeled to support construction workforce development?

RQ1. What competencies are required for effective human-robot collaboration in construction?

RQ2. How can HRC competencies be structured into modules and dependency relationships for workforce development?

RQ3. How can the relationships resulting from HRC network be computationally modeled to characterize and predict learning progression?

Methods

1. Competency Identification

Systematic Literature Review
- Content Analysis
- Guided by Task-Technology Fit Theory

- What competencies are required for effective human-robot collaboration in construction?

2. Competency Formalization and Learning Environment Characterization

Three-Round Delphi Study
- Capture industry (N=13) and academic (N=14) expert perceptions regarding the identified HRC competencies
- Determine the characteristics of a digital environment for learning HRC (Focus Group)

3. Competency Augmentation

Rule-based Natural Language Processing
- Construction robotics job ads and Industry case studies
- Text extraction and parsing
- Heuristic (KSA) classification
- HRC context filtering
- Semantic deduplication
- Expert refinement

4. Training Module Development and Evaluation

Theory-constrained NLP approach
- Cognitive classification of HRC competencies
- Learning objective generation (ABCD) and contextual grounding
- Theory-constrained module development
- Evaluation
  - Computational evaluation
  - Expert evaluation (2 Delphi rounds) of instructional modules (relevance, conceptual appropriateness, learning objective quality, and module completeness)

5. Competency Dependency Modeling

- Semantic representation and candidate screening
- Theory-constrained dependency direction
- Cognitive hierarchy
- KSA precedence
- Deterministic ordering rule
- Classification of intra- and cross-module dependencies
- Expert-elicited dependencies and evaluation

6. Learning Progression Prediction

Graph-based Prediction
- Missing competency links
- Adaptive learning pathways

Results

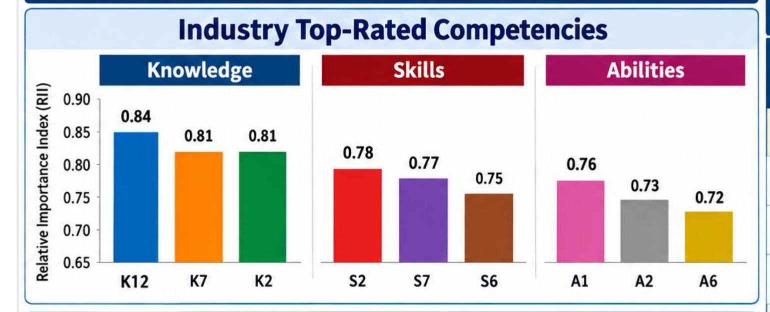
HRC Competencies

Knowledge (K) Conceptual Understanding		Skills (S) Action-Oriented Competencies		Abilities (A) Behavioral Attributes	
K1	Types of Robots	S1	Effective Communication	A1	Teamwork
K2	Construction Robot Applications	S2	Task Planning	A2	Communication
K3	Robot Anatomy and Technical Specifications	S3	Regulation Standards Compliance	A3	Continuous Learning
K4	Sensors	S4	Safety Management	A4	Problem-Solving
K5	Task Planning	S5	Technical Skill	A5	Adaptability
K6	HRC Ethics and Regulation	S6	Robot Programming	A6	Attention to Detail
K7	HRC Safety and Standards	S7	Data Analytics and Management	A7	Analytical Aptitude
K8	HRC Evaluation	S8	Human–Robot Interface Proficiency	A8	Decision-Making
K9	HRC-Related Fields	S9	Application of Machine Learning Algorithms	A9	Critical Thinking
K10	Immersive Virtual Environments	S10	Simulation and Modeling	A10	Spatial Awareness
K11	Communication Modes and Technologies			A11	Cultural and Social Awareness
K12	Human–Robot Interface			A12	Safety Awareness
K13	Robot Control System				
K14	System Integration				
K15	Programming				
K16	Modeling and Simulation				
K17	Data Analytics and Machine Learning				
K18	Robot Learning Methods				
K19	Computational Design				
K20	Robot Operating System (ROS)				

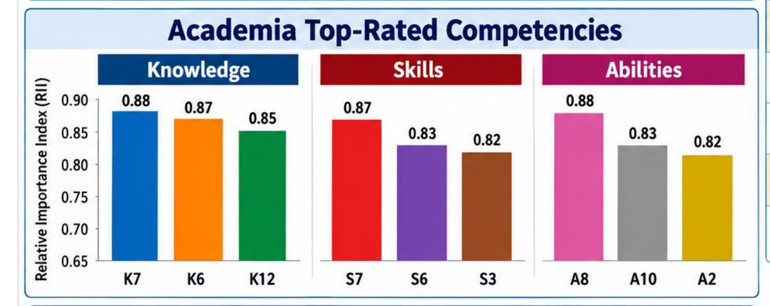
Experts' Top-Rated HRC Competencies

Top-Rated HRC Competencies
(Relative Importance Index, RII)

Industry Top-Rated Competencies



Academia Top-Rated Competencies



RII: Relative Importance Index (0–1)

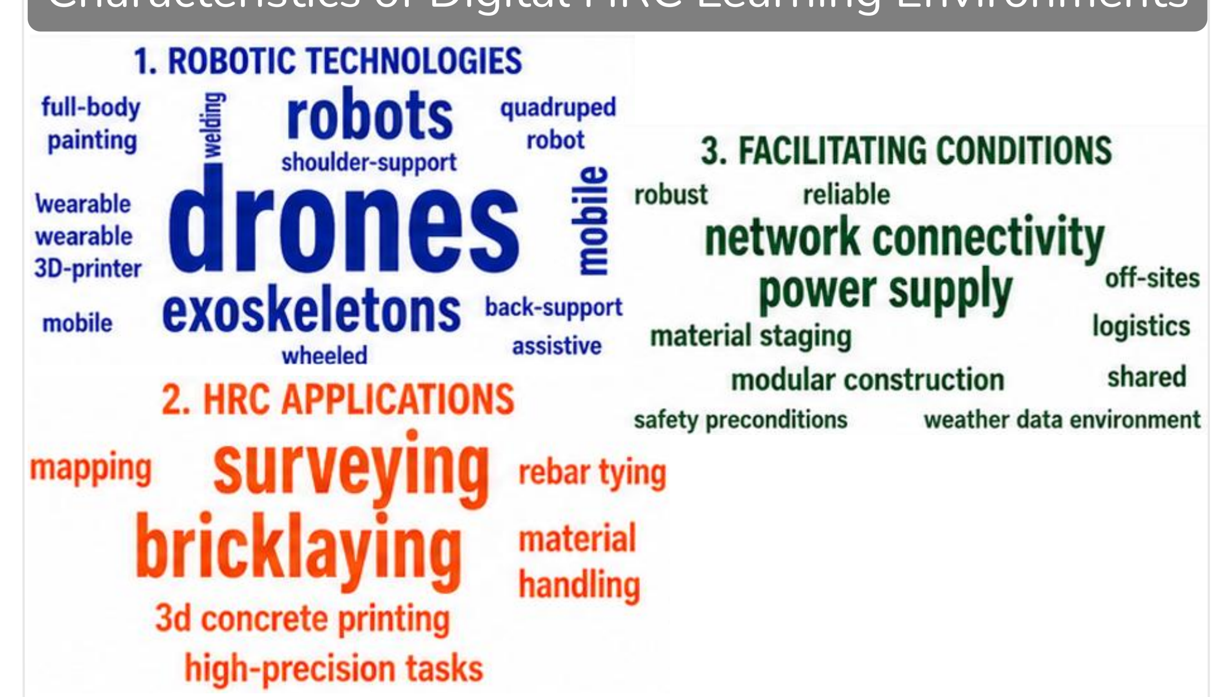
Competencies with RII 0.80–1.00 are classified as "highly important".

Where Perceptions Differed Significantly
(Top Examples)

KSA Dimension	Competency (Code)	p-Value*	Effect Size (r_b)
HRC Knowledge Areas			
Knowledge	K6	< 0.001	0.78
Knowledge	K13	0.036	0.47
Knowledge	K11	0.044	0.45
HRC Skills			
Skills	S8	0.017	0.54
Skills	S3	0.026	0.45
HRC Abilities			
Abilities	A11	0.013	0.56

* Mann–Whitney U test
Scale: 1 (Not Significant) – 5 (Extremely Significant)
r_b = rank-biserial correlation (effect size)

Characteristics of Digital HRC Learning Environments



New HRC Competencies Identified

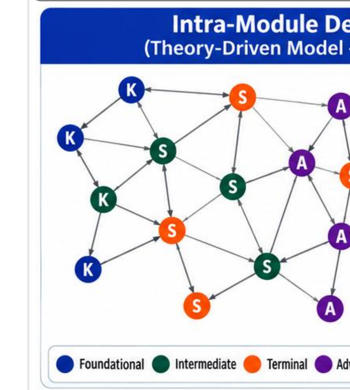
Knowledge Extensions (4 New)		Skill Extensions (2 New)		Ability Extensions (2 New)	
K21	Cost and ROI in Robotics	S11	Robot Operation and Maintenance	A13	Robotic System Reasoning
K22	Robotic Project Management	S12	Systems Thinking	A14	Robot Acceptance and Operational Reliability
K23	Robotics Sustainability				
K24	Robotics-Related Jobs				

HRC Training Module Developed

Module	Title	Competencies	Av. Cos. Sim
M1	Foundations of Construction Robotics and HRC	K1, K2, K3, K9, K20, K24, S11	0.88
M2	Human–Robot Interfaces and Communication	K4, K10, K11, K12, S1, S8, A1, A2, A10, A11, A13	0.81
M3	Task Planning, Programming, and Control	K5, K13, K14, K15, S2, S5, S6, A9	0.83
M4	Modeling, Simulation, and Systems Thinking	K16, K19, S10, S12, A4, A6, A7	0.85
M5	Data Analytics, Machine Learning, and Robot Learning	K17, K18, S7, S9, A3	0.88
M6	Safety, Ethics, Regulation, and Standards	K6, K7, S3, S4, A8, A12	0.87
M7	Evaluation, Performance, ROI, and Deployment	K21, K22, K23, K8, A14, A5	0.81

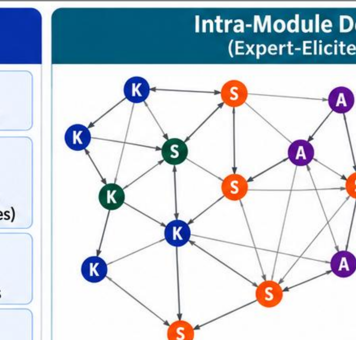
HRC Competency Dependencies

Intra-Module Dependencies
(Theory-Driven Model – Computational)



- 50 KSAs (Nodes)
- 98 Dependency Relationships (Directed Edges)
- 78 Intra-module Dependencies
- 20 Cross-module Dependencies

Intra-Module Dependencies
(Expert-Elicited – Delphi)



- 20 Experts
- 2 Rounds
- 99 Intra-module Dependencies Elicited
- 80%–100% Expert Agreement (by Module)

Comparison of Intra-Module Dependencies
(Theory vs. Expert)

Shared (Theory & Expert)	Theory Only (Modeling)	Expert Only (Delphi)
29 (29.6%)	49 (50.0%)	70 (71.4%)

Total Validated Dependencies
98
INTRA-MODULE 78
CROSS-MODULE 20

Example Intra-Module Dependencies
(Both Theory & Expert) Classified by Competency Type

Foundational → Intermediate → Terminal

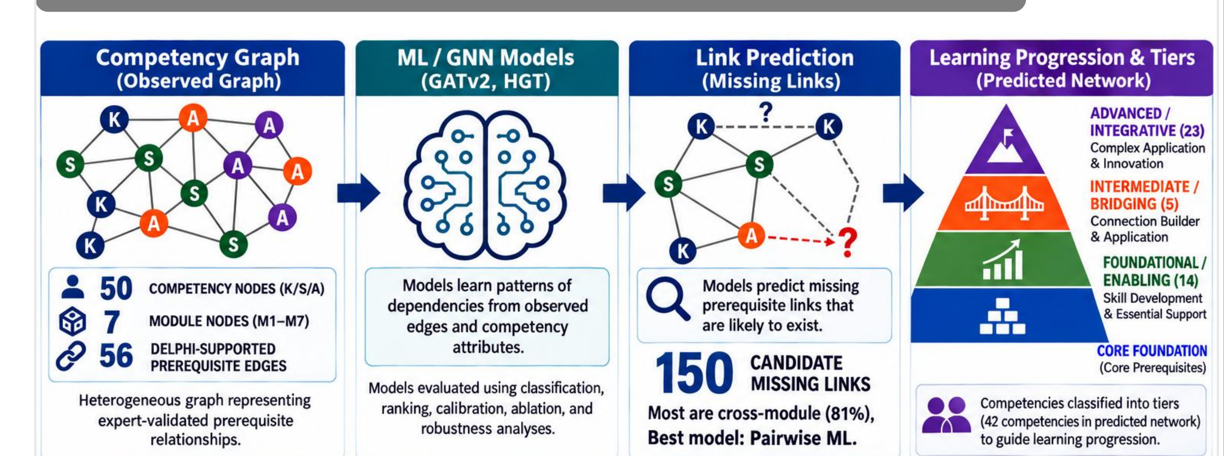
K15 | S6 | K16 | S10 | K7 | S3

Legend: K = Knowledge S = Skill A = Ability

Example Cross-Module Dependency Validation
(Theory-Driven)

From	To	Dependency	Agreement	Strength
S7	A8	Enables	93%	STRONG
A7	A8	Enables	93%	STRONG
S10	A8	Enables	80%	STRONG
K16	A8	Enables	73%	STRONG
A14	K7	Supports	73%	STRONG

GNN-based Learning Progression Prediction



Conclusion

This study provides a framework for preparing the construction workforce for HRC by identifying and structuring essential competencies, defining learning environment requirements, and organizing competencies into coherent training modules. By modeling competency dependencies and predicting learning progression pathways, the framework supports evidence-based sequencing and adaptive HRC education.