Mapping Essential Competencies for Human-Robot Collaboration in Construction: A Sociotechnical Systems Perspective

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***Abstract*—This research-to-practice full paper identifies the essential competencies for human-robot collaboration in the construction industry through a sociotechnical systems theory perspective. The construction industry grapples with significant challenges, including a shortage of skilled workers, low productivity, efficiency, and safety issues that impede its progress and growth. The integration of robots into the construction industry presents a promising solution to address these issues, thereby necessitating collaboration between humans and robots in executing construction tasks. Despite the advantages and roles played by robotic automation, there have been scarce efforts to identify essential competencies required to prepare the current and future workforce for effective collaboration with robots in construction. This study fills this gap by identifying essential competencies in the form of knowledge, skills, and abilities necessary for successful human-robot collaboration in construction. Using the sociotechnical systems theory as a framework, a qualitative literature review was conducted to establish and correlate the constructs of sociotechnical systems theory and elements of human-robot collaboration. Content analysis was employed to identify the elements of sociotechnical systems theory, human-robot collaboration, and robot task applications in construction, leading to the identification of key competencies. The study reveals a set of competencies for effective human-robot collaboration, including twenty knowledge, ten skills, and twelve abilities essential for implementing human-robot collaboration in the construction industry. These findings offer valuable insights for designing training programs and developing guidelines to facilitate successful human-robot collaboration in the construction industry. The competency model unveiled in the study could be incorporated into construction engineering and management curricula, providing a foundation for developing training initiatives targeting the current workforce and preparing the future workforce for collaborative engagements with robots in the construction industry. Recognizing the specific knowledge, skills, and abilities needed for human-robot collaboration in construction is pivotal for enhancing the efficiency and success of robotics implementation in the industry. Integrating these competencies into educational curricula and professional development programs equips the workforce to adapt to technological advancements and positions the industry for sustainable growth and improved project outcomes.**

Keywords—Human-robot collaboration, Construction industry, Sociotechnical systems theory (STS), Competency development, CEM Curriculum, Workforce development.

I. Introduction

Human-robot collaboration (HRC) within the construction industry involves integrating robotic technologies with human labor to execute various construction tasks [1]. This collaboration explores the synergy between humans and robots, envisioning collaborative endeavors across various industries, including manufacturing, healthcare, agriculture, and construction [2]. In construction, HRC entails aligning robot intelligence with human skills to enhance productivity and safety [3]. Besides these benefits, robotic technologies address critical issues such as shortage of skilled workers, cost overruns, and time delays [4, 5].

Various robotic technologies, such as robotically assisted construction of curved timber surfaces [6] and modular construction manufacturing (MCM) tasks [7], are being used in the construction industry. Collaborative robots, or cobots, are designed to work alongside humans, aiding in repetitive tasks and handling heavy loads, reducing the risk of injuries and enhancing workplace safety [8]. Cobots excel in performing both repetitive and hazardous construction tasks [9], and their integration into the workforce alongside human workers has led to increased productivity, enhanced safety measures, and a reduction in labor shortages [10]. However, successful collaborative engagements with robots necessitate that human workers develop relevant competencies to ensure safe and seamless interactions.

Despite this necessity, specific competencies for HRC in construction remain undefined. This study aims to identify these competencies through the lens of Sociotechnical Systems (STS) theory. The HRC elements are mapped using STS theory, and competencies informed by each HRC element are defined through HRC applications in construction.

II. Background

A. Examining Competencies through a Theoretical Perspective

Researchers have described competencies as a set of integrated knowledge, abilities, and skills that translate into behaviors for successful job performance [11]. According to Hartenbaum, Baker [12], competencies refer to qualifications to execute tasks or serve in a position that effectively achieves a desired outcome. El Asame and Wakrim [13] define competencies as the capability to apply knowledge, skills, and attitudes to achieve intended results. These definitions emphasize that competency involves the integration of knowledge, skills, and abilities with job performance. Pereira, Amaral [14] define knowledge as the theoretical or practical understanding encompassing facts, concepts, theories, and principles relevant to a field, distinguishable from skills, which are learned proficiencies, and abilities, which are innate or acquired qualities enabling task performance. Competencies for HRC in construction involve theoretical knowledge, practical skills, and innate characteristics necessary for safe and efficient collaboration with robots in executing construction tasks. Accurately defining competency requires thoroughly understanding the concept within a relevant theoretical framework.

Identifying competencies in different organizational contexts using a theoretical framework allows for a structured and scientific methodology for competency framework development [15] and addresses challenges such as lack of standardization and conceptual ambiguity [16]. Previous studies have focused on defining competencies through the lens of theoretical frameworks. For example, Ogunseiju, Gonsalves [17] underpinned the identification of the required competencies for deploying sensing technologies in the construction industry in a holographic learning environment with competence-based theory. Similarly, Akanmu, Akligo [18] used the theory of Learning for Use to identify the competencies needed by construction engineering and management (CEM) students to implement sensor data analytics in the construction industry. This study utilized sociotechnical systems theory to define competencies for HRC in the construction industry, providing a structured and standardized approach to competency identification.

B. Sociotechnical Systems Theory

The sociotechnical systems theory (STS) deals with the interaction between social and technical subsystems within an organization [19, 20]. It posits that an organizational work system comprises two distinct subsystems, technical and social, which impact each other and determine the performance of the work system [19, 21]. Historically, STS dates to 1950 [19, 22] and has since been expanded and applied in different areas, including digital transformation, information systems, technology, healthcare, and transportation [23]. The theory popularizes the importance of considering the technical aspects of the organization as well as the social and organizational context in which a technical system operates [24], emphasizing the joint optimization of both the social and technical subsystems. In this study, the social subsystem is the human worker, and the technical subsystem is the robotic technology. The construction industry is the organizational context where the technical and social subsystems interact to execute construction tasks. Therefore, the optimization of technology through the introduction of robots requires the optimization of the skills of human workers to enable seamless interaction between the two subsystems. The diagrammatic representation of the theory is presented in Fig. 1.

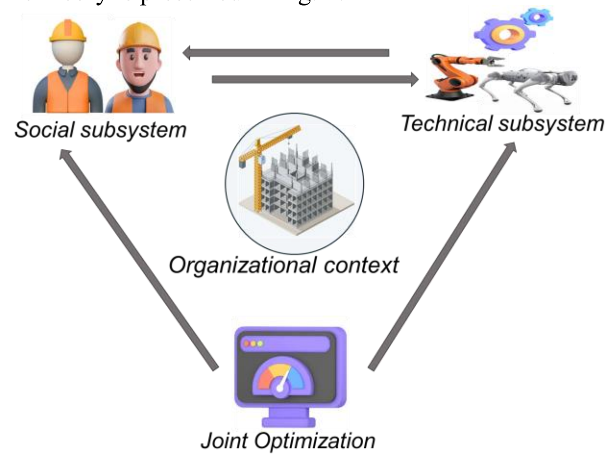

Fig. 1. Diagrammatic representation of sociotechnical systems theory (adapted from Trist [22]).

III. Method

This study aims to identify competencies for HRC in the construction industry through the lens of sociotechnical systems (STS) theory. A comprehensive literature review was conducted using Google Scholar to gather relevant peer-reviewed articles on HRC and STS theory. The search string “human-robot collaboration" OR "HRC in construction" OR "sociotechnical systems theory" OR "STS theory" AND "human-robot collaboration in construction" yielded an initial count of 380 articles. To ensure relevance and quality, the review focused on peer-reviewed conference or journal papers, excluding non-peer-reviewed sources, studies unrelated to the construction industry, or lacking a discussion of STS theory, and redundant findings. After applying these inclusion and exclusion criteria and conducting abstract and full paper screening, 37 papers were selected for detailed analysis based on their relevance to HRC in construction and their comprehensive discussion of STS theory. The selected studies were reviewed to extract information on robotic technologies, specific HRC applications in construction, and STS theoretical perspectives. Content analysis was employed to extract key STS theory and HRC elements, along with HRC task applications. These elements included various components, characteristics, and interactions pertinent to HRC and STS frameworks. Once extracted, the elements of STS theory and HRC applications were systematically correlated to understand their relationships and dependencies. The HRC applications provide context to understand how these elements interact in real-world scenarios.

IV. Results

This section describes the synthesis of HRC competencies from the STS theory. This was achieved by identifying the STS elements and the HRC elements. These two sets of elements were correlated and examined through the context of HRC applications to determine the specific competencies required for effective HRC in construction.

A. Sociotechnical Systems (STS) Elements

The STS elements described by Pasmore, Francis [25] and corroborated by Appelbaum [26] consist of elements that include social subsystem, technical subsystem, joint optimization, open system perspective, variance control, boundary location, quality of work life, and continuous learning. The social system comprises the people working in an organization, while the technical system includes tools, techniques, and technology used by the social system. Joint optimization balances the interaction between the social and technical systems. The open system perspective emphasizes interaction and adaptability to changing environmental conditions. Variance control deals with control measures, and boundary location focuses on autonomy and communication in the subsystem. Quality of work life emphasizes performance feedback, while continuous learning deals with an ongoing process of acquiring new knowledge and understanding.

B. Elements of Human-Robot Collaboration

Several key elements are important to ensure the effective functioning of HRC. These elements include the human and robot elements [27], user interfaces [28], task planning and control [29], communication [30], learning and adaptation [31], autonomy [32], feedback and evaluation [33], ethical and legal considerations [34], safety [35] and data management [36, 37].

C. Correlation of Human-Robot Collaboration Elements to the Constructs of Sociotechnical Systems

The social subsystem in STS correlates with human workers in HRC, which includes individuals actively participating in the work environment, including their roles, interactions, and social dynamics. This HRC element focuses on skills, expertise, and behaviors humans utilize when collaborating with robots [38]. Further, STS comprises the technical system, which includes the technology utilized within the organization for executing its tasks. In HRC, the technical system primarily focuses on robots, their capabilities, and functionalities [39]. An open system perspective in STS informs the interaction and adaptability of the system with its environment, which is equivalent to user interfaces and adaptability in HRC. User interfaces are the primary means for humans to interact with robots in HRC settings. Adaptability is a key characteristic of humans in HRC, enabling humans and robots to respond to changes in task conditions and environmental constraints.

Variance control in STS involves managing deviations from established standards within a socio-technical system. In HRC, it correlates with the robot's control system, which regulates its behavior and motion to achieve desired objectives. It also involves sensing the robot's environment, processing sensory information, and generating control signals to drive its actuators, such as motors or servos [40, 41]. Boundary location in STS, concerned with breaking the work of the system into smaller, more readily coordinated tasks where each workgroup can control its activities within its boundaries, informs task planning, autonomy, and communication within the HRC context. Quality of work life in STS, which emphasizes creating work environments that promote well-being and provide feedback on performance, informs safety and feedback and evaluation in HRC. Finally, STS encourages continuous learning and development. This is also important in HRC as it contributes to human workers' growth and adaptability. The STS elements are correlated with HRC elements for a better understanding of the HRC system and to identify competencies for HRC in the construction industry, as presented in Fig. 2.

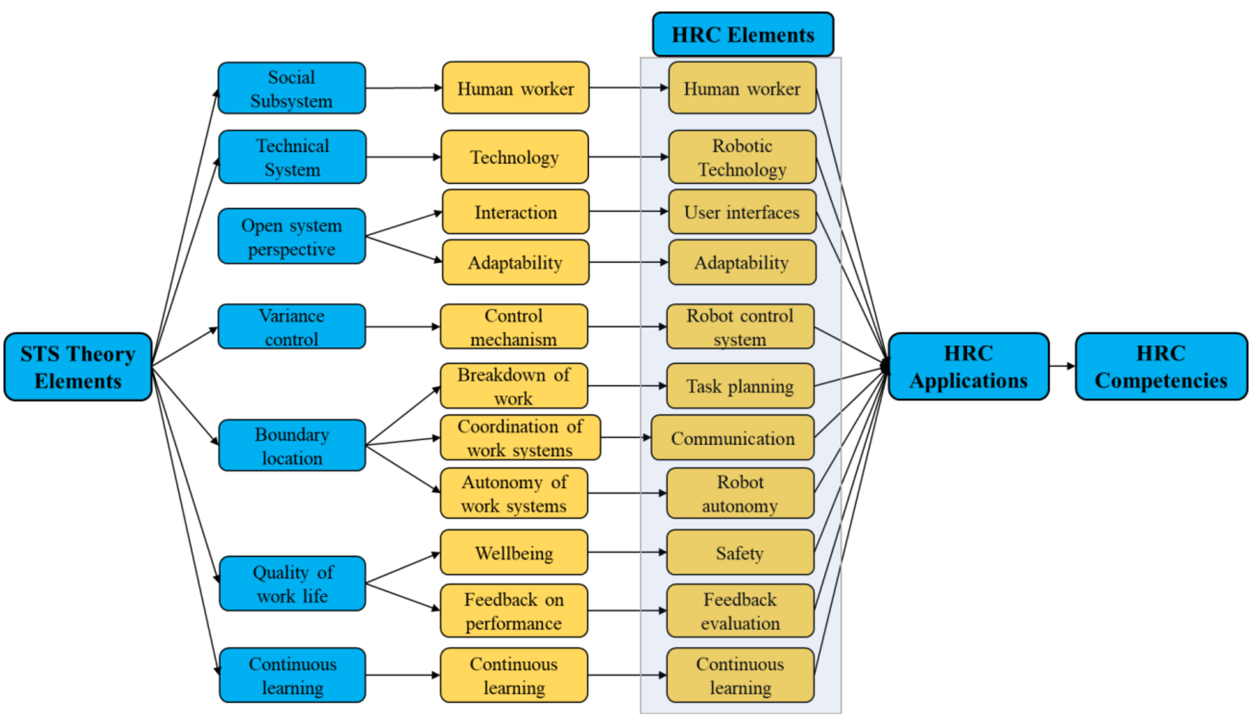

Fig. 2. Correlation between STS and HRC Elements.

D. Competencies for HRC in the Construction Industry

The study identified competencies for HRC by examining HRC applications extracted from the literature. The applications include various tasks such as additive manufacturing, automated installation systems, autonomous robotic assembly, and robotic bricklaying [42, 43]. Fine-grained construction tasks such as painting, drilling screws, and transporting material and equipment have also been executed with robots [44]. Other examples showcasing robotic task applications include surveying and aerial mapping [45], material placement [46], construction progress monitoring [47], sheathing, drywall installation, timber frame construction [48], painting [49], gypsum board installation [50], and construction waste sorting [40].

Through these HRC applications, the study mapped out the competencies for HRC in construction in the form of knowledge, skills, and abilities (see Table 1). Integrating STS theory into HRC highlights the intricate relationship between human workers and robotic systems. STS theory emphasizes a system's need for social and technical considerations, emphasizing effective communication and collaboration between humans and robots for optimal performance. This approach acknowledges the balance between humans equipped with decision-making ability, programming and technical skills, and knowledge of data analytics and robot capabilities in sensing and data generation while executing tasks, leading to improved efficiency and productivity in the construction industry. Thus, STS theory has provided a clear understanding and facilitated the mapping of competencies for HRC in the construction industry.

TABLE I. COMPETENCIES FOR HUMAN-ROBOT COLLABORATION IN THE CONSTRUCTION INDUSTRY

HRC Applications	Knowledge	Skills	Abilities
Robotic Fabrication and modular construction [7, 51-53]	**Programming** (such as C/C++, Python, Java, C#/.NET)	**Data analytics and management** (data visualization, data storage)	**Analytical aptitude (**analyzing existing processes for automation efficiency and optimizing complex fabrication processes for accuracy).
	Computational design (computational workflow)	**Simulation and modeling** (using CAD/CAM software for computational design, 3D modeling and simulation, using Grasshopper, and developing prototypes with software)	**Teamwork** (working in multidisciplinary teams, collaborating with Information Technology professionals, process experts, stakeholders, and robots for task execution)
	Control Platforms (robot haptic control and two-layer control system)	**Human-robot interface proficiency** (using an intuitive interface)	**Continuous learning (**willingness to learn and adapt to advancements in robotic technologies)
	Modeling and simulation (digital fabrication tools (CAD and CAM, BIM simulation, 3D scanning, prototype development, and Grasshopper visual programming environment)	**Programming** (robot programming, coding with Python and other programming languages)	**Attention to detail** (Ensuring precision and accuracy in design and fabrication processes)
	Data analytics and machine learning (robot path and motion planning algorithm e.g., Rapidly Exploring Random Tree (RRT), and system optimization with a genetic algorithm)	**Application of machine learning algorithm** (applying Rapidly Exploring Random Tree (RRT) algorithm for path planning, robot localization and mapping algorithm, performative algorithm, pose estimation algorithm, collision detection algorithm, and applying genetic algorithm for system optimization)	**Adaptability (**adapting to changing project requirements, technological advancements, and industry trends.
	System integration (combining subsystems into one larger system e.g., HMD with Tobii Pro eye tracker system in Unity)		**Problem-solving (**identifying challenges in integrating weaving structures, robotic arms, and mixed reality simulations and devising effective solutions).
	Sensors (force torque sensor, electroencephalogram (EEG), inertia monitoring unit (IMU))		**Spatial Awareness (**understanding and visualizing spatial relationships between weaving structures, robotic arms, and the built environment).
	Immersive virtual environments (augmented, virtual, and mixed and mobile projective augmented realities)		**Decision-Making (**Making informed decisions based on data analysis).
	Robot anatomy and technical specifications (Robotic arm, end effector, actuators)		
	Robot operating system (used as middleware and open-source development platform and communication)		

Human-robot collaboration for on-site construction [3]	**Types of robots** (3D concrete printing robots e.g., gantry and robotic arm systems, autonomous mobile robots, unmanned aerial vehicles)	**Technical skills** (work process supervision, setting up a robot manipulator for tasks, and performing security testing)	**Critical thinking (**analyzing situations critically and making informed decisions regarding safety measures and protocols)
	Construction robot applications (excavation, installation and assembly, material handling, construction waste sorting, demolition, rebar tying, and welding)	**Effective communication** (safety communication and using communication modes)	**Communication (**using different robot control devices for communication)
	Human-robot communication modes and technologies (gesture, voice, gaze, bio-signal, and vision-based commands)	**Safety management** (risk assessment and emergency measure implementation)	
	Human-robot interface (manual interface, teleoperation interface, VR and AR interfaces, and laser pointer)	**Regulation standard compliance** (safety protocol and ethical regulation implementation)	
	HRC safety and standards (collaborative safety mechanism, risk assessment, industrial safety requirements e.g. ISO 10218-1/2)		
Task planning [54, 55]	**Task planning** (task scheduling, task planning, task allocation)	**Task planning** (task allocation, task scheduling, task decomposition into subtasks)	
Construction robots learning [56]	**Robot learning methods** (trajectory demonstration (such as kinesthetic, teleoperation, and extended reality (XR) demonstrations) and passive observation (such as visual and sensors demonstrations))		
Robot ethics and social implications [57]	**HRC ethics and regulation** (robot legal and social consideration, ethical task allocation)		**Cultural and social awareness** (implementing HRC law and regulations)
HRC evaluation [58, 59]	**HRC evaluation** (HRC evaluation methods such as behavioral analysis, interviews, and usability testing)		
Ergonomics consideration in HRC [58, 60]	**HRC-related fields** (Psychology, Ergonomics, Cognitive Science, and Cybersecurity)		

V. Discussion

The implications of identifying competencies for HRC in the construction industry are profound for both the industry and its workforce, both current and future. Firstly, by delineating the competencies required for effective collaboration between humans and robots, this study provides valuable insights for construction companies seeking to integrate robotic technologies into their operations. Understanding these competencies enables firms to develop focused training programs to upskill their workforce and ensure they possess the essential knowledge, skills, and abilities to collaborate seamlessly with robots. This, in turn, enhances the efficiency, productivity, and safety of construction projects [9, 61]. Moreover, the identification of HRC competencies has significant implications for the current workforce. As robotic technologies become increasingly prevalent in construction, workers must adapt and acquire new competencies to remain competitive in the labor market [10]. This necessitates investment in continuous learning and development initiatives to equip workers with the skills to operate alongside robots effectively. Failure to do so may result in skills mismatches and workforce displacement. For the future workforce, understanding HRC competencies guides educational institutions in designing curricula that align with the evolving needs of the construction industry. Integrating HRC competencies into CEM programs ensures graduates are equipped with the skills employers demand, enhancing their employability and facilitating smoother transitions into the workforce. Additionally, fostering interdisciplinary collaboration between engineering, robotics, and construction disciplines prepares students to navigate the complexities of HRC in real-world construction environments [5, 58].

VI. Conclusion

In this study, we have identified and correlated the elements of both STS theory and HRC to define competencies for HRC in the construction industry. STS theory has been utilized in this study to determine HRC competencies for human workers to provide a means of jointly optimizing the two subsystems of HRC in the construction industry. The construction industry can significantly improve productivity, safety, and innovation by integrating the identified HRC competencies. This research has contributed to knowledge by identifying competencies for human-robot collaboration in construction and contributed to the frontiers of STS theory in the construction industry

A limitation of this study is the limited generalizability of the findings, as they may be specific to the construction industry. Additionally, the rapid pace of technological advancements in robotics could quickly render the identified competencies outdated, making it challenging to ensure the relevance and applicability of the competency framework.

Future research could focus on refining these competencies as robotic technology advances. Furthermore, construction task-specific competencies could be explored to achieve more granularity in defining the competencies for HRC in the industry.

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