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WORKFORCE SUSTAINABILITY AND HUMAN RELIABILITY: An Integrated Conceptual Framework Based on Competency Management and Women's Participation in Nuclear Organizations

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1. Introduction

In Brazil, the Brazilian Multipurpose Reactor (RMB), Angra 3, and potential future nuclear expansion reinforce the relevance of long-term workforce planning and highly qualified human resources [12]. At the same time, workforce ageing, retirements, competition for specialists, and the potential loss of critical organizational capabilities pose challenges to nuclear programmes [1,2,10].

In this context, Workforce Sustainability refers to an organization's capacity to maintain, renew, and develop the competencies required for long-term operation, encompassing Critical Competencies, Knowledge Management, Organizational Learning, Succession Planning, and Talent Retention [1,2,10]. Women's Participation is also relevant to this discussion, particularly regarding the development and retention of a broader talent pool. IAEA and OECD/NEA publications identify gender imbalance as a challenge for the nuclear workforce [3,4]. However, its relationship with Competency-Based Human Reliability in the proposed framework remains a conceptual proposition requiring empirical validation rather than a demonstrated causal effect on human reliability or nuclear safety.

Human Reliability Analysis (HRA) has historically addressed human error probabilities in nuclear tasks [7], while contemporary HRA frameworks also consider performance-shaping, human, and organizational factors within nuclear installations [9]. Broader safety perspectives further emphasize the systemic conditions that shape human performance [6]. Recent empirical research has also identified associations among individual, cognitive, and attitudinal factors and unsafe behaviours in nuclear work settings [11]. From this perspective, the proposed concept of Competency-Based Human Reliability considers the potential relevance of maintaining Critical Competencies over time, together with organizational practices related to competency and knowledge management, transfer, and renewal [5,10].

Although these dimensions are recognized in the literature, their treatment remains predominantly fragmented. This study therefore proposes an Integrated Conceptual Framework that articulates Workforce Sustainability, Critical Competencies, and Competency-Based Human Reliability. The proposed relationships are theoretical and provide a basis for future empirical investigation rather than demonstrated causal effects.

2. Methodology

This study employed a structured narrative literature review with a qualitative approach and conceptual synthesis. The search strategy, sources, terms, temporal coverage, and selection criteria are summarized in Table 1. The selected literature was critically examined to identify converging evidence, differences in evidentiary strength, contextual limitations, conceptual relationships, and research gaps. The analysis comprised: (i) identification of the main concepts; (ii) critical analysis of the literature; (iii) thematic synthesis; and (iv) development of the Integrated Conceptual Framework. The framework represents a

theoretical interpretation derived from this synthesis rather than an empirically validated organizational model; therefore, its proposed relationships require future empirical investigation.

TABLE 1 — Literature Review Strategy

Aspect	Revised description
Information sources	IAEA Safety Standards and Nuclear Energy Series; OECD/NEA and INSAG publications; peer-reviewed articles; conference papers; seminal and institutional works
Search sources	Google Scholar; ScienceDirect; IAEA and OECD/NEA institutional repositories
Search terms	Workforce Sustainability; Competency Management; Knowledge Management/Retention/Transfer; Succession Planning; Talent Retention; Women's Participation; Gender Diversity; Human Reliability; Nuclear Workforce/Safety; High Reliability Organizations
Temporal coverage	Seminal references and recent literature, emphasizing publications from 2014 onward
Selection criteria	Relevance to the research question; theoretical contribution; scientific or institutional authority; coverage of the investigated dimensions
Exclusion criteria	Exclusively technological or engineering publications without organizational, human, or managerial dimensions

3. Results and Discussion

The literature reviewed identifies workforce ageing, retirements, competition for qualified professionals, and the potential loss of critical knowledge and competencies as relevant challenges to Workforce Sustainability in the nuclear sector [1,2,10]. IAEA publications emphasize competency management, knowledge transfer, succession planning, and talent retention as relevant to preserving organizational capabilities over time [1,2,10].

Broadening and diversifying the available talent pool are also relevant considerations for the future nuclear workforce. The OECD/NEA report on gender balance, based on data from more than 8,000 women across 32 countries and human resources data from 96 nuclear organizations in 17 countries, highlights persistent female underrepresentation and barriers affecting women's entry, development, and retention [4]. IAEA publications similarly identify gender imbalance as a workforce challenge [3]. In Brazil, sociocultural aspects of women's participation have also been examined in a nuclear-sector institution, underscoring the importance of organizational and national context [8]. Women's Participation can therefore be considered a relevant dimension of workforce availability, diversity, and renewal. However, the evidence reviewed does not support the conclusion that increased Women's Participation directly produces measurable improvements in human reliability or nuclear safety; this relationship remains a conceptual proposition requiring empirical investigation.

An empirical study involving 177 commissioning workers from two Chinese nuclear power plants identified associations among individual characteristics, executive function, safety attitudes, and unsafe behaviours [11]. These findings are consistent with a broader perspective on human performance in which individual and organizational factors are considered jointly [6,9,11]. However, the study did not directly assess Competency-Based Human Reliability; accordingly, it provides contextual support for the organizational perspective adopted rather than empirical validation of the framework.

Overall, the literature shows convergence regarding the relevance of competency management, knowledge preservation and transfer, succession, and workforce development, but the strength of evidence is not uniform across the dimensions examined. Part of the foundation derives from institutional and conceptual publications, while empirical findings may be specific to particular countries, organizations, functions, and populations. Relationships involving workforce diversity, organizational resilience, and human reliability therefore remain context-dependent and require further integrated empirical investigation. Based on this synthesis, Fig. 1 integrates these dimensions into the proposed framework. Its connections represent conceptual relationships derived from the literature rather than empirically demonstrated causal pathways.

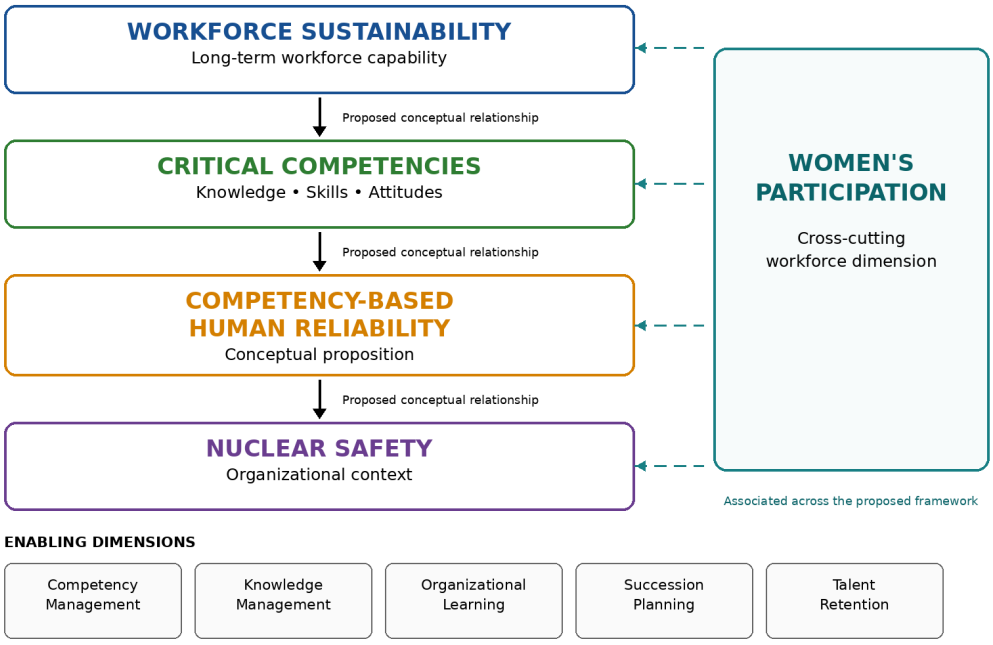


Fig. 1. Integrated Conceptual Framework for Workforce Sustainability and Competency-Based Human Reliability. Arrows represent proposed conceptual relationships and not empirically demonstrated causal pathways.

4. CONCLUSION

This study proposes an Integrated Conceptual Framework that articulates Workforce Sustainability, Critical Competencies, and Competency-Based Human Reliability, integrating dimensions that have predominantly been addressed separately in the literature. Although scientific and institutional evidence supports the relevance of the individual dimensions, their proposed relationships remain conceptual. In particular, the relationship among Women's Participation, Competency-Based Human Reliability, and nuclear safety should not be interpreted as a demonstrated causal effect.

The framework has not yet been validated through organizational data, expert evaluation, case studies, longitudinal analyses, competency indicators, or statistical modelling, and its relationships may vary across organizational and national contexts. Future research should therefore test and refine the framework across different types of nuclear organizations and, where applicable, other high-reliability organizations, using complementary quantitative and qualitative approaches to determine which relationships are supported, modified, or potentially refuted by empirical evidence.

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