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Human factors integration in complex systems: Awareness, challenges and strategies

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ABSTRACT

Human Factors Integration (HFI) is crucial for the development of complex systems, ensuring both effectiveness and safety. This research presents a case study on HFI awareness and implementation in a missile and guided weapons development company, focusing on the application of HFI principles, the challenges faced, and potential areas for improvement. Semi-structured interviews were conducted with twelve respondents across various roles in the company, and thematic analysis was used to analyse interview data. Key themes were identified concerning HFI awareness, organisational dynamics and practical challenges. The findings revealed significant gaps in formal HFI training, limited integration of HFI into project specifications and inconsistent end-user involvement. Organisational and cultural resistance hindered HFI due to cost and timeline constraints. The study suggests that early integration of HFI into the Systems Engineering process, alongside enhanced training programmes and a cultural shift towards prioritising HF, are essential for overcoming these challenges.

PRACTITIONER SUMMARY: This case study investigates Human Factors Integration (HFI) awareness and implementation within a missile system development company. Using semi-structured interviews and thematic analysis, the study identified some challenges of HFI, including organisational and cultural resistance, lack of formalised processes, insufficient training, limited end-user involvement, verification issues and integration complexities.

Abbreviations: CONOPS: Concept of Operations; HCD: Human-Centred Design; HF: Human Factors; HFI: Human Factors Integration; ROI: Return on Investment; SE: Systems Engineering

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Introduction

The human element is essential to the success of complex systems, and it is considered at every stage of the system lifecycle to ensure the system is optimal, safe, efficient and robust. Human Factors (HF) provides an understanding of human capacities, limitations, and variations, and utilises this understanding to optimise system performance (Shorrock and Williams 2017). Engineering of a complex system that expands its application to address HF is known as Human Systems Integration (HSI) or Human Factor Integration (HFI). The terms HSI and HFI are used interchangeably, with HFI being the term adopted in this paper. HFI traces its roots back to systems theory, emerging as a response to the growing complexities of industrialised systems during the age of rapid technical advancement (Bridger 2014). It recognises the human element as integral to the overall system performance. HFI is a process to ensure that the human elements are appropriately addressed and integrated into a system, particularly during system development. Through the integration of people, processes, and technology, HFI aims to optimise system performance, safety, effectiveness, and efficiency across diverse operational environments (Cullen 2007; UK Ministry of Defence 2023).

The adoption of HFI is typically integrated into system development and formalised within the Systems Engineering (SE) process. SE is an interdisciplinary approach that enables the realisation of successful systems through the specification, architecture, design, implementation and operation of the system to its disposal. HFI is explicitly recognised in the International

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Council on Systems Engineering (INCOSE) SE Handbook, Section 3.1.4 (version 5) (INCOSE 2023). Throughout the system lifecycle, HFI manages activities to identify, track, and resolve human-related issues. It integrates human considerations into every stage of the system life cycle, addressing aspects such as staffing levels, training, workload, job design, procedures, and the design of equipment and facilities. HFI extends beyond HF by incorporating a holistic perspective that balances technological and human dimensions. It ensures that all human-related aspects, including the interfaces between humans and technology (Leveson 2004), are systematically considered and effectively managed.

The literature shows that HFI investment, especially in the early system development, has financial benefits. It saves additional time and cost from modifications and retrofitting efforts at a later date (Greig et al. 2019; O'Neil, Shattuck, and Sciarini 2015; Rountree and Thomas 2021). Best practices have been published in a variety of case studies highlighting the effectiveness of HFI during system development (Landsburg et al., 2008). Among these case studies, the most frequently cited example is the US Department of Defense (DoD)'s Comanche helicopter acquisition programme. The programme demonstrated the benefits of HFI with its $75 million investment and $3.29 billion of cost avoidance, or 44:1 ROI (Burgess-Limerick, Cotea, and Pietrzak 2010; Burgess-Limerick et al. 2011). Similarly, the critical design improvements project of the Apache Longbow helicopter resulted in $269 million savings from a $12 million HFI investment (22:1 ROI). Meanwhile, the Fox M93A1 reconnaissance vehicle development achieved an estimated 33:1 ROI (Burgess-Limerick et al. 2011). One successful example of HFI in a missile development project is the Javelin antitank guided missile system. In this project, HFI contributed to optimising overall system performance within constrained operational envelopes by balancing key factors such as portability, gunner survivability, accuracy and usability (Booher 2003). Although there is no literature that provides a precise ROI value for missile systems, the US Air Force's Human Systems Integration Handbook (US Air Force 2009) provides a general indication of the potential value of HFI in defence projects. The handbook suggests that HFI typically accounts for 2–4.2% of total system acquisition costs, with an estimated ROI that can reach up to 40–60 times the initial investment.

That said, these outcomes are enabled by specific factors within the US DoD, such as the mature HFI practices, which may not be present in other settings. Moreover, although HFI may play a significant role in improving system usability, maintainability and safety, its financial return should be seen as part of a broader engineering effort supported by strong leadership and a structured organisational process. For example, driven by the US Air Force's 'Reliability, Maintainability and Sustainability' programme, HFI was adopted early in the development of a reliable engine for the F-22 stealth fighter by Pratt & Whitney. Yet, the success of this development was also supported by strong leadership and organisational accountability in aligning engine development with the Air Force's goals (Liu et al. 2010).

Nevertheless, HFI has demonstrated significant impact across diverse industries, as summarised in various reports cited by Burgess-Limerick et al. (2011). National Aeronautics and Space Administration (NASA) highlights historical successes, for example, Apollo missions, and more recent programmes, such as Constellation's Crew Exploration Vehicle, Lunar Lander, and extra-vehicular systems, attributed to HFI efforts. The oil and gas sector has claimed safety improvements linked to HFI initiatives. A nuclear energy project has identified critical safety issues through HFI programmes. Federal Aviation Administration (FAA) safety inspection processes reported a significant time reduction due to usability improvements. In addition, HFI improved safety and efficiency in healthcare, such as intensive care units, and public transport, such as train control systems. These examples demonstrate that the implementation of HFI drives significant benefits in complex civilian systems (Burgess-Limerick et al. 2011).

On the other hand, when the human element is neglected, the consequences can range from costly to disastrous. It can lead to increased costs, system redesign, system failure, injury or loss of life (O'Neil, Shattuck, and Sciarini 2015; Rountree and Thomas 2021). This highlights the critical importance of HFI. A recent example of a project that has suffered severe damage due to multiple systemic factors, including human factors, is the Boeing 737 MAX, which led to the loss of 346 lives in two crashes. The accident investigation revealed that the main cause was the introduction of a new software system, the Manoeuvring Characteristics Augmentation System (MCAS). The system was not supported by a training requirement for pilots who had been certified for the previous aircraft model (Rountree and Thomas 2021). Similarly, the challenges encountered with the 'BOWMAN' radio system development highlight the consequences of neglecting HFI principles (Walker et al. 2009). Despite substantial investment and intended technological advancements, the system faced usability issues, including complexity, weight, and compatibility limitations with other UK military assets (Walker et al. 2009). Moreover, the US Army's Stinger missile system assumed perfect operator performance and overlooked the realistic variability of soldier capabilities during the early design stages (Booher 2003). As a result, the system delivered only half of its expected performance, significantly reduced its operational effectiveness and compromised mission success. These shortcomings incurred additional costs and delays, highlighting the significance of HFI in addressing personnel concerns, engineering complexity and health hazards.

The capabilities of military systems are certainly crucial in modern defence acquisition. However, their effectiveness depends on, not only on the cutting-edge technology they exhibit, but also on how they function within the dynamic and demanding military environments. The shift from a platform-centric to a capability-centric approach in defence, acknowledges that effective defence capability encompasses more than just tangible assets like infrastructure, hardware and software. Even within seemingly autonomous systems, it remains vital to recognise that their operation, maintenance and support, eventually rely on human involvement. The core of defence capability involves not only the technological components but also the individuals who operate them. Therefore, in the defence industry, HFI is important in addressing human considerations in complex defence systems, including weapon systems (Liu, Valerdi, and Rhodes 2009).

Within military system development, HFI is thoroughly designed to enhance the seamless interaction between human users and sophisticated technological platforms. However, despite its significance, HFI faces complicated challenges that impede its effective implementation and integration into the systems life cycle, particularly during system development. Although it has been a component of defence policy for over 25 years, HFI has not been seamlessly integrated into the systems development and acquisition process, and it remains largely unfamiliar to those outside specialised HF practitioner circles (Corbridge et al. 2016). HFI is frequently considered too late in the programme lifecycle, resulting in many HFI contributions that require rework and hindering its effectiveness (Bruseberg 2006). Furthermore, the research-practice gap presents another challenge in bridging the divide between theoretical insights and practical implementation.

Although traditional SE frameworks, such as the V-model, outline defined stages, deliverables and decision gates, they lack mechanisms to ensure continuous human considerations across the lifecycle (Sprehn, Gretchen, and Hechinger 2022). HF is not systematically embedded within these stages, partly due to the inherent complexity of modelling human behaviour (Sprehn, Gretchen, and Hechinger 2022). The requirements process, one of the most critical stages in SE for incorporating HF, often prioritises technical specifications and system performance metrics over human-centred concerns. As noted by Muhammad et al. (2024), organisations, particularly in technology-driven projects such as autonomous vehicles, often view tasks like the driving task as focused on computer automation and disconnected from humans. As a result, human capabilities and limitations in the requirements process are frequently treated as external constraints rather than as integral components of the system. Similarly, requirements traceability processes often lack mechanisms to ensure that human requirements are properly verified and traced throughout the system lifecycle. Mucha et al., (2024) suggested that pre-requirements specification traceability, the process of identifying and documenting the sources of system requirements, often overlooks HF. In addition, during the design stage, there is also a lack of structured methodology for integrating HF. HF is frequently limited to basic physical measurements, neglecting broader cognitive, behavioural and social dimensions (Puig-Poch, Galán Serrano, and Felip-Miralles 2025). These studies indicate a structural gap in SE practices that limits the effectiveness of HFI and results in a system development that overlooks HF.

HFI has also faced resistance, as it was regarded as a secondary priority, limiting leadership commitment and resource allocation. Although progress has been made in narrowing this gap, challenges remain in translating research findings into actionable practices (Chung and Williamson 2018). It is hoped that with the release of the new version of the INCOSE SE Handbook (INCOSE 2023), it will be recognised as a key component of system development.

All these concerns highlight the need for a significant transformation in HFI implementation. Therefore, this research hypothesises that a deeper understanding of the current state of HFI awareness and its integration during the development stage of complex system lifecycles is essential for improving outcomes. This study seeks to test the hypothesis by taking a case study approach in the missile and guided weapons, specifically a relatively underexplored area. The objectives of this study are as follows:

1. Assess employee awareness and integration of HFI principles.
2. Identify key challenges in integrating HF considerations.
3. Evaluate current strategies and tools for integrating HF.
4. Propose recommendations to enhance HFI awareness and implementation.

This case study provides empirical evidence that critical HFI challenges exist within the defence industry, offering new insights and actionable implications for policymakers, defence contractors and system designers. Its significance lies in its potential to enhance the implementation of HFI in missile and guided weapon system development, thereby improving system safety, usability and performance. Although this study examines the challenges of HFI within the defence industry and military procurement environments, the findings may be applicable to other domains with comparable industry practices and structures. The insights also contribute to the ongoing discourse on HFI within the academic community, providing a foundation for further academic exploration and enriching the body of knowledge on HFI, SE and their intersection.

Literature review: Human Factors integration

Initially concentrating on physical human considerations, ergonomics and HF underwent a significant shift in the 1980s, by becoming more involved in design processes, which were previously dominated by engineering (Boy 2021). While the principles of HF have been acknowledged since the 1950s, the formalisation of management and technical procedures, exemplified by initiatives like the US Army's 'MANPRINT' programme, emerged in the mid-1980s with the objective of systematically integrating HF considerations into equipment development (Harris 2008). The Army's successful implementation of the MANPRINT programme marked a significant advancement in government efforts to influence the acquisition process, effectively addressing issues related to cost, performance and safety enhancements. Building upon this success, similar initiatives, modelled after MANPRINT, have been adopted across various branches of the military, including the US Navy with 'SEAPRINT', the US Air Force with 'AIRPRINT', and the UK MoD HFI.

Military equipment, often bespoke in design, offers a unique opportunity for purchasers to specify HF requirements with precision. This approach allows for early and comprehensive consideration of HF, providing an advantage to ensure that systems are designed with human capabilities and limitations in mind. In the design of complex systems, longevity and safety are vital considerations. Especially, military systems are built to last decades, requiring attention to safe decommissioning and the treatment of human operators who may face changes such as redundancy or early retirement (Boy 2021). However, traditional acquisition approaches often stumble in accommodating cutting-edge technologies, leading to cost escalations and underperformance. Proper consideration of HF at the design stage is crucial. Furthermore, the process of systems design typically unfolds within a contractual environment between a customer and a solution provider (Chatzimichailidou, Whitcher, and Suzic 2024). While both parties share the objective of designing a successful system, differing interests can lead to conflicts. HFI serves as a tool to mitigate these conflicts by separating the roles of the customer and solution provider from the outset. This ensures alignment towards designing systems that integrate people effectively with technology.

Fundamental to these deliberations, is the INCOSE assertion emphasising the early initiation and continuous integration of HFI activities throughout system development (INCOSE et al. 2024). The necessity for early HFI gains additional significance in the usability domain, as symbolised by the 1:10:100 rule-of-thumb. As per this heuristic, addressing usability issues during design incurs minimal costs compared to modification post-development or during operational phases (Bruseberg 2008). This principle emphasises the exponential increase in costs associated with delayed HF considerations, reinforcing the convincing argument for proactive integration of HF principles. Furthermore, as illustrated by the US Air Force's efforts discussed in the 'Air Superiority 2030 Flight Plan Study', the requirement for holistic collaboration and continuous integration emerges as essential (Novitske (2019).

In the context of UK defence acquisition, HFI is not only a theoretical concept, but a vigorous management process. It aims at mitigating project risks and enhancing solution quality, ultimately achieving operational and organisational benefits. The UK MoD operationalises HFI through a structured model, comprising five HFI domains and six high-level process activities, enabling systematic identification, tracking, and resolution of human-related considerations throughout procurement and implementation (Corbridge et al. 2016). These five domains are Personnel, Training, HFE, System Safety & Health Hazards and Organisational & Social. These domains represent the key areas of focus across the six high-level stages of the HFI process. These stages include User Need Definition, System Requirements Definition, Assess Tenders, Detailed System Design, Test and Acceptance and In-Service Feedback. The stages are tailored to accommodate the diverse requirements of defence capabilities, systems and equipment. These HFI activities are coordinated by three key groups:

- Capability Sponsor, responsible for defining user requirements.

- Capability Acquirer, tasked with specifying system requirements.
- Supplier, or Solution Provider, responsible for developing the solution.

UK MoD (2023) defines specific goals that support HFI activities within defence projects. These include identifying and managing people-related risks, specifying Human Factors Process Requirements (HFPRs), Human Factors User Requirements (HFURs) and Human Factors System Requirements (HFSRs). The goals are achieved by adopting a Human-Centred Design (HCD) approach, leveraging established principles and best practices, and aligning HFI programmes with the SE lifecycle. HFI considerations, encompassing Risks, Assumptions, Issues, Dependencies and Opportunities (RAIDO), serve as a collective term, as outlined in the UK Joint Service Publication (JSP) 912 (UK MoD 2022). The overarching goal of HFI is to unite people, processes and technology into an integrated system capable of operating safely, effectively and efficiently across a spectrum of anticipated operating conditions. This holistic view encompasses the entirety of the system lifecycle, from concept to disposal, ensuring that HF is considered at every stage.

HFI stands as a critical component within the broader framework of SE. Central to the argument is the idea that the integration of HF should not be an isolated endeavour but rather deeply connected with the whole system development process (Walker et al. 2006, 2008). This argument underlines the necessity of acknowledging human elements as integral components of any system, particularly within the domain of defence systems acquisition and development. Certainly, the fundamental principle emphasises that without the inclusion of the user, a system remains incomplete, thus requiring the incorporation of HFI throughout the system lifecycle. This involves an approach covering both engineering and support facets of the solution. Remarkably, HFI prompts the consideration of human elements within projects or programmes where users might not traditionally be perceived as part of the system. Examples include midlife updates, procurement of Off-The-Shelf products, or the management of an in-service organisation. All require the integration of HFI to ensure holistic system development and operation (Narkevicius 2008).

Beyond military domains, HFI concepts have increasingly entered non-defence agencies and international fields. Significantly, the FAA has directed comprehensive guidelines aimed at integrating HF seamlessly into the acquisition process. It underscores the growing recognition of the importance of human-centric design across diverse sectors. While HFI finds its roots in the defence sector, its principles extend across safety-critical industries, including transportation, energy, architecture, construction and medical device design (Boy 2023; Burgess-Limerick et al. 2011; Hamilton et al. 2013; Rajabalinejad, van Dongen, and Ramtahalsing 2020). Its success lies in its systematic approach to identifying, tracking and addressing human-related considerations, ensuring a balanced development of technological and human aspects. This approach encapsulates not just technical considerations but also organisational and training aspects, emphasising the socio-technical nature of HFI.

Methods

The research was structured as a qualitative exploration, employing a case study centred on a defence industry company specialising in missile systems. The selection of this company was purposeful, given the lack of existing literature on HFI and the absence of published case studies in missile and guided weapon system development. The case study approach enabled a rich, context-specific investigation, with implications that may extend beyond the individual company to the wider industry and academic community. It enabled an in-depth, multi-dimensional exploration of complex dynamics within the organisation (Yin, 2015).

Semi-structured interviews with defence industry professionals served as the primary data collection method. This qualitative method was considered highly effective for in-depth exploration of complex issues, offering a detailed view of participants' attitudes, practices and challenges with HFI. Semi-structured interviews allowed for open-ended questions and follow-up probes. They facilitated detailed discussions and enabled participants to share their experiences and insights on HFI. This method supported the exploration of both expected and emergent themes, providing an inclusive understanding of the research problem (Fletcher et al. 2013). Moreover, semi-structured interviews were particularly effective for engaging with diverse participants, each of whom may have different insights and experiences related to HFI. This approach facilitated a holistic view of the integration of HF across different roles and stages of the missile development lifecycle (St. John et al. 2014).

The interview questions were developed based on the insights gained from the literature review on HFI. Initially, a list of 34 questions was created, addressing various HFI aspects covered in the research objectives, key areas including awareness, integration strategies, specific practices and encountered challenges. This preliminary set was then refined to 19 questions to improve clarity, focus and relevance. The refinement process involved evaluating each question's ability to elicit meaningful and detailed responses, ensuring that the final set of questions effectively aligned with the research objectives.

This study followed a purposive sampling strategy. Participants were selected from a company where the researcher had obtained permission to conduct the study. Selection was based on participants' roles and experiences, and their involvement and expertise in HFI within missile system development projects. The sample size of 12 participants was determined based on a combination of practical and methodological considerations. Practically, the number of interviews was limited by time constraints for data collection. A total of 12 participants was considered a realistic and practical number within the available timeframe. Methodologically, the sample aligned well with evidence-based recommendations on achieving data saturation. Data saturation is a data adequacy point at which it is unlikely that new information would be obtained from participants in qualitative research. Hennink and Kaiser (2022) found that saturation is commonly reached with small sample sizes, often between 9 and 17 interviews. Guest, Bunce, and Johnson (2006) claimed that saturation often occurs within the first 12 interviews, with basic elements of meta-themes emerging as early as six interviews. The sample of 12 participants aligns with the ranges recommended in these studies and thus guided the sample size decision for this research.

The interviews were conducted face-to-face, to foster a personal and engaging interaction. This setup enabled participants to share their views and experiences in depth. Each invited participant received an information sheet outlining the purpose and scope of the research, along with a consent form. The information sheet ensured that participants were fully informed about the study and their role in it, while the consent form secured their voluntary participation and agreement to the terms of the study. All interviews were recorded and then transcribed for detailed analysis. This approach enabled the main researcher to incorporate direct quotes and data visualisations for effective presentation of the results.

The data analysis process employed thematic analysis, a qualitative technique that involves identifying, analysing and reporting patterns and themes within the collected data. It involved systematically searching and arranging interview transcripts to enhance the understanding of the phenomenon under study. The analysis began with coding, which involves categorising and organising data into themes. This method reduced the volume of raw information, identified significant patterns, and built a logical chain of evidence from the data (Wong 2008). This method also aided in uncovering key themes related to HFI awareness, integration challenges and potential improvements. NVivo software was utilised to support the systematic coding, sorting and retrieval of data, integrating these functions with qualitative linking, shaping and modelling. Coding was a crucial aspect of the qualitative data analysis process. It involved subdividing large amounts of raw data and assigning them into categories or themes. These codes served as tags or labels for identifying significant topics from the compiled data. The coding process included several steps: after each interview, insights and observations were documented. Notes, called memos, were kept, helping in understanding the reasoning behind the coding decisions. This process was repeated for all interviews to identify recurring themes across different transcripts. Finally, codes were combined to develop broader themes that capture the essence of the data. This thematic analysis was conducted by the lead researcher (first author), who developed the codebook. The codes and the emergent themes were shared with the second researcher (second author), who reviewed them independently and provided feedback through regular discussions. A third researcher (third author) participated in these discussions by contributing broader insights. In addition, to strengthen the analysis, this study also utilised different theories to analyse and interpret data.

Ethical considerations influenced this study, from data collection to analysis and reporting (Creswell and Poth 2018). The ethical issues addressed included potential risks to participants, methodological refinements, and adherence to the ethics approval granted by the university ethics approval system, reference number CURES/22656/2024.

Interview results

The thematic analysis of the semi-structured interview data identified four major themes, grouped into twelve themes, and twenty-two subthemes, using a total of 156 codes. These themes and subthemes are provided in Figure 1, and the frequency of themes, and their associated subthemes is illustrated in Figure 2.

Table 1 provides an overview of the participants' professional titles while preserving their anonymity. Detailed demographic information, such as age, years of experience, or specific job roles, was not collected, in accordance with prior arrangements made with the participating company. Considering the relatively small and specialised nature of the defence sector in the region, where data collection was conducted, disclosing these details was considered to potentially compromised participant anonymity. Although this limited demographic profiling, the research still collected participants' professional titles to ensure the data remained contextually informative.

Awareness and Relevance of HF and HFI

The first major theme, Awareness and Relevance of HF and HFI, covers a detailed exploration of participants' perspectives on the understanding and significance of HFI within the missile development industry. This theme emerged as the most frequently discussed theme, with all 12 participants contributing to a total of 164 mentions.

Lack of HFI awareness emerged as a significant issue during the interviews. Participant 2 pointed out that 'despite mixed awareness, HF is often overlooked, particularly by younger engineers'. Participant 3 estimated that only 'maybe 50 percent' of employees are

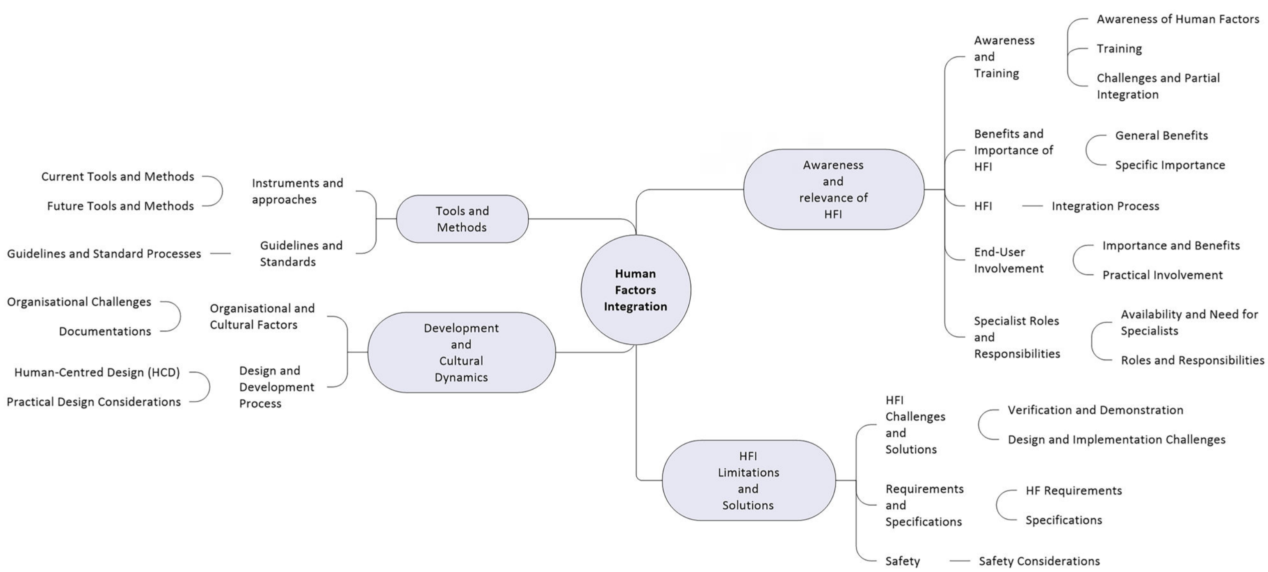

Figure 1. Thematic analysis categorisation.

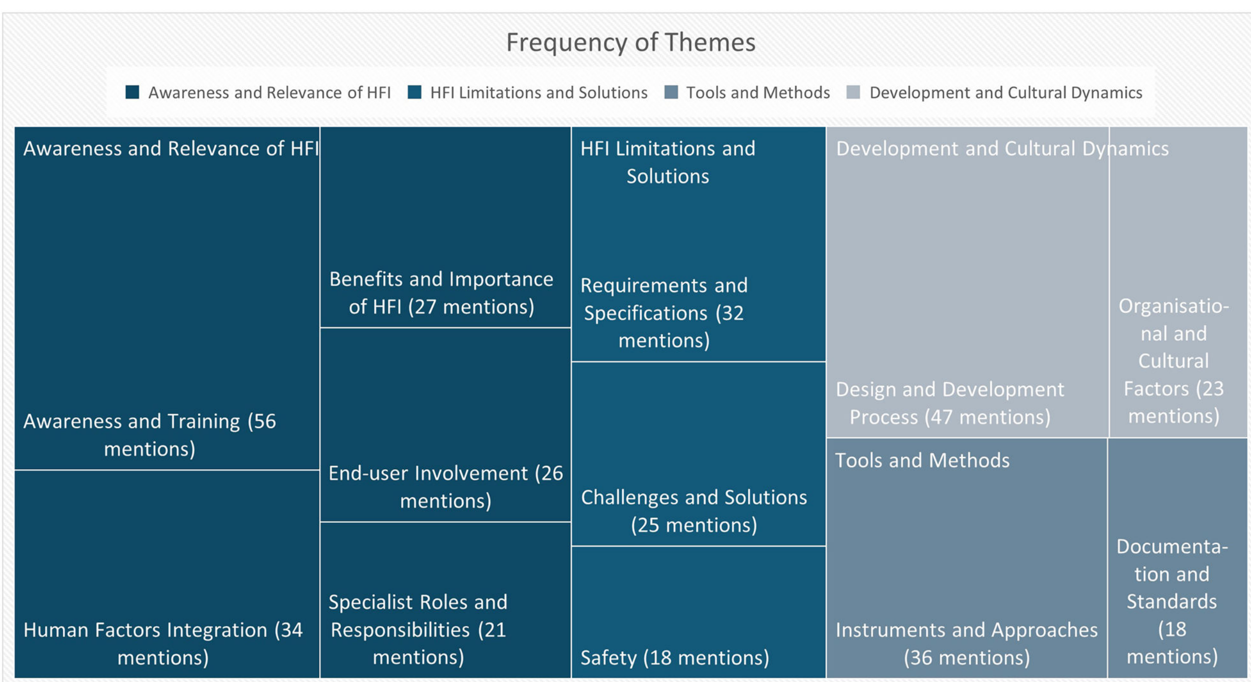

Figure 2. Frequency of themes and subthemes.

Table 1. Participants matrix.

Participant	Professional title
1	Chief Systems Engineer
2	Senior Systems Engineer
3	Junior Systems Engineer
4	Integrated Logistics Support Manager
5	Procurement Associate
6	Project Manager
7	Development Engineer
8	Project Manager
9	Platform Integration Manager
10	Safety and Airworthiness Engineer
11	Senior Development Engineer
12	Retired Brigadier General

familiar with HF, let alone HFI, indicating a clear gap in fundamental understanding. This lack of awareness was further highlighted by Participant 4, who observed that employees might be aware of HF in theory but fail to implement it effectively. The participant particularly noted that 'to the extent that they do implement it, not fully', reflecting a disconnection between understanding and practice.

Participants consistently emphasised the need to raise HF and HFI awareness. Specifically, Participant 7 noted a 'need for greater awareness and understanding of HF', which Participant 12 reiterated by stating the need for improved HF awareness. Participant 12 noted that the awareness of incorporating HF requirements is still developing, and suppliers are hesitant to include such requirements in contracts due to potential complications.

Closely linked to awareness, the need for HF training also emerged as a significant concern among participants. Participant 1 acknowledged a general lack of 'training on HF among employees'. This absence of structured training programmes and reference materials was a recurring concern among participants. Participant 4 stated, 'I have not seen any [HF training and reference materials]. So, therefore, I do not think there is such', highlighting a clear gap between theoretical awareness and implementation.

Despite a lack of awareness and training, most participants recognised the practical benefits of HFI. Participant 3 emphasised user-friendly design and safety, while Participant 4 pointed to the effectiveness of operations and maintenance. Meanwhile, Participant 10 noted reduced errors and enhanced safety. Participant 10 also highlighted other benefits, such as reduced concession requests and fewer mistakes in operation and maintenance. Drawing from a study in civil aviation, Participant 10 noted that 'Only 10% [of incidents] are due to technical failures. It is either human or operational reasons, such as bad weather, but a large majority is due to the human', underscoring the benefits of HFI in reducing errors and enhancing safety.

Participants also discussed the importance of HFI specifically within the context of missile development organisations. Participant 1 emphasised that 'human considerations are essential for effective [missile] operation', which was aligned with the argument from Participant 3, who stated that it is important to consider HF 'during the whole life cycle of the missile [systems]'. This view was further mirrored by Participant 6, who stressed that HF is integral to the missile and guided weapon system development process. In addition to that Participant 4 mentioned the importance of considering HF for the missile and guided weapon system's operational and maintenance. These participants acknowledged that human elements are critical to ensure that the missile and guided weapon systems can be maintained and operated by people during the system lifecycle.

The integration aspect of HFI was another important point described by participants. Participant 1 emphasised that HF should be implemented throughout the SE process rather than treated as separate HF activities, supporting a holistic view of system development. Participant 4 emphasised the importance of early integration by asserting, 'When you do your system specification, [HF] really need to be included in your system specification'. However, Participant 7 criticised the current SE processes and mentioned that the current processes do not adequately consider human components from the beginning. HF is only integrated after the design phase. Building on this, Participant 10 underscored the necessity of incorporating HF during requirements capture.

End-user involvement, another recurring aspect during the interview, is considered important to ensure that the systems address real-world operational challenges. Participant 1 pointed out key interactions between missile systems and operators, such as the ground control systems, while Participant 11 provided another key interaction between the pilot and the navigation system. Participants 11 described how pilots may need to manually input data if automatic methods fail, illustrating a direct human interaction with the system. The Participant stated, 'The pilot actually should physically write down the coordinates or the location of where he is right now', highlighting the need for user-friendly design in critical operational contexts.

Furthermore, some participants pointed out the critical need for HF specialists throughout the missile development process. There was a recognised lack of available HF experts within the organisation, with Participant 2 declaring the insufficient consultation with HF specialists during the development stages. Participant 10 mentioned that there is a limited application of HF expertise, which was primarily restricted to cockpit integration rather than missile design. Participant 3 further acknowledged that 'We currently, we do not have any [HF specialists]' and Participant 4 recognised the potential benefits of these specialists and highlighted their role in ensuring understanding of HF requirements during system development.

HFI limitations and solutions

The second major theme, HFI Limitations and Solutions, includes 75 mentions from 12 participants, comprising all the issues and problems faced in implementing HFI in the context of missile development. This theme offers a clear picture of the practical realities and concerns that emerge in this multifaceted area.

Several participants suggested that the lack of HF requirements is the major challenge of HFI. Participant 10 indicated that Human Factors System Requirements (HFSR) are not usually provided by clients. Participant 12 said, 'The culture of man-machine interface [HF] did not exist. It does not exist. Therefore, people do not put it in the specifications or requirements documents'. Furthermore, Participant 12 highlighted that suppliers often resist incorporating detailed HF requirements due to potential complications and costs. The participant suggested that buyers must explicitly request these requirements, as suppliers will generally not introduce them independently. Participant 1 agreed that high-level HFSR, such as adequate manpower, training, error reduction and mental workload, are relevant and important. He/she believed that these requirements should be incorporated into the design process to ensure the systems are user-friendly, safe and efficient. Similarly, Participant 3 found high-level HFSR relevant but stated limited exposure with them, saying, 'I have not seen them from my experience', except for requirements related to error probability. This indicates that such requirements are not commonly included or emphasised in the company's projects. It also highlights the need for clear, measurable requirements to prevent misinterpretation and ensure that HF considerations are adequately addressed.

Realising this requires early and detailed discussions between buyers and suppliers to guarantee that user needs are effectively represented and incorporated. However, another emerging challenge is the reluctance of suppliers to incorporate HF due to potential complications and increased costs. Participant 6 stressed that 'Suppliers may resist including HF requirements due to the potential for complications and increased costs'. Similarly, Participant 12 stated that 'Suppliers might avoid adding HF requirements unless explicitly requested by the buyer', which indicates that proactive engagement from acquirers is necessary to ensure that HF are considered and included in the development process. Closely related, Participant 5 highlighted challenges in the procurement process, noting that procurement personnel are more concerned with commercial issues rather than HF issues. This participant also highlighted resistance from procurement employees towards early-stage HFI, as they typically view HF as a technical issue instead of part of their commercial responsibilities.

The HFI process should emphasise HF requirement verification and validation to align with user needs and expectations. However, several challenges were also identified in verifying and validating HF requirements. Participant 9 pointed out that while some HF-related aspects are addressed, they are not explicitly labelled as HF considerations. Furthermore, this participant acknowledged the difficulty in demonstrating HF-related requirements, noting that the current validation focuses more on system capabilities than on HF aspects, which highlights a gap in validating human aspects and user interaction aspects during system demonstrations.

Participant 10 observed that challenges in integrating HF are also evident from the disconnection of designers and maintenance realities. 'The biggest challenge is that in the design world, we have to design something and write the instructions to maintain it, when some of those guys writing it have never even changed the spare wheel on their own car'. This disconnection leads to impractical instructions and design flaws, as designers often lack practical maintenance experience. In addition, Participant 10 noted that HF considerations often occur too late in the design process: 'It often does not happen, and if it does happen, it is the later stages where it is often difficult to change it'. This participant believed that the resistance to integrating HF was mainly because of a perception of additional workload. He/she believed that some formalised HFI guidelines and standards, such as JSP 912 of the UK MoD are only applicable to government procurement and not the industry. This participant emphasised a challenge in aligning industry practices with these standards. In a related point, Participant 12 stressed the need for cultural change and awareness-building about the importance of HFI. This challenge highlights the need for educating local suppliers and end-users about international standards and practices to enhance the development and usability of missile systems.

Development and cultural dynamics

The third major theme, Development and Cultural Dynamics, was mentioned 70 times, with all 12 participants contributing. It explores the complex interaction between the design and development processes and the broader organisational and cultural factors that influence them.

Many participants discussed the current processes and the challenges of implementing HFI during the design stage. They focused on the lack of adoption of an HCD approach despite being recognised for its potential benefits for product quality and acceptance if integrated early in development. Participant 1 admitted that 'HCD is not practised'. Participant 2 said that HCD is only applied in limited contexts, primarily within Integrated Logistic Support (ILS), but not as a comprehensive design principle. Participant 3 admitted that the company lacks a mature HCD process, stating, 'We try to apply it, yes, but.the processes are still not yet matured'. Participant 9 explicitly stated, 'That is something that we do not do, unfortunately, and we need to do it', reinforcing the recognition of this gap. Participant 9 also emphasised the benefits of involving client representatives in design reviews so the company can more effectively capture the real user needs and ensure the design aligns with those needs.

Due to the limited input to design and development from actual users, Participant 3 explained that the responsibility for creating the Concept of Operations (CONOPS) often falls only to systems engineers. 'We were the ones who were coming up with the CONOPS', Participant 3 noted. Similarly, Participant 9 emphasised the importance of CONOPS in aligning system functionality with user needs. The iterative process of developing CONOPS with client feedback is needed to ensure the system is tailored to meet real-world operational demands. Moreover, Participant 9 believed that 'CONOPS is everything', underscoring its importance in ensuring systems are usable in real-world conditions. They described their best approach for CONOPS development that involved the end-users: 'We will write the first draft [of CONOPS], review it with them [users]', illustrating a collaborative process aimed at aligning system functionality with user needs. This proactive measure seeks to address practical challenges, although it is currently viewed more as an initiative from the manufacturer rather than a client-mandated requirement.

While recognising the benefits of involving end-users in design processes, their engagement is often limited and inconsistent. Participant 10 acknowledged the lack of current practice in involving all stakeholders, especially the end-users, during the design stage. However, this participant emphasised its value, particularly in safety assessments. Participant 9 provided an example of the need to incorporate user feedback into the design. He/she explained that they currently plan to acquire an aircraft simulator that communicates with missile systems to better understand user interactions. However, some other participants recognised the complexity of end-users' involvement in the design process. Participant 4 noted that while end-users should contribute to design principles, 'They should not get involved in the details of the design'. Participant 6 highlighted the complexities of integrating end-user feedback, mentioning that while it can enhance outcomes, it can also introduce conflicts if users lack understanding of the development details. Participant 7 also acknowledged potential conflicts between engineers and end-users due to differing perspectives on performance requirements. This reflects a balanced view of user involvement, advocating for their input on principles rather than detailed design aspects. This also reflects the need for user involvement to be carefully managed and should be documented thoroughly, with clear descriptions and agreed-upon changes managed carefully.

Participants also discussed the role of organisational and cultural factors in shaping HFI practices. Participant 1 mentioned that the company does not receive detailed Target Audience Documents (TAD) from clients. As a result, it limits the understanding of user needs that may result from the company's failure to stress and communicate the necessity of these documents to clients, as well as broader organisational issues. It also indicates cultural challenges in prioritising user-centred design. This participant and Participant 4 noted that tools like Human Task Analysis (HTA) and Failure Mode Effect Analysis (FMEA) were used selectively, often as an afterthought rather than an integral part of the development process. Furthermore, according to Participant 4, 'Many local suppliers are not accustomed to integrating HF into their development processes'. Participant 12 elaborated on the cultural shift required, as the culture of human considerations does not exist. 'People do not put it in the specifications or requirements documents'. This reflects a gap between traditional practices and modern requirements, emphasising the need for a cultural and procedural shift towards valuing HFI. As Participant 12 further stated, the culture of HF, 'I think, needs to develop much more. How much they value the ergonomics, you know, and how much they see the importance of ergonomics in their products'.

Tools and methods

The fourth major theme identified in the research is Tools and Methods. With 54 mentions from 11 participants, this theme encompasses the tools, methodologies, and standards used to incorporate HF in missile development.

Within this theme, Participant 1 believed that integration should be guided by high-level frameworks and addressed in lower-level procedures, tailored to specific product needs. This participant believed that the HFI plan could be part of the Systems Engineering Management Plan (SEMP) document or the Systems Engineering Manual. Similarly, Participant 2 suggested that HFI considerations should be integrated into SEMPs and design reviews, including user feedback. The integration of HF into the SE process was a recurring subject during the interview. Most participants agreed on the need for specialised tools, teams, and methods tailored to different system types and project stages. Particularly, Participant 8 stressed the necessity of this integration by stating, 'HF processes and tools should be integrated into SE to ensure consistent application across projects'. This view was supported by Participant 12, who suggested establishing 'a special division and special tools and processes and procedures available in the organisation' to handle the unique challenges of each project, reflecting an agreement on the need for dedicated resources and expertise.

Participant 3 advocated for a formal HFI process, arguing, 'If we have a process for integrating HF, it will be very, very beneficial. everyone will get training, awareness on the benefits' and accentuating the need for a standardised process. Participant 4 supported the formalisation of HF processes, suggesting, 'If there is such, it will be very much integrated with the work that we are doing'. This participant expressed support for future mandates, as 'A system has a specification. So therefore, the specification will then have requirements for HF included in it as well'. This implies a belief in the potential of formal mandates to overcome cultural resistance. In addition, Participant 7 saw value in establishing a formal HFI policy to raise awareness and emphasise the role of each employee in contributing to the company's success. This highlights the need for recruiting personnel with HF awareness and providing relevant training. To better integrate HF into the development cycle, Participant 2 recommended increasing education and exposure to HFI concepts. This would make HFI a formal part of the development lifecycle and eventually mandate human consideration in all development projects. He/she admitted that this approach requires buy-in from all stakeholders to be effective.

Participant 10 acknowledged the role of training but argued it was not sufficient on its own. They suggested, 'Training is part of it, but it is also a checklist of processes to say, have we thought of this?'. He/she also stressed the need for changing the narrative around HF: 'You need to change the narrative from telling them what they should do, to explaining why'. This approach aims to foster understanding and genuine buy-in among employees.

In addition, effective documentation and communication between buyers and suppliers were highlighted as fundamental for clearly defining and meeting HF requirements. Participant 3 articulated this need: 'Proper documentation and communication are key to ensuring that HF requirements are understood and met'. On the aspect of documentation and communication, Participant 12 suggested that user involvement, along with their communication and discussions, should also be thoroughly documented. The documentation includes clear descriptions and agreed-upon changes managed carefully to avoid excessive revisions. This participant underlined the importance of clarity to prevent misunderstandings, stating, 'Make sure that everything is written down as clearly as possible to avoid any misinterpretation later'.

Discussion

Methodological reflections

The interview participants represented a diverse range of roles within the company, including systems engineers, project managers and safety managers. The diverse composition offered a holistic view of HFI across the system lifecycle. This was in alignment with Taherdoost (2022), who suggests that samples of qualitative research should be purposely selected as a rational cross-section of individuals most likely to provide relevant and comprehensive insights into the research objectives. Underpinned by data source triangulation, which involves collecting data from different types of participants, the study gained a holistic perspectives and improved the validity of the data through cross-validation (Carter et al. 2014). Rather than aiming to generalise the findings from a single stakeholder group, focusing on depth and variation across relevant roles, enabled capturing insights from different and intersecting viewpoints. The findings from the case study can act as a reference model which other companies in the defence sector can implement. Such applicability of findings can help in enhancing HFI practices in the field, which in turn can lead to improvements in the missile and guided weapon systems.

The thematic analysis involved multiple researchers and incorporated a collaborative peer debriefing process. As recommended by Nowell et al. (2017), this process worked as a form of investigator triangulation. It enabled critical feedback on the emerging codes and themes, facilitated diverse perspectives during the analysis, and helped to mitigate individual bias. In addition, peer debriefing served as an external check on the research process to improve the validity of results and the credibility of the research (Nowell et al. 2017).

Theoretical triangulation contributed to a comprehensive interpretation of the findings by allowing the use of different theories to analyse and interpret data (Carter et al. 2014). This approach enabled researchers to support or challenge findings by comparing, contrasting or interpreting them through various theoretical perspectives and improves the validity of research by incorporating insights from diverse sources (Carter et al. 2014). Some key theories used in this study include organisational culture and change theories, such as those proposed by Kotter (1996) and Schein (2010); as well as the safety science perspective of Reason (2016), among others.

Interpreting the findings

The study found that HFI is fundamentally important in missile development, particularly in ensuring systems are practical, safe and effective during handling, assembly, operation and maintenance. Despite this, this study reveals that HF remains underappreciated. Awareness of HF and HFI principles among employees is varied, with a remarkable gap in training. This implies that the current induction and continuous professional development programmes are insufficient in preparing the employees with the required skills and knowledge to implement HFI in their work. This finding is concerning given the firm link between thorough HF training and the successful implementation of HFI principles (Salas et al. 2012).

The application of HCD within the company is inconsistent. While there are efforts to involve end-users, this involvement typically occurs later in the development cycle, primarily during design reviews and acceptance testing, rather than in the initial design phases. This delayed involvement inhibits applying discoveries made during these gate points, as the cost of modifying the system at later stages of development is significantly higher. Moreover, the company has no systematic way of doing HCD, which is a weakness in the design and development process. This observation contradicts Norman's (2013) and Sherman's et al. (2024) user-centred design, which stresses the importance of incorporating user needs and feedback throughout the design process for intuitive and efficient systems. The lack of consistency in the use of HCD within the company also implies a disconnect between theoretical best practices and practical implementation. Giacomin (2014) emphasises the need for systematic approaches to HCD, suggesting that systematic methodologies are important to achieve usability and effectiveness. This view is reinforced by the ISO 9241-210:2019 standard that outlines systematic and iterative processes for designing usable and effective interactive systems (International Organization for Standardization 2019).

The study found that while HF are indirectly included in the current SE process in the focused company investigated in this case study, their integration is not sufficient. The findings highlight the importance of eliciting user input during the CONOPS process. Without incorporating feedback from both direct users (those interacting with the system) and users by command (those overseeing operations), the resulting CONOPS may reflect only the developer's perspective, potentially overlooking the needs of key stakeholders. Continuous user involvement throughout the development cycle and the use of specialised tools and methods are recommended to improve this integration. This balance between user feedback and project efficiency reflects broader concerns within SE, where the need for human considerations must be balanced against technical and logistical constraints. Maguire (2001) emphasised that this approach is difficult to manage due to competing priorities and the complexity of integrating diverse stakeholder inputs. This is supported by Berlin et al. (2021) who highlight the difficulty of balancing diverse stakeholder interests and priorities. Despite these challenges, specialised HF tools and methods, when tailored to different system types and project stages, could promote the integration of HF processes into the SE process (Burgess-Limerick et al. 2011; Stanton et al. 2017).

Effective documentation and communication are important to ensure that HF requirements are effectively incorporated. Participants emphasised the importance of clear and measurable specifications to prevent misunderstandings and ensure that HF requirements are met. This reflects broader industry challenges where miscommunication and ambiguous documentation can lead to costly rework, project delays and even safety risks. This view is further backed by literature on documentation in engineering. It points out that documentation must be precise and unambiguous to ensure that all the stakeholders have a common understanding of requirements and specifications. Misinterpretation of requirements is a common issue in complex projects, often leading to divergence in implementation and the need for rework, which can threaten project success (Boehm 2004; Pavate et al. 2024).

The study suggests that integrating HF into contractual processes is necessary for aligning design and procurement practices with HF requirements. Early specification of HF requirements in contracts is important to prevent misalignment and potential issues later in the development process. Moreover, establishing a formal HFI mandate within the company, supported by a unified policy or framework within client organisations like the MoD, would substantially enhance HFI implementation. The support for high-level frameworks, specific procedures and formal mandates demonstrates an awareness that ad hoc strategies are inadequate for reliably incorporating HF into complex systems such as missiles or guided weapons. Although there is scepticism about the effectiveness of mandating, concerns mainly focus on the risk that mandated tasks may be completed only superficially. This could lead to a lack of full intellectual engagement, going against the intended purpose. Nevertheless, the literature supports mandating. It highlights that formalised processes and frameworks are critical for achieving consistency and effectiveness in HFI across different projects and stages (Dul and Neumann 2009). This is reinforced by military standards like JSP 912 (UK Ministry of Defence 2022) which provides detailed policies, guidance and best practice to ensure the consistent and systematic HF integration throughout the system lifecycle.

Several challenges hinder effective HFI in missile development. One set of challenges relates to directly to the project itself, particularly the technical aspects, such as requirements, design and verification. Another set of challenges is more contextual. These are rooted in organisational and societal cultures that influence how projects are managed and what priorities are pursued. There was a clear bias towards technical and logistical expertise, reflecting an organisational culture that values engineering over human factors and limits HF integration. This finding aligns with Vicente (2013) and Muhammad et al. (2024), who discusses the challenges of integrating HF into engineering domains where technical priorities tend to overshadow HF. Vicente (2013) highlights how engineering cultures frequently emphasise reliability, efficiency, and functionality, sometimes at the expense of usability and human well-being. This illustrates a systemic cultural challenge across similar organisations. Meanwhile, Muhammad et al. (2024) emphasises that technology-driven organisations, particularly those relying on computer automation, often prioritise data-driven methods and overlook the critical role of human capabilities and limitations. This cultural orientation leads to a reactive instead of a proactive approach to HFI. HF activities are often delayed until the later stages of development, primarily used to solve emerging problems rather than to inform early design decisions. A key factor contributing to these observations is that the engineering culture, and the culture of acquisition are heavily influenced by emphasis on the objective achievement of specified outcomes. These cultures often do not accommodate attributes of systems that are not quantitatively described, or visibly verifiable. Consequently, HF are often treated as an afterthought rather than a fundamental component of the design process.

The selective use of tools like HTA and the inconsistent integration of HF in the SE process align with Reason's (2016) concept of 'latent conditions' where organisational practices and norms create an environment where HF are not fully integrated into the design process. These latent conditions sustain a cultural acceptance of 'good enough' technical solutions, often overlooking the systemic risks introduced by the neglect of HF. These patterns resonate with organisational culture theory (Schein 2010), which suggests that deeply ingrained cultural assumptions influence how organisations approach change and innovation. These finding aligns with the broader literature on organisational change, which suggests that resistance to new practices is common, especially in industries where traditional methods are deeply established (Kotter 1996).

Furthermore, suppliers are often reluctant to incorporate HFI due to unclear specifications and ineffective verification processes. This hesitation is especially common among local suppliers with limited HFI experience, who see it as an added cost and complexity. Their unwillingness to adopt HFI unless explicitly mandated by the client highlights a broader gap in the supply chain's commitment to HFI. This pattern reflects an industry culture that focuses more on contractual compliance and technical deliverables than HF integration. It also reflects wider societal cultural factors towards change and innovation, where HFI is seen as disruptive to established norms and is therefore met with passive or active resistance. These findings aligns with the broader literature on change management, which suggests that resistance to new practices is common, especially in industries where traditional methods are deeply established (Kotter 1996).

The idea of culture as a barrier to change is well supported in the literature, and the results of this study support that without the right culture in place, the implementation of HFI will remain a challenge (Schein 2010). The call for cultural change to embrace HF aligns with Schneider, Brief, and Guzzo (1996) those who stress the importance of fostering an organisational culture that supports HFI. Kotter's (1996) eight-step model outlines a structured change process including urgency creation, coalition-building, vision development, clear communication, empowerment, short-term wins, and anchoring new behaviours in organisational culture to ensure lasting impact (Appelbaum et al. 2012; Kotter 1996). In the context of the missile and guided weapon system development company under this case study, such a transformation would entail a change in the current processes, training and development, and culture that supports HCD and the use of HF tools and standards. This involves incorporating HF principles not only in formal procedures but also in everyday practices, ensuring that all employees are valued HFI and motivated to apply HFI, supported by leadership that models and reinforces these behaviours. This is also in agreement with Dul et al. (2012) those who assert that HF should be incorporated into strategic business processes to improve organisational performance, thereby fostering a culture where HF considerations become integral to decision-making and project success.

Strategies for strengthening HFI practice

This section translates the study's key findings into actionable strategies aimed at improving HFI implementation in missile and guided weapon system development. These strategies are structured into two categories: (1) organisational and cultural strategies and (2) process, tool and technical mechanisms. Together, these actionable strategies provide a practical roadmap for integrating HF more

Organisational and cultural strategies

Enhance training programmes. The study shows that while some employees are aware of HFI principles, there is a major gap in training. To address this, the company should develop structured training programmes that emphasise the importance of HFI and provide practical guidance on its implementation. These programmes should target all levels of the organisation, from engineers to management, ensuring that HFI principles are understood and integrated across the development lifecycle.

The traditional training in HFI might go a long way in alleviating the problem of cultural resistance, but it would usually remain within the general idea of teaching topics and tools for HF. A new avenue could include the concept of 'mental models' and how they shape the preconditioning and barriers to learning (Sterman 2006). Cultural norms are shaped by our current perception and interpretation of reality, which in turn may be misaligned from one shaped by reasoned evidence of that reality. Bringing this awareness to trainees would be a first step in targeting some defensive routines, unscientific reasoning, judgmental biases and so on (Sterman 2006).

Consult HF specialists. To improve HFI implementation, it is important to recruit or involve HF specialists in the development process. The expertise can provide informed guidance and support the thorough integration of HFI principles.

Integrating HFI into the SE process. The study reveals that HFI considerations are often limited to later stages of development. To enhance implementation, HFI needs to be integrated into the SE process from the outset. This includes involving end-users earlier in the design phase, using HF methods and tools, conducting HF analyses, and ensuring that HF requirements are captured and addressed in system specifications and user requirements.

Foster a HF-oriented culture. To enhance awareness and implementation, the company needs to foster a culture that values HFI as a critical component of the development process. This can be achieved through leadership commitment, continuous communication on the importance of HFI and the alignment of organisational goals with HFI objectives.

Encouraging consistent end-user involvement. To manage the inconsistencies in user involvement identified in the study, the company should establish a formalised approach to HCD. This approach could guarantee that end-users are consistently involved not just in design reviews and later stages but throughout the entire development process.

Facilitate practical exposure for engineers. To reduce the gap between design and practical application, the company could implement a programme where engineers, especially early career engineers, are temporarily placed in practical environments, such as assembly and manufacturing plants. This experience allows engineers to gain firsthand insights into the challenges faced by technicians and maintainers, leading to designs that are more user-friendly, manufacturable and operable.

Establishing a dedicated HFI division. To achieve a focused and effective implementation of HFI, the company could consider establishing a dedicated HFI division within the SE department. This division should have its own tools, methods, and specialists who can lead HFI initiatives, ensuring that HF are consistently integrated and tailored into all projects.

Recruiting retired operators. Another strategy recommended by a couple of participants of the study is to enhance HFI by recruiting retired operators, such as former military personnel, to work within the defence industry. These individuals can bring valuable operational experience that can inform the design process, ensuring that systems are developed with real-world usability and practicality in mind.

Establishing an HFI mandate. To further reinforce the importance of HFI, the company could invest in establishing a formal HFI mandate. This mandate would enforce the integration of HFI principles in all phases of missile development, making it a standard practice rather than an optional consideration. However, the effectiveness of this mandate could be significantly enhanced if a unified HFI policy or framework existed within the clients or acquirers of missile systems. The absence of such a policy in certain key client organisations could hinder HFI implementation among missile supplier companies, potentially limiting the emphasis and priority given to HFI across the supply chain.

Process, tools, and technical mechanisms

Develop a shared HF requirements database. Inspired by the UK MoD's practice (UK Ministry of Defence 2022), an inclusive set of HF requirements such as HFURs, HFPRs and HFSRs, can be integrated into a shared database accessible by both the clients and the supplier companies. This approach aims to define the human role in system capabilities in generic yet applicable terms. It also aims to enhance HFI in requirements documents and improve guidance on acceptance criteria. This ensures HF are consistently addressed throughout system development, enabling both acquirers and suppliers to integrate them effectively across all capabilities and systems.

Model role-specific tasks. Defence suppliers could adopt an approach to modelling role-specific tasks for both supplier and client perspectives. Grounded in user-centred systems design (Boy 2021), this approach recognises that users encompass various roles beyond end-users and operators. It promotes a holistic understanding of human-system interaction, enabling HFI strategies to be tailored to the unique requirements of each user group, ensuring that all operational, maintenance and support needs, are addressed in the system design. By systematically analysing these roles and tasks, they can enhance training, improve system usability, and ensure that HFI considerations are fully integrated throughout the missile development lifecycle. Table 2 proposes the key roles and tasks relevant to missile development, highlighting the importance of addressing the specific needs of each user group individually

Facilitate HFI through MBSE and Human-in-the-Loop (HITL) modelling. The integration of HF into SE is often facilitated through Model-Based Systems Engineering (MBSE), which helps ensure coherence between HF methods and existing SE practices by embedding HF considerations into system models. For example, Airbus Defence and Space recognised deficiencies in addressing HF within their existing architectures and proposed changes. This recognition prompted a comprehensive investigation that led to the incorporation of HFI into various aspects of their MBSE process (Sharples 2015, 2016). Facilitate HFI through MBSE by explicitly representing users within system models, assisting the identification of human tasks, interactions, interfaces and information flows and enabling the precise definition of requirements related to equipment, personnel, manpower and training. Furthermore, Human-In-The-Loop Simulations (HITLS) empower designers to consider not only specified tasks but also actual users (Boy 2020). This approach represents a shift from simply accommodating users through interfaces to actively integrating their needs and behaviours into the design process. It aligns closely with Human-Computer Interaction (HCI) principles, which emphasise observing human activity and understanding user experiences (Boy 2021). Coupling HF with HITL simulations enables real-time simulation and validation of user-centred requirements.

Implement an HFI Plan. For every project, a formal HFI plan (Bridger 2014) should be created and integrated into the project documentation, outlining specific HF activities to be conducted at every stage, from initial concept through to operation. This can help to systematically integrate HF considerations throughout the project lifecycle, resulting in more effective and efficient outcomes. Since the HFI process is both goal-based and risk-based, the plan can be tailored to the specific circumstances and risks of each project, ensuring that HF activities are appropriately scaled to achieve the desired goals while managing potential risks effectively.

Appoint an HFI integrator in SE teams. A dedicated HFI integrator within the SE team (INCOSE et al. 2024), who would be responsible for coordinating HFI activities, could be considered to ensure that HF considerations are systematically integrated across all

Table 2. Missile development user roles and tasks.

User role	Tasks	Perspective
Missile Loaders and Maintainers	Perform inspections, loading, unloading, maintenance, code checks and recoding of missile systems. They are trained to handle sensitive components and perform missile disablement.	Solution Provider (supplier company)/ Customer (system acquirer)
Missile Operators/Crew	Operate missile systems, including pre-launch checks, target acquisition and launch execution. Perform physical inspections and may consult maintainers for complex issues.	Customer (system acquirer)
General Military Personnel	Provide operational support, including transportation, securing and positioning of missile systems. Trained to perform missile disablement when required.	Customer (system acquirer)
HFI Specialists	Develop and implement HFI strategies, ensuring that missile systems are user-friendly, safe and meet operational requirements.	Solution Provider (Supplier company)
Engineers and Technicians	Design, test and troubleshoot missile systems. Ensure compliance with military standards and customer requirements.	Solution Provider (Supplier company)
Trainers	Train military personnel, operators and maintainers on the use, inspection, maintenance and safety protocols related to missile systems.	Solution Provider (supplier company)/ Customer (system acquirer)
Quality Assurance Personnel	Conduct inspections and evaluations to ensure missile systems meet specified standards and operational readiness.	Solution Provider (Supplier company)

programmes and engineering efforts. Key duties include developing or contributing to HFI plans, tailoring HFI efforts for the project lifecycle, ensuring HFI aspects (e.g. ergonomics, HMI, human reliability) are adequately considered throughout the project, supporting domain personnel, balancing trade-offs to optimise performance and cost, coordinating with other programme elements, and managing HFI-related risks, issues and opportunities throughout the project.

Ensure activities are conducted by qualified personnel. It is recommended that all HFI activities conducted by defence supplier companies be performed by Suitably Qualified and Experienced Personnel (SQEP). Specifically, these activities should be carried out by professional Ergonomists or Human Factors Engineers who acquire experience in defence-related HFI. To meet this standard, all HFI personnel should hold a registered membership with the Chartered Institute of Ergonomics and Human Factors (CIEHF), for example. This recommendation is inspired by the UK MoD's practice, as outlined in JSP 912 Part 1 (UK Ministry of Defence 2022).

Justify HFI using cost-benefit models. A strong financial justification for HFI can be developed by employing a cost-benefit model during the project planning phase. Demonstrating that early application of HFI can lead to substantial cost savings, as supported by Miles and Hignett (2018), will educate and encourage clients, to support and prioritise HFI in their projects. By utilising financial justification, this approach not only proves the financial benefits but also strengthens the leadership's commitment to HFI, ensuring that it is incorporated early into the development process and sustained throughout the project lifecycle. The cost-benefit analysis needs to be done, including the whole system lifecycle, including costs paid by the supplier, which affect the acquisition price and costs incurred through the operations and maintenance as well as disposal phases, paid by the acquirer and user organisations.

Establish a human-related data repository. It is recommended that defence supplier companies collaborate with end-users to establish a shared database for human-related data (Rantanen et al. 2003). This effort should collect information such as human performance data, ergonomic standards, human errors and other relevant HF metrics. By maintaining this shared database, both suppliers and end-users can access essential information to make informed decisions and ensure effective integration of human considerations throughout the design and development process.

Adopt structured HF methods and tools. Defence supplier companies could adopt and implement structured HF methods and tools to enhance the early identification and management of HFI issues throughout the SE process. Given the wide range of HF methods available, such as those outlined in Stanton et al. (2017) who categorise 107 HF methods into 11 categories, can be tailored to address varying levels of complexity in HF problems. Some issues may require only basic interventions, while others might necessitate a combination of methods, planned and prepared in advance, to achieve optimal outcomes. By utilising a broad set of methods, including data collection, task analysis, cognitive task analysis, human reliability and safety analysis and more, the company can systematically integrate HF considerations into system design, ensuring that human related concerns are addressed at every stage of development.

The use of HF methods in missile system development is documented in the literature. For example, user testing supported with human performance data was employed in the development of the US Line-of-Sight Forward-Heavy (LOS-FH) missile system to inform decision-making during the acquisition process (Booher

2003). In the case of the F/A-18 Hornet and Super Hornet weapon systems, descriptive and experimental studies, along with laboratory and flight testing, were conducted to improve pilot situational awareness and overall system performance (Heck 2007). Systems-Theoretic Accident Model and Process (STAMP) and its hazard analysis method, Systems-Theoretic Process Analysis (STPA), were applied in a Royal Navy Hawk missile simulation task (Stanton, Harvey, and Allison 2019). The methods enabled the mapping of key stakeholders, identification of potential risks, and improvements the overall system safety (Stanton, Harvey, and Allison 2019). Similarly, the application of STPA to Generic Raytheon Missile Systems (GeRMS) showed its benefits in developing applicable hazard mitigations (Chiesi 2016). Furthermore, Fault Tree Analysis (FTA) was applied to the guided weapon system of laser-guided terminal projectiles during live firing tests (Gao et al. 2019). The method helped to identify critical failure points and improve system reliability. In addition, simulation and experimentation that integrate anthropometric modelling with technologies such as game animation and virtual reality were developed to support early design decisions for future naval missiles and weapon systems (Leahy and Vance 2019).

Creating an HFI checklist. Even without a formal HFI policy, developing a checklist (Al Rashdi 2019) that covers various aspects of HFI could be beneficial and adaptable to each project. This tool helps engineers and project managers ensure that key HF elements are considered throughout design, development and evaluation.

Use an HFI generic question set. To facilitate HFI in missile development, using a generic question set designed to guide the definition and scaling of HFI activities can help ensure an appropriate integration of HF considerations throughout the missile system's lifecycle. The question set helps elicit evidence at each stage, ensuring that the process aligns with the key HFI goals of feasibility, usability and reliability, as adapted from Hamilton et al. (2013). Table 3 proposes some essential HFI goals and key questions that could guide HFI. By systematically addressing these elements, defence suppliers can guarantee that missile systems are designed with a clear understanding of user roles, operational requirements and potential risks.

Conclusion, limitations and future work

Conclusion

The study concludes that although HFI is essential in missile development, it remains underappreciated in the case study company, with a significant gap in employee awareness and training. HCD is applied inconsistently, end-user involvement typically occurs too late in the design cycle, and integration of HF into SE is inadequate. These findings confirm the hypothesis introduced in the Introduction that within the missile development company investigated, a deeper understanding of the current state of HFI awareness and its integration during the development stages of complex system lifecycles is needed to improve outcomes. Through a case study approach, the research reveals a significant lack of awareness of HF and inconsistent implementation of HFI principles.

These findings also contribute to advancing HFI practice by offering a practical roadmap and actionable strategies aimed at improving HFI implementation across the system lifecycle. These strategies, which can be tailored to defence-sector applications, consist of organisational and cultural strategies, as well as process, tool and technical mechanisms.

From a theoretical perspective, this study contributes by linking organisational and cultural barriers, where technical expertise is valued over HF, and wider industry and societal resistance, where suppliers view HFI as costly and complex, to established change management theories such as Schein and Kotter. This adds new insight into how the dynamics within organisations, wider industry and society can enable or hinder HFI adoption. This, therefore, bridges the gaps between HFI and organisational transformation literature.

The study also highlights the necessity of formally integrating HF into procurement contracts and supporting this with unified HFI frameworks. Although there are concerns about superficial compliance with mandated processes, the literature supports that formalisation is important for achieving consistency and effectiveness.

Limitations and further studies

This study not only reinforces the need for policy-level reform but also lays the foundation for future research aimed at bridging the persistent gap between the recognised importance of human considerations and their practical integration into real-world defence system development.

This study acknowledges several methodological limitations. One significant limitation is the selection of a single missile and guided weapons developer and manufacturer as a case study. While this company provides valuable insights into the awareness and implementation of HFI in missile development, it may not be sufficient to generalise the findings across the entire

Table 3. Generic HFI key questions.

HFI goal	Key questions	Example missile development evidence
To define a feasible role for people	Is there a concept of operations for the role to be performed by operators and maintenance personnel?	A description of the CONOPS for missile systems, outlining how roles interact with system design and operation.
	Has the target workforce been defined?	Ensure that the capabilities, characteristics, and numbers of the target users (operators, maintainers) are considered in system design.
	How many people are needed?	Demonstrate that the missile development process includes an analysis of staffing requirements to ensure effective operation and maintenance.
	What will be their jobs?	Document the specific roles and responsibilities needed for different phases, such as development, testing and deployment.
	What are the knowledge and skill requirements?	Ensure all personnel involved in missile development are SQEP to carry out their roles.
	Is there a training plan?	Develop and implement a comprehensive training program that covers the necessary skills and knowledge for each role.
	How will competence be assured?	Establish a system for ongoing training and certification to maintain and update the skills of personnel involved in missile development.
To specify usable interfaces to workspaces, equipment and technology	Are reference anthropometric data available?	Use anthropometric data to design control panels, workspaces and interfaces that accommodate the target user population.
	What are the requirements for facilities and workspaces?	Apply ergonomic principles in the design of missile development workspaces and facilities to ensure comfort and efficiency.
	Are the requirements for physical interfaces defined?	Create a style guide or similar documentation that outlines design principles, standards and conventions for interfaces.
	Is the operator population defined?	Consider the capabilities, characteristics, and numbers of the target users during the specification and design of interfaces.
	Are the requirements for HMI defined?	Develop guidelines for the design of HMI and ensure allocation-of-function analysis supports the design.
	Is there a plan for testing and acceptance by operators?	Implement a process for design validation and verification, including operator testing and feedback.
To assure the reliability of human performance	Is there a risk control plan for hazards?	Develop a safety case that identifies failure modes and demonstrates that hazard control and residual risks are As Low As Reasonably Practicable (ALARP).
	Have all safety-critical tasks been identified?	Conduct HTA or a similar process to identify and define all safety-important tasks and potential human errors.
	Have the opportunities for human error in critical tasks been identified?	Use task analysis and operational experience data to identify and mitigate human error opportunities in critical tasks.
	Has the risk from human error been controlled?	Ensure that the design process includes measures to control risks associated with human error, covering both normal and abnormal operations.
	Have the requirements for a safety culture been defined?	Develop and communicate a clear safety policy, emphasising a commitment to a safety culture within the missile development process.
	Have occupational hazards been identified?	Identify and address potential occupational hazards for personnel involved in missile development, including during testing and deployment phases.

industry or other geographical regions. Another limitation relates to the sample of employees interviewed. Although data triangulation was applied by carefully selecting participants from diverse roles to provide a cross-section of the company's workforce, the sample may still introduce bias and may not capture the full diversity of opinions within the organisation.

A further limitation is the lack of demographic information collected from the interview participants. Although professional titles were reported, details such as age, years of experience, and other demographic factors were not recorded, as agreed with the company, to protect participant anonymity, given the small and specialised defence sector in the region where the study was conducted. This omission restricted the ability to perform a demographic analysis, which could have provided additional insights into how these factors might influence perspectives on HFI. Moreover, only one retired military officer was interviewed in this study. Because of access constraints, it was not feasible to recruit active-duty military personnel at the time of data collection. However, this individual was purposefully selected due to his/her high-level expertise and broad operational experience and was able to provide a high-level overview of military operational challenges in relation to HFI. More granular operational insights from a broader range of military roles could have enriched the findings, offering a more thorough view of HFI implementation from a military perspective.

The reliance on qualitative data introduces interpretive biases. Despite efforts to maintain objectivity, including researcher triangulation through collaborative analysis and peer debriefing, and theory triangulation by applying multiple theoretical lenses to interpret the data (Nowell et al. 2017), qualitative data analysis may vary among researchers, potentially affecting the consistency of the findings (Bryman 2012). The subjective nature of coding and theme identification means that different researchers might interpret the same data differently, leading to variations in the results. In addition, the context-specific nature of the case study may also limit the generalisability of the findings. While the detailed exploration of this particular company provides in-depth insights, it may not fully encompass all the challenges or solutions applicable to other missile development projects or companies operating in different environments (Flyvbjerg 2006).

Several avenues for future research could be explored to enhance further understanding and implementation of HFI in missile development. Future research could broaden the scope by including multiple companies within the missile development sector. This would allow for comparative analysis across different cultural, organisational and regulatory contexts, providing a complete understanding of HFI practices in diverse environments. Moreover, as technology advances rapidly, future research could explore how emerging technologies, such as AI and simulation tools, can be utilised to enhance HFI practices. This could include investigating how these technologies can be integrated into the early stages of the design process to better address HF. In addition, research could also focus on developing more effective tools and methods for integrating HFI into existing missile development processes. This could involve creating new frameworks or adapting existing ones to ensure that HFI is considered at every stage of the development lifecycle.

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Data will be made available on request.

References

Al Rashdi, A. 2019. "HFE Implementation Journey in PDO, Benefits and Challenges." *Abu Dhabi International Petroleum Exhibition & Conference*, D031S067R001. doi:10.2118/197267-MS.

Appelbaum, S. H., S. Habashy, J. Malo, and H. Shafiq. 2012. "Back to the Future: Revisiting Kotter's 1996 Change Model." *Journal of Management Development 31* (8): 764–782. doi:10.1108/02621711211253231.

Berlin, C., L. O. Bligård, M. B. Chafi, and S. Eriksson. 2021. "Development of a Stakeholder Identification and Analysis Method for Human Factors Integration in Work System Design Interventions – Change Agent Infrastructure." *Human Factors and Ergonomics In Manufacturing* 32 (1), 151–170. doi:10.1002/hfm.20910.

Boehm, B. 2004. "Balancing Agility and Discipline: A Guide for the Perplexed." In *Software Engineering Research and Applications*, edited by C. V. Ramamoorthy, R. Lee, and K. W. Lee, Vol. 3026, 1–1 Berlin Heidelberg: Springer. doi:10.1007/978-3-540-24675-6_1.

Booher, H. R. (Ed.). 2003. "Human Systems Integration in Army Systems Acquisition." In *Handbook of Human Systems Integration*. New York, NY: Wiley-Interscience.

Boy, G. A. 2020. *Human–Systems Integration: From Virtual to Tangible* (1st ed.). Boca Raton, FL: CRC Press. doi:10.1201/9780429351686.

Boy, G. A. 2021. "Human Systems Integration and Design." In *Handbook of Human Factors and Ergonomics*, edited by G. Salvendy and W. Karwowski, 1st ed., 38–54. Hoboken, NJ: Wiley. doi:10.1002/9781119636113.ch2.

Boy, G. A. 2023. "An Epistemological Approach to Human Systems Integration." *Technology in Society 74*: 102298. doi:10.1016/j.techsoc.2023.102298.

Bridger, R. 2014. *Human Factors Integration in the Systems Lifecycle.* 3rd South East Asian Network of Ergonomics Societies International Conference. https://www.researchgate.net/publication/269093944_Keynote_Address_Human_Factors_Integration_in_the_Systems_Lifecycle.

Bridger, R. 2014. *Human Factors Integration in the Systems Lifecycle*. 3rd South East Asian Network of Ergonomics Societies International Conference, Singapore.

Bruseberg, A. 2006. "The Design of Complete Systems: Providing Human Factors Guidance for COTS Acquisition." *Reliability Engineering & System Safety 91* (12): 1554–1565. doi:10.1016/j.ress.2006.01.016.

Bruseberg, A. 2008. "Presenting the Value of Human Factors Integration: Guidance, Arguments and Evidence." *Cognition, Technology & Work 10* (3): 181–189. doi:10.1007/s10111-007-0100-1.

Bryman, A. 2012. *Social Research Methods* (4th ed.). New York, NY: Oxford Univ. Press.

Burgess-Limerick, R., C. Cotea, and E. Pietrzak. 2010. *Human Systems Integration is worth the money and effort! The argument for the implementation of Human Systems Integration processes in Defence capability acquisition*, 1–163. http://burgess-limerick.com/download/d11.pdf.

Burgess-Limerick, R., C. Cotea, E. Pietrzak, and P. Fleming. 2011. "Human Systems Integration in Defence and Civilian Industries." *Australian Defence Force Journal 186*: 51–65.

Carter, N., D. Bryant-Lukosius, A. DiCenso, J. Blythe, and A. J. Neville. 2014. "The Use of Triangulation in Qualitative Research." *Oncology Nursing Forum 41* (5): 545–547. doi:10.1188/14.ONF.545-547.

Chatzimichailidou, M., T. Whitcher, and N. Suzic. 2024. "Complementarity and Compatibility of Systems Integration and Building Information Management." *IEEE Systems Journal 18* (2): 1198–1207. doi:10.1109/JSYST.2024.3387064.

Chiesi, S. S. 2016. "STPA Application for Safety Assessment of Generic Missile Systems." *2016 Annual Reliability and*

Maintainability Symposium (RAMS), 1–7. doi:10.1109/rams.2016.7447975.

Chung, A. Z. Q., and A. Williamson. 2018. "Theory Versus Practice in the Human Factors and Ergonomics Discipline: Trends in Journal Publications from 1960 to 2010." *Applied Ergonomics 66*: 41–51. doi:10.1016/j.apergo.2017.07.003.

Corbridge, C., M. Anthony, D. McNeish, and G. Shaw. 2016. "A New UK Defence Standard for Human Factors Integration (HFI)." *Proceedings of the Human Factors and Ergonomics Society*, 1734–1738. doi:10.1177/1541931213601398.

Creswell, J. W., and C. N. Poth. 2018. *Qualitative Inquiry & Research Design: Choosing Among Five Approaches* (4th ed.). Thousand Oaks, CA: SAGE.

Cullen, L. 2007. "Human Factors Integration – Bridging the Gap Between System Designers and End-Users: A Case Study." *Safety Science 45* (5): 621–629. doi:10.1016/j.ssci.2007.01.002.

Dul, J., R. Bruder, P. Buckle, P. Carayon, P. Falzon, W. S. Marras, J. R. Wilson, and B. Van Der Doelen. 2012. "A Strategy for Human Factors/Ergonomics: Developing the Discipline and Profession." *Ergonomics 55* (4): 377–395. doi:10.1080/00140139.2012.661087.

Dul, J., and W. P. Neumann. 2009. "Ergonomics Contributions to Company Strategies." *Applied Ergonomics 40* (4): 745–752. doi:10.1016/j.apergo.2008.07.001.

Fletcher, S., E. McKinley, K. C. Buchan, N. Smith, and K. McHugh. 2013. "Effective Practice in Marine Spatial Planning: A Participatory Evaluation of Experience in Southern England." *Marine Policy 39*: 341–348. doi:10.1016/j.marpol.2012.09.003.

Flyvbjerg, B. 2006. "Five Misunderstandings About Case-Study Research." *Qualitative Inquiry 12* (2): 219–245. doi:10.1177/1077800405284363.

Gao, M., Y. Lin, Z.-W. Deng, C. Li, and X.-Q. Lv. 2019. "Failure Mode Analysis of Terminal Guidance Projectile." *2019 International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering (QR2MSE)*, 51–56. doi:10.1109/qr2mse46217.2019.9021255.

Giacomin, J. 2014. "What Is Human Centred Design?" *The Design Journal 17* (4): 606–623. doi:10.2752/175630614X14056185480186.

Greig, M. A., J. Village, S. M. Dixon, F. A. Salustri, and W. P. Neumann. 2019. "Assessing Human Factors and Ergonomics Capability in Organisations–the Human Factors Integration Toolset." *Ergonomics 62* (10): 1254–1272. doi:10.1080/00140139.2019.1572228.

Guest, G., A. Bunce, and L. Johnson. 2006. "How Many Interviews Are Enough? An Experiment with Data Saturation and Variability." *Field Methods 18* (1): 59–82. doi:10.1177/1525822X05279903.

Hamilton, W. I., M. L. N. Kazem, X. He, and D. Dumolo. 2013. "Practical Human Factors Integration in the Nuclear Industry." *Cognition, Technology & Work 15* (1): 5–12. doi:10.1007/s10111-012-0213-z.

Harris, D. 2008. "Human Factors Integration in Defence: Preface." *Cognition, Technology & Work 10* (3): 169–172. doi:10.1007/s10111-007-0096-6.

Heck, T. B. 2007. *Pilot Vehicle Interface Improvements to the F/A-18 Weapon System (Using Human Factors Solutions to Increase Efficiency)* [The University of Tennessee]. https://trace.tennessee.edu/cgi/viewcontent.cgi?article=1321&context=utk_gradthes.

Hennink, M., and B. N. Kaiser. 2022. "Sample Sizes for Saturation in Qualitative Research: A Systematic Review of Empirical Tests." *Social Science & Medicine 292*: 114523. doi:10.1016/j.socscimed.2021.114523.

INCOSE 2023. *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities* (5th ed.). Hoboken, NJ: Wiley.

INCOSE, IEEE Systems Council, & Stevens Institute of Technology. 2024. *Human Systems Integration-SEBoK*. https://sebokwiki.org/wiki/Human_Systems_Integration.

International Organization for Standardization. 2019. *ISO 9241-210:2019: Ergonomics of Human-System Interaction – Part 210: Human-centred design for Interactive Systems*. https://www.iso.org/standard/77520.html.

Kotter, J. P. 1996. *Leading Change*. Boston, MA: Harvard Business School Press.

Landsburg, A. C., LARRY. Avery, R.. Beaton, J. R. Bost, C. Comperatore, R. Khandpur, T. B. Malone, C. Parker, S. Popkin, and T. B. Sheridan. 2008. "The Art of Successfully Applying Human Systems Integration." *Naval Engineers Journal* 120 (1): 77–107. doi: 10.1111/j.1559-3584.2008.00113.x.

Leahy, D., and C. Vance. 2019. "Integrated Use of 3D Modelling Tools and Virtual Reality to Facilitate Design." *Conference Proceedings of MECSS*. 2019: 1–11. doi:10.24868/issn.2515-8198.2019.007.

Leveson, N. 2004. "A New Accident Model for Engineering Safer Systems." *Safety Science 42* (4): 237–270. doi:10.1016/S0925-7535(03)00047-X.

Liu, K. K., R. Valerdi, D. H. Rhodes, L. Kimm, and A. Headen. 2010. *The F119 Engine: A Success Story of Human Systems Integration in Acquisition*. https://apps.dtic.mil/sti/pdfs/ADA518530.pdf.

Liu, K., R. Valerdi, and D. Rhodes. 2009, April. "*Economics of Human Systems Integration: A Systems Engineering Perspective*." 7th Annual Conference on Systems Engineering Research (CSER 2009). https://www.researchgate.net/publication/228646777_Economics_of_human_systems_integration_A_systems_engineering_perspective.

Maguire, M. 2001. "Methods to Support Human-Centred Design." *International Journal of Human-Computer Studies 55* (4): 587–634. doi:10.1006/ijhc.2001.0503.

Miles, G., and S. Hignett. 2018. "Can the NHS Learn about Human Factors from the Ministry of Defence? Contemporary Ergonomics & Human Factors." *Proceedings of the Annual Conference of the Chartered Institute of Ergonomics & Human Factors*. https://publications.ergonomics.org.uk/uploads/Can-the-NHS-learn-about-human-factors-from-the-Ministry-of-Defence.pdf.

Mucha, J., A. Kaufmann, and D. Riehle. 2024. "A Systematic Literature Review of Pre-Requirements Specification Traceability." *Requirements Engineering* 29 (2): 119–141. doi: 10.1007/s00766-023-00412-z.

Muhammad, A. P., A. Knauss, E. Knauss, and J. Bärgmann. 2024. "Requirements Strategy for Managing Human Factors in Automated Vehicle Development." *2024 IEEE 32nd International Requirements Engineering Conference (RE)*, 180–192. doi:10.1109/RE59067.2024.00026.

Narkevicius, J. M. 2008. "Human Factors and Systems Engineering – Integrating for Successful Systems Development." *Proceedings of the Human Factors and Ergonomics Society Annual Meeting 52* (24): 1961–1963. doi:10.1177/154193120805202409.

Norman, D. A. 2013. *The Design of Everyday Things*. Cambridge, MA: The MIT Press.

Novitske, Z.A., 2019. *Measuring Human Systems Integration in Directed Energy Weapon Acquisition Programs (No. AFITENSMS19M142).*

Nowell, L. S., J. M. Norris, D. E. White, and N. J. Moules. 2017. "Thematic Analysis: Striving to Meet the Trustworthiness Criteria." *International Journal of Qualitative Methods 16* (1): 1609406917733847. doi:10.1177/1609406917733847.

O'Neil, M. P., L. G. Shattuck, and L. W. Sciarini. 2015. "A Framework for Assessing and Communicating Human Systems Integration Efficacy Across the System Lifecycle." *Procedia Manufacturing 3*: 3054–3061. doi:10.1016/j.promfg.2015.07.851.

Pavate, V., M. Patil, S. Dharmadhikari, G. Dalavi, S. Sawant, and V. Powar. 2024. "A Study on Factors Affecting Time, Cost and Quality in Construction Project…." *International Journal for Research in Applied Science and Engineering Technology 12* (4): 2627–2635. doi:10.22214/ijraset.2024.60295.

Puig-Poch, M., J. Galán Serrano, and F. Felip-Miralles. 2025. "Development of a Methodological Framework for the Integration of Human Factors Throughout the Design Engineering Project." *Theoretical Issues in Ergonomics Science 26* (2): 178–196. doi:10.1080/1463922X.2024.2391311.

Rajabalinejad, M., Leo van Dongen, and M. Ramtahalsing. 2020. "Systems Integration Theory and Fundamentals." *Safety and Reliability 39* (1): 83–113. doi:10.1080/09617353.2020.1712918.

Rantanen, E., D. A. Wiegmann, B. O. Palmer, and K. M. Musiorski. 2003. "A Human Factors Database for Matching Human Errors and Technological Interventions." *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *47*, 782–786. doi:10.1177/154193120304700426.

Reason, J. 2016. *Managing the Risks of Organizational Accidents* (1st ed.). London, UK: Routledge. doi:10.4324/9781315543543.

Rountree, I., and L. D. Thomas. 2021. "Expanding Mbse to Incorporate Human Systems Integration Modelling." *AIAA Scitech 2021 Forum*, 1–8. doi:10.2514/6.2021-0096.

Salas, E., S. I. Tannenbaum, K. Kraiger, and K. A. Smith-Jentsch. 2012. "The Science of Training and Development in Organizations: What Matters in Practice." *Psychological Science in the Public Interest: a Journal of the American Psychological Society 13* (2): 74–101. doi:10.1177/1529100612436661.

Schein, E. H. (Ed.). 2010. *Organizational Culture and Leadership* (4th ed). San Fransisco, CA: Jossey-Bass.

Schneider, B., A. P. Brief, and R. A. Guzzo. 1996. "Creating a Climate and Culture for Sustainable Organizational Change." *Organizational Dynamics 24* (4): 7–19. doi:10.1016/S0090-2616(96)90010-8.

Sharples, R. A. 2015. "Implementation of Human System Integration (HSI) and 'Non-Functional Characteristics' into the Systems Engineering Lifecycle – A Practical Approach at Airbus Defence and Space." *Procedia Manufacturing 3*: 1896–1902. doi:10.1016/j.promfg.2015.07.232.

Sharples, R. A. 2016. "Implementation of Human System Integration into the System Engineering Lifecycle and Model Based System Engineering at Airbus Defence and Space." *Advances in Intelligent Systems and Computing 492*: 67–75. doi:10.1007/978-3-319-41935-0_7.

Sherman, B. W., E. Stiehl, R. Gupta, and P. L. Pratap. 2024. "The Importance of Human-Centered Design in Equitable Health Promotion Initiatives." *American Journal of Health Promotion: AJHP 38* (3): 443–447. doi:10.1177/08901171241232057f.

Shorrock, S. T., & Williams, C. (Eds.)2017. "Introduction: Human Factors and Ergonomics in Practice." *In Human Factors and Ergonomics in Practice: Improving System Performance and Human Well-Being in the Real World*. Boca Raton, FL: CRC Press Taylor & Francis Group.

Sprehn, K, Gretchen, and Hechinger, M. 2022. "Human Factors in the Systems Engineering Jungle." *Proceedings of the Human Factors and Ergonomics Society Annual Meeting 66* (1): 1790–1794. doi:10.1177/1071181322661029.

St. John, F. A. V., A. M. Keane, J. P. G. Jones, and E. J. Milner-Gulland. 2014. "Robust Study Design is as Important on the Social as It is on the Ecological Side of Applied Ecological Research." *Journal of Applied Ecology 51* (6): 1479–1485. doi:10.1111/1365-2664.12352.

Stanton, N. A., C. Harvey, and C. K. Allison. 2019. "Systems Theoretic Accident Model and Process (STAMP) Applied to a Royal Navy Hawk Jet Missile Simulation Exercise." *Safety Science 113*: 461–471. doi:10.1016/j.ssci.2018.12.020.

Stanton, N. A., P. M. Salmon, L. A. Rafferty, G. H. Walker, C. Baber, and D. P. Jenkins. 2017. *Human Factors Methods: A Practical Guide for Engineering and Design* (1st ed.). London, UK: CRC Press. doi:10.1201/9781315587394.

Sterman, J. D. 2006. "Learning from Evidence in a Complex World." *American Journal of Public Health 96* (3): 505–514. doi:10.2105/AJPH.2005.066043.

Taherdoost, H. 2022. "How to Conduct an Effective Interview; a Guide to Interview Design in Research Study Authors." *International Journal of Academic Research in Management (IJARM) 1* (11): 39–51.

UK Ministry of Defence. 2022. *Human Factors Integration in defence systems (JSP 912)*. https://www.gov.uk/government/publications/human-factors-integration-in-defence-systems-jsp-912.

UK Ministry of Defence. 2023. *Defence Safety Management System (JSP 815 Volume 2)*. https://www.gov.uk/government/publications/defence-safety-management-system-jsp-815-volume-2.

US Air Force. 2009. *Air Force Human Systems Integration Handbook*. https://www.acqnotes.com/Attachments/Air%20Force%20Human%20System%20Integration%20Handbook.pdf.

Vicente, K. J. 2013. *The Human Factor: Revolutionizing the Way People Live with Technology* (1st ed.). Abingdon, UK: Routledge. doi:10.4324/9780203944479.

Walker, G. H., H. Gibson, N. A. Stanton, C. Baber, P. Salmon, and D. Green. 2006. "Event Analysis of Systemic Teamwork (EAST): A Novel Integration of Ergonomics Methods to Analyse C4i Activity." *Ergonomics 49* (12-13): 1345–1369. doi:10.1080/00140130600612846.

Walker, G. H., N. A. Stanton, P. M. Salmon, and D. P. Jenkins. 2008. "A Review of Sociotechnical Systems Theory: A Classic Concept for New Command and Control Paradigms." *Theoretical Issues in Ergonomics Science 9* (6): 479–499. doi:10.1080/14639220701635470.

Walker, G., N. Stanton, P. Salmon, and D. Jenkins. 2009. "From Clansman to Bowman: HFI Principles for NEC System Design." *International C2 Journal 3* (2): 1–33.

Wong, L. 2008. "Data Analysis in Qualitative Research: A Brief Guide to Using Nvivo." *Malaysian Family Physician: The Official Journal of the Academy of Family Physicians of Malaysia 3* (1): 14–20.

Yin, R. K. 2015. "Case Study Research Design and Methods." *Canadian Journal of Program Evaluation 30* (1): 108–110. doi:10.3138/cjpe.30.1.108.

Human factors integration in complex systems: awareness, challenges and strategies

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