Burgess-Limerick, R., Cotea, C., Pietrzak, E., & Fleming, P. (2011). Human Systems Integration in Defence and Civilian Industries. *Australian Defence Force Journal, 186,* 51-60

Human Systems Integration in Defence and Civilian Industries

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Introduction

‘Human systems integration’ (HSI) is defined as the process of integrating the domains of human factors engineering, system safety, training, personnel, manpower (crewing), health hazards and survivability into each stage of the defence systems capability life cycle (needs, requirements, acquisition, service and disposal)[1] where:

- ‘Human factors engineering’ (HFE) is defined as the systematic application of information about human capabilities, limitations, characteristics, behaviour and motivation to the design of equipment, facilities, systems and environments,
- ‘Systems safety’ is the process of minimising safety and health risks through identifying, assessing and controlling hazards associated with the system,
- ‘Manpower’ (crewing) refers to the number of persons required to operate, maintain, sustain and provide training for systems,
- ‘Personnel’ refers to the aptitudes, experience and other personal characteristics required,
- ‘Training’ refers to the instruction and training required to fulfil the person’s role in the system,
- ‘Health hazards’ refer to conditions inherent in operation and use of a system that may cause death, injury, illness, disability or reduce the performance of personnel, and
- ‘Survivability’ refers to the characteristics of a system in order to reduce fratricide, the probability of being attacked and war fighter injury.

The aim of this article is to describe current strategies for implementing HSI employed by defence and civilian industries, and the evidence which exists for the benefits arising from such implementation.

Defence implementation

The US Department of Defense (US DoD) and UK Ministry of Defence (UK MoD) have formal HSI policies in place for major systems acquisition, and the Canadian Department of National Defence is in the process of establishing such a program.[2] While the details vary, the general procedure is to place responsibility on the program manager to ensure that implementation of HSI occurs during equipment acquisition. For example, US DoD instruction 5000.02 includes an enclosure which requires the program manager:

> ... to have a plan for HSI in place early in the acquisition process to optimize total system performance, minimize total ownership costs, and ensure that the system is built to accommodate the characteristics of the user population that will operate, maintain, and support the system.[3]

The US DoD's 'Human Systems Integration Management Plan'[4] sets out a plan for HSI management within the DOD, and describes formal responsibilities, authorities and accountabilities. The plan encompasses the organisational structures, roles, responsibilities, processes, tasks, metrics and enabling resources provided for the implementation of HSI. A range of guidance material is provided, including a comprehensive on-line 'Defense Acquisition Handbook', Chapter 6 of which 'provides the program manager with the necessary background and understanding to design and develop systems that effectively and affordably integrate with human capabilities and limitations'.[5]

The US DoD's 'Manpower and Personnel Integration' publication[6] defines a process for the implementation of the US Army's longstanding program that aims to ensure that human considerations are integrated into the system acquisition process.[7] This is achieved by ensuring that personnel are fully and continuously considered as part of the total system in the development and/or requisition of all systems. Human performance is considered to be a key factor in 'total system performance' and it is recognised that enhancements to human performance will correlate directly to enhanced total system performance and reduced life cycle costs.[8]

Similarly, the US Air Force's 'Air Force Human Systems Integration Handbook'[9] provides a description of its HSI process and identifies key considerations for the development of HSI plans and implementation of HSI programs. The US Navy undertakes a 'System Engineering, Acquisition and PeRsonnel INTegration' (SEAPRINT) program[10] which aims to insert HSI throughout the systems engineering process. Wallace *et al*11 and Landsburg *et al*[12] provide further commentary on the importance of the implementation of HSI within the US Navy.

The UK MoD refers to 'human factors integration' (HFI), rather than HSI, however the intent is similar. The formal requirements are set out in a series of Defence Standards 'Human Factors for Designers of Systems', Part 4 of which provides information about a large array of HFI methods, tools and techniques.[13] Additional guidance is also available in an 'HFI Technical Guide', provided by the UK MoD's Sea Systems Group.[14] Detailed guidance for high speed craft has also been sponsored by the Directorate of Sea Systems.[15]

The UK Human Factors Integration Defence Technology Centre (HFIDTC) is a virtual centre of excellence, funded by the MoD, which undertakes research to develop and evaluate processes methods and tools.[16] Reviews of a wide range of human factors design and evaluation methods[17,18] are provided, as well as a series of advisory documents, including 'The People in Systems TLCM Handbook'[19] which deals with the consideration of the human element during through life capability management. A 2006 HFIDTC document provides 'cost arguments and evidence for human factors integration',[20] while a more recent article[21] provides detailed guidance regarding the methods to be employed to make the cost case for HFI projects or programs.

Civilian implementation

A range of civilian agencies, including NASA, the US Federal Aviation Administration (FAA) and the European Organisation for the Safety of Air Navigation,[22, 23] include HSI within equipment procurement policies and provide a range of guidance material. For example, section 4.7 of the FAA's 'Acquisition Management System Policy' stipulates that:

> Human factors are a *critical* [as italicised in the original] aspect of aviation safety and effectiveness. Service organizations must assure that planning, analysis, development,

> implementation, and in-service activities for equipment, software, facilities, and services include human factors engineering to ensure performance requirements and objectives are consistent with human capabilities and limitations. Human factors engineering should be integrated with the systems engineering and development effort throughout the lifecycle management process, starting with concept and requirements definition and continuing through solution implementation and in-service management.[24]

The FAA also provides a ‘Human Factors Acquisition Job Aid’[25] and ‘Human Factors Design Standard’[26] to assist this process.

Similarly, NASA’s procedural requirements include ‘Human-Rating Requirements for Space Systems’,[27] which explicitly mandates the application of HFE throughout the development lifecycle[28] and refers to NASA-STD-3001, Volume 1 (Crew Health),[29] the ‘Human Integration Design Handbook’,[30] which provides guidance for the crew health, habitability, environment and HFE design of all NASA human space flight programs and projects, as well as NASA-STD-3001.[31] The European Organisation for the Safety of Air Navigation provides extensive guidance material via its ‘Human Factors Integration in Future ATM Systems’ website (see: <http://www.eurocontrol.int/hifa/>).

HSI methods and tools

Regardless of the domain of application, a similar set of tools and methods are utilised. Particular emphasis is placed on methods, such as scenario-based requirements capture,[32,33] and HSI top-down requirements analysis,[34-36] which are applicable early in the design process. Similarly, Rhodes *et al*[37] describe the extension of systems engineering leading indicators to HSI as a means of enhancing the consideration of HSI early in the design process. Newman *et al*[38] describe management tools developed by the HFIDTC, including the ‘desktop support tool’ and ‘human factors impact tracking tool’.

Modelling and simulation techniques are commonly employed throughout the defence equipment lifecycle.[39,40] ‘The Human View Handbook for MoDAF’[41] describes how ‘human views’ are employed in a systems engineering modelling approach to communicate human-related design concerns to engineers, with the aim of enabling early application of HSI methods in the cognitive systems engineering process.[42,43]

Adelstein *et al*[44] emphasise the use of ‘preliminary hazard analysis’ to identify potential human errors early in the design process. The use of ‘fault tree analysis’ (a top-down approach) in conjunction with ‘human factors process failure modes and effects analysis’ (a bottom-up approach) is suggested. Other methods and tools commonly utilised include:

- Task analysis techniques,[45]
- Cognitive task analysis techniques (for example, critical decision methods),
- Field observations and ethnography,
- Participatory analysis,
- Charting techniques,
- Human error identification techniques (for example, systematic human error reduction and prediction approach),
- Situation awareness measurement techniques (for example, situation awareness global assessment technique),

- Mental workload assessment techniques (for example, NASA's task load index),
- Team performance analysis techniques,
- Interface analysis techniques (for example, link analysis),
- Performance time assessment techniques,[18-46] and
- Physical ergonomics techniques.[47]

Recent publications have focused in particular on the assessment of team performance.[45,48-50]

Evidence of HSI benefits

Evidence regarding the effectiveness, efficiency, productivity and safety of HSI is widely available. The case studies below were identified in the literature and describe successful implementation of HSI, or the undesired consequences of failing to implement HSI in either military or civilian domains. While cost-benefit has been of interest[51], and techniques for estimating the health costs associated with Army materiel have existed for some time,[52] detailed guidance for assessing cost-benefit associated with HSI has only been provided relatively recently[21,42,53,54]—and relatively few detailed cost-benefit case studies are available in the public literature.

Defence case studies

The most widely-cited example, and one of the most detailed available, is the Comanche helicopter acquisition program. Booher[51] and Booher & Minninger[55] cite a 1995 report by Minninger (which unfortunately is not readily accessible) as demonstrating that the implementation of HSI within the acquisition program for a design investment of 4 per cent of the research and development budget (or US$75m) resulted in cost avoidance of US$3.29bn, a 44:1 return on investment (ROI)—in addition to avoiding 91 fatalities and 116 disabling injuries over 20 years. Other examples reported in some detail by Booher & Minninger[55] include critical design improvements to the Apache Longbow helicopter, where costs savings of US$269m were attributed to an HSI investment of US$12m (22:1 ROI), and the Fox M93A1 nuclear, biological and chemical reconnaissance system reconnaissance vehicle, where a 33:1 ROI was calculated.

The US Air Force's 'Human Systems Integration Handbook'[56] suggests that HSI typically comprises 2.0-4.2 per cent of the total system acquisition cost and leads to a ROI of between 40-60 times the investment. The handbook cites an evaluation of the implementation of HSI within a fighter jet program as leading to lifecycle cost savings in maintenance, manpower and support in excess of US$4bn.

Defence Research and Development Canada applied an HSI program to a range of acquisition projects[57] and estimated the resulting cost-benefit. C$3.3m was invested in HSI application across eight case studies, resulting in C$3.5m in immediate savings, that is, an immediate cost benefit of 106 per cent. An extrapolated savings for one system of C$131m resulted from reduced manning levels, while C$2m was assessed as the consequence of the elimination of an unnecessary display on a shipboard system. The report also includes an instructive summary of 'lessons learned', which concluded that:

> Simulation-based, iterative design and experimentation cycles can effectively address a range of HSI variables. Military operators are able to effectively extrapolate their experiences in

> medium fidelity virtual simulation environments to provide structured feedback on task performance, workload, situational awareness, useability, training, system safety, health hazard and personnel impacts of future system designs. Objective measures used in virtual simulation-based experimentation can provide data sets on task performance, workload, usability and learning time.[57]

The largest demonstrated savings in the Canadian program resulted from reduced manning, and this is a common theme across US Navy case studies. For example:

- Anderson *et al*[58] described an application of decision-aiding techniques which allowed the reduction in aircraft carrier manning levels by 11 per cent, while at the same time reducing the time taken for aircraft launch and recovery by 20 per cent.
- Anderson *et al*[59] suggest that implementing HSI achieved reduced manning, while retaining or improving system operability and effectiveness. The DD21 destroyer program manning levels versus the previous DDG79 were noted to be a reduction of 144 sailors (from 188 to 44)—an annual cost avoidance of US$9.4m and, assuming 40 ships and 30 years life, a total saving of US$11.3bn.
- Militello *et al*[60] reviewed a number of optimised manning case studies, including the first ship to be outfitted as a 'smart' ship, the USS *Yorktown*, and documented the methods used to achieve reduced manning and reduced workloads, and improved quality of life for the remaining personnel. Spindel *et al*[61] similarly cited the 'smart ship' program as demonstrating that technology and process improvements can reduce manning, maintain capability and improve shipboard quality of life.
- Johnson *et al*[34] describe in some detail the execution of a top-down requirements analysis which suggested that a 25 per cent reduction in manning of landing helicopter dock (LHD) amphibious-assault-class ships can be achieved using mature or relatively mature technologies and no major redesign, leading to life cycle savings of US$1bn per ship, with 35 per cent manning reductions being a realistic goal for the future.
- Malone *et al*[35] reported that the use of top-down requirements analysis reduced the manning requirements for the 'Fast Sealift' from 47 to 12, and described a similar process for the JCC(X) (Joint Command and Control) ship. The results suggested that a 30 per cent reduction in workload was possible through the introduction of technology and expanded use of automation.
- A US General Accounting Office investigation[62] estimated that an emphasis on HSI early in the DD(X) destroyer program reduced personnel by 70 per cent, leading to US$18bn in savings over the life of the 32-ship class. The report recommendations included that the Secretary of the Navy:
  - 'requires that ship programs use human systems integration to establish crew sizes and help achieve them,
  - clearly defines the human systems integration certification standards for new ships, and
  - formally establishes a policy evaluation function to examine and facilitate the adoption of cost-saving technologies and best practices across Navy systems'.
- An example from the French Navy[63] describes the use of the *Illustrateur de Besoin d'Exploitation Operationnelle* process and simulation tools to specify and assess work

organisation, automation, human computer interaction modes and training needs for future naval platforms featuring reduced manning levels. The process features the iterative use of full-scale models running realistic operational scenarios with current and future operators.

- The need to reduce naval crewing levels was also the impetus for a report to the Canadian Defence Force[64], which catalogued techniques for achieving such reductions and concluded that the Canadian Navy should develop its own capability to evaluate workload and crewing reduction technologies. Reducing naval costs and, in particular, the costs of a 'Future Aircraft Carrier Programme', was the subject of a report to the UK MoD.[65] The report reviewed complement reduction options employed internationally, and identified six particularly promising options, all of which were dependent on HSI implementation for success.
- Cost reductions from effective HSI have also been demonstrated by the US Air Force. Lizza *et al*[66] cite a 2007 DoD review as finding that a US$2m analysis of manpower, personnel and training associated with the F-22 Raptor resulted in an estimated US$700m in lifetime cost avoidance, and subsequent manpower implementation was credited with approximately US$3bn in lifecycle savings. HSI evaluations during the C-12 Huron acquisition process were also cited as leading to the automation of tasks previously requiring a flight engineer, with a consequent reduction in crew complement and lifecycle cost savings greater than US$3bn.
- Human factors issues associated with remotely-piloted vehicles, or unmanned vehicles, have been the subject of considerable attention.[67,68] Tvaryanas *et al*[69] highlighted human factor causes of US military unmanned aerial vehicle (UAV) mishaps and concluded that attending to HSI is critical for the design of such equipment.[70] Questions addressed by these analyses include the operator training needs, workload issues and the role of automation. Hunn and Heuckeroth[71], in particular, provide a detailed description of the use of an 'Improved Performance Research Integration Tool' (IMPRINT) model to assess operator workload levels associated with the Shadow UAV.

Other publications describe success in achieving improvements in military equipment design at a more restricted level. For example:

- Improved maintainability of the F119 engine (F22 Raptor) is described by *Liu et al*[72,73] as a consequence of implementing HSI. Only five hand tools are required to service the engine; all line replaceable units are designed to be serviceable without replacing any other; each unit is replaceable using a single tool within 20 minutes; and maintenance is possible while wearing hazardous environment protection clothing. Importantly, the extensive commitment by the manufacturer to improving maintainability was a direct consequence of the emphasis placed on this issue by the US Air Force during the acquisition process, and was central to the manufacturer's competitive strategy.
- Hamburger[74] describes the use of a bridge design mock up to identify design deficiencies in the DDG-1000 program, suggesting that a US$20k investment achieved cost avoidance of US$10m.
- Hendrick[75] claimed that US$500k in human factors efforts saved more than US$5m for the USAF C-141 Starlifter aircraft.

- Osga[76] describes a multi-modal watch station project and highlights the improved performance demonstrated over the legacy Aegis integrated naval weapons system.
- Runnerstrom[77] describes an example of effective HSI for shipboard damage control. Tests in an environment, replicating the effects of an anti-ship missile hit, demonstrated that effective damage control was possible in the redesigned systems with 60 per cent fewer personnel.
- Dobbins *et al*[78] provide a series of case studies of the implementation of HFI within the design of high speed craft with defence purposes. The examples provided demonstrate improved performance, reduced manning, improved maintainability, and increased occupant comfort and safety benefits.
- Folds *et al*[79] cite 'astonishing' improvements in engine change time for a high mobility multi-purpose wheeled vehicle arising from an HSI approach.

Civilian case studies

Relatively few examples of well-documented case studies of HSI implementation exist in the civilian area. Examples which are available include:

- NASA authors[28,80] refer to successful HSI implementation in civilian aerospace, including references to historical successes of HFE in the Apollo program, as well as more recent examples such as the Constellation program's Crew Exploration Vehicle, Lunar Lander and extra-vehicular systems.
- HSI implementations in oil and gas industry are described by a number of authors,[81-83] claiming improvements in safety as a result.
- Kirwan[84] describes the implementation of a human factors program for a new nuclear power plant which identified important safety issues.
- Hastings *et al*[85] describe the implementation of an organisational change to the work of FAA safety inspectors, which allowed inspectors to log their work using portable computers. An evaluation found that better usability was accompanied by a 19 per cent time saving.
- Becker[86] describes the design of a complex intensive care workstation through use-cases and a set of safety goals.
- Heape and Low[87] describe HFI in the design of signal and train control systems for the Victoria line upgrade of the London Metro rail network.

Sub-optimal outcomes

Another avenue for assessing the value of HSI implementation is to examine situations in which HSI was insufficient. For example, a 2006 HFIDTC document titled 'Cost Arguments and Evidence for Human Factors Integration'[20] lists MoD acquisition failures resulting from poor HSI as including the Bowman man-portable radio; RB44 light vehicles; SA-80 Rifle and Light Support Weapon; and the single role mine hunter's recovery of remote control mine disposal system.

Other examples referred to in the literature include:

- Deficiencies of human factors, manpower, personnel and training were identified during the 'reverse engineering' of the Black Hawk helicopter acquisition program.[88]
- Many HSI problems discovered during testing and development of the US Army's Aquila remotely-piloted vehicle led to the cancellation of the program.[89]
- A premature decision regarding manning levels constraints for the Oliver Hazard Perry class guided missile frigate (FFG-7 class) led to expensive redesign of accommodation, and difficulties manning the vessels upon completion.[90]
- Patriot air and missile defence units were involved in two incidents occurring during Operation IRAQI FREEDOM (18 per cent of engagements), in which fatalities of allied forces resulted. Hawley[91] examined the HSI lessons to be learned from this unacceptable fratricide rate, concluding that the causes of operator errors can be traced to decisions made by designers and others responsible for the development of the system over 25 years. The dominant mode of control changed from manual to supervisory control as increasing levels of automation were added. However, the operators' role change was not reflected in design and evaluation, or training practices.
- MIL-HDBK-46855A[92] provides details of several catastrophic events caused by failure to consider human capabilities, including the downing of Korean Air Lines flight 007, which strayed into Soviet air space; the Three Mile Island nuclear accident; the downing of Iran Air flight 655 by the USS *Vincennes*; the Bhopal release of methyl isocynate; the 1972 crash of a Lockheed L-1011 in the Florida everglades; and additional lessons learned from more minor incidents.
- Hobbs *et al*[93] cite the fatal decompression of Salyut 11 as an example of a failure to consider human capabilities in design.
- Tvaryanas *et al*[69] highlighted human factor causes of US military UAV mishaps and concluded that attending to HSI is critical for the design of such equipment.
- Cockshell & Hanna[94] nominate two ADF examples of sub-optimal HSI, noting that:
  - the operations room of the ANZAC class frigates required redesign to correct deficiencies which resulted in poor situation awareness for the command team, space restrictions, excessive reach distances and visibility issues; and
  - Seasprite helicopter cockpit design issues, with detrimental operational consequences, cost an estimated A$100-200m to rectify.
- An insufficient focus on 'the incorporation of OHS concerns into engineering design' was also identified as a factor which contributed to the chemical exposure of Air Force maintenance workers during F-111 fuel tank maintenance, leading to recommendations by the Board of Inquiry that 'occupational health and safety should be integrated into the engineering change management process. This means, in particular, that designs should undergo a risk management process' and that 'the Air Force should review its acquisition policies to ensure that suppliers have systematically identified the hazards posed to personnel who use or maintain the equipment and, as far as possible, designed out these hazards'.[95]

Summary and conclusions

Formal HSI implementation programs have been established within the US DoD, and more recently in the UK MoD, as well as civilian agencies such as NASA, the FAA and the European Organisation for the Safety of Air Navigation. Program managers within these agencies are required to develop and implement an HSI plan. Program managers require support to develop and implement HSI plans, and extensive direction, guidance and advisory documentation is provided by these agencies and others, such as the UK's HFIDTC. An extensive range of tools and techniques have been developed for use within HSI activities.

Quantification of safety benefits arising from HSI is problematic because of the relatively low baseline incident rates and is generally not attempted. An exception is the evaluation of the Comanche helicopter acquisition program which estimated the HSI implementation as avoiding 91 fatalities and 116 disabling injuries over 20 years. Claims for safety improvements arising from the implementation of HSI in civilian oil and gas, and nuclear industries have also been made. The number of fatalities, injuries and illnesses which have been attributed to sub-optimal HSI also lends weight to the potential for effective HSI implementation to prevent fatalities, injuries and illnesses. The evidence sustains a conclusion that effective implementation of HSI will reduce the probability of adverse safety and health outcomes.

Productivity, effectiveness and efficiency have been assessed in a variety of ways. Examples of improved ability to undertake mission critical tasks resulting from HSI have been provided, while improved platform availability will result from improved engine maintainability. Increased efficiency through decision aiding and increased automation leading to reduced workload and manning has been well documented, and HSI is essential for the successful introduction of automation. Numerous sub-optimal effectiveness outcomes have also been attributed to insufficient HSI. Implementing HSI will improve productivity, effectiveness and efficiency; as a corollary, these actions will reduce the probability of acquisition program failure. Assessments of cost-benefit of HSI of varying complexity have been conducted with generally positive results. The largest cost benefits calculated have been associated with reductions in manning levels.

Considerable direction, guidance and advisory material is available to assist in the implementation of HSI, and this literature includes guidance in the evaluation of cost-benefit and cost-effectiveness. The assessments are not straight forward, however, because investments occur over time, returns are uncertain and may be indirect and/or intangible. Even tangible outcomes, such as reduced injury rates, are difficult to translate to economic gain. Rouse & Boff[53] describe a seven-step method utilising a multi-attribute utility model, and provide three examples of the application of this technique to assess performance improvements resulting from HSI in military systems. More recently, the UK's HFIDTC[21] has provided a 'practical guide' for cost-benefit analysis which describes a six-step process (establish objectives; identify and quantify project risks; specify HFI influence; quantify required HFI effort; specify options; choose preferred option).

Relatively few detailed case studies of the consequences of HSI implementation during equipment acquisition are available in the public literature. However, on the basis of the evidence cited above, a conclusion is justified that investments in HSI implementation will have a positive, and probably large, return on investment in terms of:

- Reduced probability of adverse safety and health outcomes;
- Reduced probability of program failure;

- Improved equipment effectiveness; and
- Reduced overall costs.

Financial returns are likely to be greatest, or at least most straight-forward to estimate, where HSI implementation allows personnel levels to be reduced.

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