Extending Systems Engineering Leading Indicators for Human Systems Integration Effectiveness

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Abstract

Human Systems Integration (HSI) is the integrated, comprehensive analysis, design and assessment of requirements, concepts, and resources for system Manpower; Personnel, Training, Environment, Safety, Occupational Heath, Habitability, Survivability and Human Factors Engineering. This paper describes a new research effort to extend a set of systems engineering leading indicators developed in prior research, to more effectively address HSI considerations. HSI is tightly coupled with the systems engineering process, particularly in large defense and government programs, making it challenging to determine if HSI is sufficiently considered to ensure a successful program. It is also challenging to isolate and identify HSI issues, particularly in the early stages of acquisition and program development. The objective of the research is to augment and extend the current systems engineering leading indicators, including interpretive guidance, to enhance the predictability of programmatic and technical performance on a program to include adequate HSI consideration.

Keywords – human systems integration, leading indicators, economics, systems engineering, metrics, measurement

1 Introduction

Human Systems Integration (HSI) considerations are an integral part of the overall systems engineering process in all engineering application sectors, and are critically important for defense systems. The research described in this paper, sponsored by the US Air Force (USAF), defines HSI as "the integrated and comprehensive analysis, design, and assessment of requirements, concepts, and resources for system manpower, personnel, environment, training, safety, occupational health, habitability, personnel survivability, and human factors engineering"[1].

The tight coupling of HSI processes to the overall systems engineering process, particularly in large defense and government programs, creates a challenge for assessing whether HSI is sufficiently considered to ensure a successful program. By its nature, HSI must be considered in early phases of acquisition and development, and given adequate focus throughout development, fielding and operations. The complexity of military systems and systems-of-systems (SoS) motivates this need for "a robust process by which to design and develop systems that effectively and affordably integrate human capabilities and limitations" [1].

Yet, a challenge exists for program leadership to predicatively assess whether HSI considerations have been adequately addressed to result in desired system performance. Over the past five years a collaborative research initiative has resulted in a set of thirteen leading indicators for systems engineering aimed at providing predictive insight. These indicators, however, currently have weak characterizations as related to human systems integration. This paper describes the approach and early insights from a new research effort undertaken in August 2008, which is investigating how the systems engineering leading indicators can be enhanced and extended to more adequately address this important need.

2 Economics-based Systems Engineering

In August 2008, MIT's Systems Engineering Advancement Research Initiative (SEAri), was awarded a research contract by the US Air Force for "Economics Based Human Systems Integration". The overall objective of the research is to contribute to the goals of making acquisitions more cost effective and to better support the warfighter by effectively meeting HSI requirements. The research includes two areas of investigation: (a) percentage of HSI effort that can be estimated as a function of the total systems engineering effort and used for predictive purposes on future programs; and (b) current systems engineering leading indicators that can be extended for HSI and used to improve the predictability of HSI programmatic and technical performance on a program. The latter is addressed in this paper, and a companion paper [2] addresses early work in support of the effort estimation task.

The targeted goal is to provide methodologies and tools that will be applicable throughout the Defense Acquisition Life Cycle. These will enhance the ability for acquisition leaders to develop and evaluate the HSI aspects of proposals, and enable program leadership to assess effectiveness of HSI investment and effort within programs. The research initiative aims to assist the USAF in its goal to enhance human performance, safety and health of personnel to increase total capability effectiveness and minimize risks to the environment, personnel and the public. Additionally this research contributes to increasing total systems performance and decreasing total ownership costs by reducing human errors, optimizing interface design, and eliminating occupational hazards. While directed toward the USAF goals, the research outcomes will benefit other engineering sector. HSI incorporates functional areas, referred to as domains. The defined HSI Domains are: Manpower; Personnel; Training (sometimes combined into MPT); Human Factors Engineering; Environment; Safety; and Occupational Health (the previous three are commonly grouped as ESOH); Survivability; and Habitability. A brief description of these is shown in Table 1 below.

Table 1 – *HSI Domain Descriptions* [1]

HSI Domains	***Description***
Manpower	The number and mix of personnel (military, contractor) authorized and available to train, operate, maintain, and support each system acquisition.
Personnel	The human aptitudes, skills, knowledge, experience levels, and abilities required to operate, maintina and support the system at the time it is fielded and throughout its life cycle.
Training	The instruction and resources required to provide personnel with requisite knowledge, skills, and abilities to support the system.
Human Factors Engineering	The comprehensive integration of human capabilities and limitations (cognitive, physical, sensory, and team dynamic) into system design, development, modification and evaluation to optimize human-machine performance for both operation and maintenance of a system. Human Factors Engineering designs systems that require minimal manpower, provide effective training, can be operated and maintained by users, and are suitable and survivable.
Environment	Environmental factors concern water, air, and land and the interrelationships which exist among and between water, air, and land and all living things.
Safety	Safety factors are design and operational characteristics that minimize the possibilities for accidents or mishaps to operators which threaten the survival of the system.
Occupational Health	Occupational Health factors are design features that minimize risk of injury, acute and/or chronic illness, or disability, and/or reduced job performance of personnel who operate, maintain, or support the system.
Survivability	The characteristics of a system that reduce risk of fratricide, detection, and the probability of being attacked; and that enable the crew to withstand man-made or natural hostile environments without aborting the mission or suffering acute and/or chronic illness, disability, or death.
Habitability	Factors of living and working conditions that are necessary to sustain the morale, safety, health, and comfort of the user population which contribute directly to personnel effectiveness and mission accomplishment, and often preclude recruitment and retention problems.

Specifically, the leading indicators research uses an empirical approach to capture data from recent/ongoing programs with significant HSI components and synthesizing the results into predictive models to aid program managers and systems engineering leaders in decision making. Expert surveys and interviews, gathered through both formal workshops and individual contact, are first used to gain meaningful insights on which this more rigorous data gathering, investigation and analysis is based.

3 Systems Engineering Leading Indicators

As discussed above, this research project has two components, one of which extends from prior research to define system engineering leading indicators [3]. The targeted goal is to augment and extend the current systems engineering leading indicators to enhance predictability of programmatic and technical performance to include adequate application of HSI considerations resulting in high performance over the system lifespan.

In 2004, MIT and the USAF sponsored a workshop on the topic of *systems engineering for robustness*, resulting in six initiatives including one on systems engineering leading indicators [4]. A leading indicator is a measure for evaluating the effectiveness of a how a specific activity is applied on a program in a manner that provides information about the impacts that are likely to affect the system performance objectives. Leading indicators are designed to assist program leadership in delivering value to stakeholders, assisting in interventions and corrective actions to avoid problems, rework and wasted effort.

Conventional systems engineering measures provide status and historical information, while leading indicators use an approach that draws on trend information to allow for more predictive analysis. By analyzing the trends in context of program environment and known factors, predictions can be forecast on the outcomes of certain activities. Trends are then analyzed for insight into both the entity being measured and potential impacts to other entities and activities. Resulting information is used to make informed decisions and where necessary, take preventative or corrective action during the program in a proactive manner. Thirteen leading indicators for systems engineering programmatic and technical performance, as related to good systems engineering practice have been developed and published in a guidance document in July 2007 [6].

The initiative to develop the systems engineering leading indicators defined a set of thirteen initial indicators:

1. Requirements Trends
2. System Definition Change Backlog Trend
3. Interface Trends
4. Requirements Validation Trends
5. Requirements Verification Trends
6. Work Product Approval Trends
7. Review Action Closure Trends
8. Risk Exposure Trends
9. Risk Handling Trends
10. Technology Maturity Trends
11. Technical Measurement Trends
12. Systems Engineering Staffing & Skills Trends
13. Process Compliance Trends

As of publication of this paper, an effort is underway to add six additional indicators to the set of thirteen; these include:

1. Test Completeness Trends
2. Resource Volatility Trends
3. Complexity Change Trends
4. Defect and Error Trends
5. Algorithm and Scenario Trends
6. Architecture Trends

Each of the indicators is described by a measurement specification which includes a detailed description, insights provided, interpretation guidance and usage guidance, as shown in Appendix A. Within the measurement specification is a description of the leading insight provided by each indicator. Three examples are shown in Table 2.

Table 2 – Example leading insights for indicators.

Leading Indicator	***Leading Insight***
***Requirements Trends*:**	Indicates rate of maturity of the system definition against the plan. Also characterizes stability and completeness of requirements which could potentially impact design and production.
***Interface Trends*:**	Indicator of interface specification closure against plan. Lack of timely closure could adversely impact system architecture, design, implementation and/or V&V any of which could have technical, cost and schedule impact.
***Validation Trends*:**	Indicator of progress against plan in assuring that the customer requirements are valid and properly understood. Adverse trends would pose impacts to design activity with corresponding impacts to technical, cost & schedule baselines and customer satisfaction.

4 Extending Leading Indicators for HSI

The research team is exploring how best to augment the current leading indicator specifications (as described in Appendix A). As a first step, the domains are being investigated in regard to what types of insight would be important. Examples of preliminary ideas on leading insights relative to HSI effectiveness as related to the domains are:

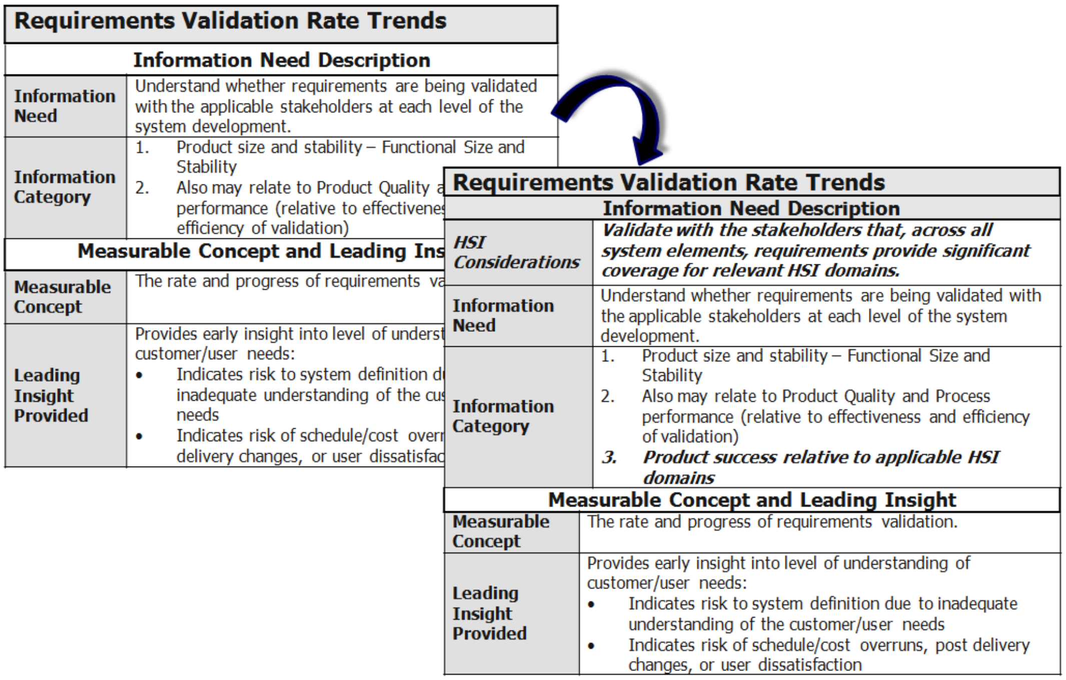
Manpower:
Early identification of an escalation or reduction in manpower requirements may warn of an unexpected increase in system complexity. Initial insights provided by a manpower assessment of the entire system life cycle may bring to light hidden costs often overlooked in the maintenance and disposal phases.

Training:
Initial insight into the adequacy of training resources may inform managerial decisions and improvements, resulting in an increased speed of adoption among the user population, the reduction of user errors, or alternatively the reduction in unnecessary training costs.

Environment:
A holistic evaluation of the environment within which a system operates, the environment's possible states of flux, and system impacts on that environment provide valuable insight that will influence the strategic design and operation of that system. For example, the recognition of probable material resource scarcity or the identification of generated noise pollution, may inform the redesign of major components.

As a next step in the research, interviews and surveys will be conducted to examine these considerations in more depth. Resulting insights will lead to the augmentation of the existing systems engineering leading indicators, development of useful filters for the indicators in regards to HSI, and possibly the development of new indicators. Different concepts for extending the indicator specifications will be considered.

Figure 1 shows a possible approach where a field is added to the specification to include “HSI Considerations” and other information is added to fields such as the information category. The concept in the figure is notional; the research team is currently investigating possible options with a goal of integrating as much HSI information as possible such that it is not necessary to define many new leading indicators specifically for HSI.



Requirements Validation Rate Trends	
Information Need Description	
Information Need	Understand whether requirements are being validated with the applicable stakeholders at each level of the system development.
Information Category	1. Product size and stability – Functional Size and Stability 2. Also may relate to Product Quality a[nd Process] performance (relative to effectivenes[s and] efficiency of validation)
Measurable Concept and Leading Ins[ight]	
Measurable Concept	The rate and progress of requirements va[lidation.]
Leading Insight Provided	Provides early insight into level of underst[anding of] customer/user needs: • Indicates risk to system definition d[ue to] inadequate understanding of the cu[stomer/user] needs • Indicates risk of schedule/cost overr[uns, post] delivery changes, or user dissatisfac[tion]

Requirements Validation Rate Trends	
Information Need Description	
HSI Considerations	***Validate with the stakeholders that, across all system elements, requirements provide significant coverage for relevant HSI domains.***
Information Need	Understand whether requirements are being validated with the applicable stakeholders at each level of the system development.
Information Category	1. Product size and stability – Functional Size and Stability 2. Also may relate to Product Quality and Process performance (relative to effectiveness and efficiency of validation) ***3. Product success relative to applicable HSI domains***
Measurable Concept and Leading Insight	
Measurable Concept	The rate and progress of requirements validation.
Leading Insight Provided	Provides early insight into level of understanding of customer/user needs: • Indicates risk to system definition due to inadequate understanding of the customer/user needs • Indicates risk of schedule/cost overruns, post delivery changes, or user dissatisfaction

Figure 1 – *Example of adapting leading indicator specification to include HSI considerations.*

Once the leading indicators have been augmented for HSI considerations, it may also be important to define next level measurement detail to be looked at through further data analysis, and graphical portrayal of the information. A notional example is shown in Figure 2, where requirements validation information might be examined more closely for requirements that are allocated to the HSI domains. Graphical constructs can provide assistance in seeing where variances against historical data in similar systems occur.

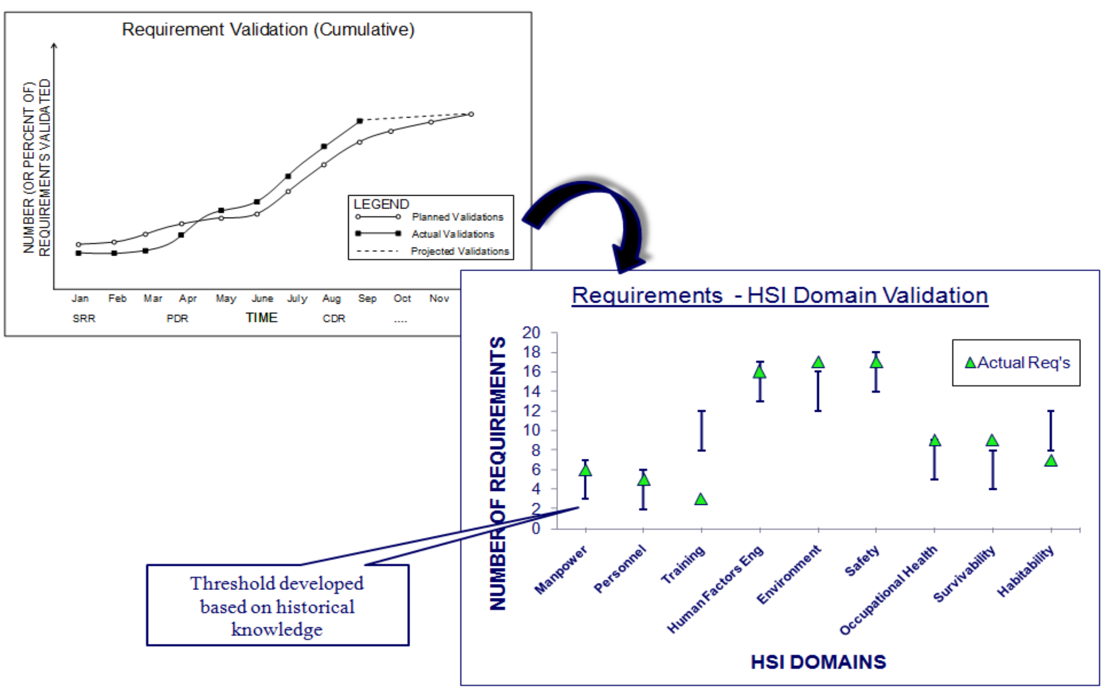


Figure 2 – *Graphical aid to check number of HSI requirement validation against accepted historical range*

5 Observations and Soft Indicators

As a means to understand how the existing leading indicators may be augmented and the set of indicators extended to include additional useful indicators, the research team is gathering expert data through workshop discussions, surveys, and interviews, to be followed by additional supporting data from case studies. In this discovery process, the goal was to identify observations and "soft indicators" (that is, early insights and qualitative indicators) as a first step toward developing mature leading indicators drawing on quantitative information.

The interim efforts include six areas which are likely to have relevancy for augmenting the set of current systems engineering leading indicators, including use and interpretation guidance for these indicators. It is also possible that one or more additional leading indicators will be necessary to achieve the goal of effectively considering human systems integration as part of the overall systems engineering effort.

Allocation of Requirements to HSI Domains. During the definition of the system and subsystem level requirements it is very important that performance and behavioural requirements covering all of the human systems integration domains be adequately specified. Where requirements relate to complex interdependencies between the human and the system, potential exists for using the requirements-related leading indicator information to monitor negative trends in requirements growth, volatility, verification and validation specific to this focus. Indicators of high volatility in the allocation of requirements could warrant further investigation to determine if appropriate HSI personnel are involved since requirements that are misallocated to humans (or not to humans when they should be) in the early phase can result in major issues downstream.

Impact Assessment of Allocations/Allocation Changes. A related observation is that highly effective organizations have a mature process for impact assessment of requirements allocation (usually once some level of requirements stability has been established). Of particular interest will be the assessment of changes related to allocation from hardware/software to human, or human to system. Requirements volatility, verification and validation trend indicators will be of interest, with lower level details to support investigation.

Adequacy of Stakeholder Involvement. Within the overall footprint of HSI there are many types of stakeholders that need to have a voice in the system development. Leading indicators related to staffing and work product approval, for example, may show whether all necessary stakeholders are (or are not) in key activities such as participating in requirements review and design reviews. The absence of HSI personnel, particularly in early system definition activities, will likely result in inadequate consideration of the HSI requirements, possibly leading to significant system failures.

Orientation for HSI in Engineering Organization. Another soft indicator that has been highlighted by systems engineering experts as important is the existence of an orientation within the engineering organization for the HSI perspective. Whether or not there are dedicated HSI specialists, there is variation in engineering organizations in regard to how much focus and priority is placed on the HSI considerations. A highly effective engineering team has cognizance of the full set of HSI domains, and the organization (customer and contractor) proactively establishes HSI related technical measurements (KPP, MOE, etc.), for example human survivability MOEs. Within the mature engineering organization there will be individuals with roles and authorities to provide coverage for all of the domains appropriate to each program.

Adequacy of Domain-specific Expertise. HSI includes multiple domains which require unique expertise that is rarely found in one individual. A soft indicator of a less mature organization will be assignment of all the domains to one speciality unit or specialty engineer. Leading indicators that look at staffing in regard to coverage of the HSI domains can provide insight to whether the systems will ultimately perform well as related to the domains. Failure to provide coverage for these necessary skills and roles will likely have negative implications for performance in the operational system.

Understanding Situational Factors Impacting HSI. In the definition and specification of leading indicators, it is important to understand underlying situational factors that may impact the effectiveness of HSI and accordingly how the leading indicator information may be interpreted. Factors may include severity of threat or operational environment, complexity of system interfaces, newness/precedence of system technologies, and socio-political relationship of constituents in SoS. As an example, where the system has very complex system interfaces involving new technology and inexperienced users, the *interface trends* leading indicator may need to be reported and monitored on a more frequent basis, and interface allocation to humans designed to accommodate the inexperience user base.

6 Discussion and Conclusions

The research described in this paper will progress over an additional eighteen month period with several outcomes expected. The first of these will be to strengthen the definition and guidance for thirteen leading indicators that were previously developed. This will include refinement of definitions and development of appropriate guidance for interpretation and use of the indicators for predictive purposes. The second outcome is to contribute directly to the formulation of six new indicators that are being added to the existing thirteen indicators. The results of these two areas of contribution will be incorporated into Version 2.0 of the existing guide [5] planned for late 2009. The results of one or more case studies to be conducted during the research will be shared with the systems community through thesis and conference publications. As the work progresses, it is likely that additional insights, research questions, and areas of inquiry outside the scope of this effort will be uncovered. The research team will make these known to the systems community through multiple means, including meetings, workshops, and conferences. This information may help to inform the development of new or updated guidance and handbooks [5, 6] to strengthen the human systems integration knowledge as an integral part of the systems engineering process.

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9 Appendix A

Table 4 shows the measurement specification for the leading indicators. Each indicator is characterized with the information shown and is often customized for the organization using the indicators. The measurement specification is based on the work described in [9].

Table 4 - Leading Indicator Measurement Specification [5]

{Name of Leading Indicator}	
Information Need Description	
Information Need	*Specifies what the information need is that drives why we need this leading indicator to make decisions*
Information Category	*Specifies what categories (as defined in the PSM) are applicable for this leading indicator (for example, schedule and progress, resources and cost, product size and stability, product quality, process performance, technology effectiveness, and customer satisfaction)*
Measurable Concept and Leading Insight	
Measurable Concept	*Defines specifically what is measurable*
Leading Insight Provided	*Specifies what specific insights that the leading indicator may provide in context of the measurable concept - typically a list of several or more*
Base Measure Specification	
Base Measures	*A list of the base measures that are used to compute one or more leading indicators - a base measure is a single attribute defined by a specified measurement method*
Measurement Methods	*For each base measure, describes the method used to count the base measure, for example simple counting or counting then normalized*
Unit of Measurement	*Describes the unit of measure for each of the base measures*
Entities and Attributes	
Relevant Entities	*Describes one or more particular entities relevant for this indicator – the object is to be measured (for example, requirement or interface)*
Attributes	*Lists the subset of particular attributes (characteristics or properties) for each entity that are of interest for this leading indicator*
Derived Measure Specification	
Derived Measure	*Describes one or more measures that may be derived from base measures that will be used individually or in combination as leading indicators*
Measurement Function	*The function for computing the derived measure from the base measures*
Indicator Specification	
Indicator Description and Sample	*A detailed specific description and display of the leading indicator, including what base and/or derived measures are used*
Thresholds and Outliers	*Describes thresholds and outliers for the indicator; this information would be company (and possibly program) specific*
Decision Criteria	*Provides basic guidance for triggers for investigation and when possible action to be taken*
Indicator Interpretation	*Provides some insight into how the indicator should be interpreted; each organization would be expected to tailor this*
Additional Information	
Related Processes	*Lists related processes and sub-processes*
Assumptions	*Lists assumptions for the leading indicator to be used, for example, that a requirements database is maintained*
Additional Analysis Guidance	*Any additional guidance on implementing or using the indicators*
Implementation Considerations	*Considerations on how to implement the indicator (assume this expands with use by organization)*
User of Information	*Lists the role(s) that use the leading indicator information*
Data Collection Procedure	*Details the procedure for data collection*
Data Analysis Procedure	*Details the procedure for analyzing the data prior to interpretation*