DEVCOM DAC-TN-2022-019
October 2022

The Human Systems Integration (HSI) Metric Tradespace Exploration Environment (HMTee): A Paradigm for Integrating Quantitative Models of Human System Performance

by Christopher Garneau

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE
October 2022

2. REPORT TYPE
Technical Note

3. DATES COVERED (From - To)
1 October 2021–30 September 2022

4. TITLE AND SUBTITLE
The Human Systems Integration (HSI) Metric Tradespace Exploration Environment (HMTee): A Paradigm for Integrating Quantitative Models of Human System Performance

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Christopher Garneau

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Director
DEVCOM Analysis Center
6896 Mauchly Street
Aberdeen Proving Ground, MD 21005

8. PERFORMING ORGANIZATION REPORT NUMBER
DEVCOM DAC-TN-2022-019

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The Human Systems Integration (HSI) Metric Tradespace Exploration Environment (HMTee) provides a toolset to optimize system designs or requirements for HSI domains implemented as a convenient R Shiny application. It enables practitioners or researchers to explore and document assumptions, parameters, and performance metrics, and to subsequently perform trade-offs among competing factors to develop quantitative guidance to inform decisions. This technical note introduces the tool, describes the HMTee approach and "interaction model" paradigm, provides a user's guide for the HMTee interface, and suggests a path forward for expanding the functionality of the tool and its analytical capabilities.

15. SUBJECT TERMS
Human Systems Integration, HSI, analysis tools, modeling and simulation, M&S, Human Factors Engineering, HFE

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UU	31	Christopher Garneau
					19b. TELEPHONE NUMBER (include area code) 410-278-5814

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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Acknowledgments

The U.S. Army Combat Capabilities Development Command (DEVCOM) Analysis Center (known as DAC) funded this report and development of the Human Systems Integration Metric Tradespace Exploration Environment (HMTee) as part of its Innovation Program (fiscal year 2022 cohort). The DAC Innovation Program was established to harness the passion of the workforce, enhance collaboration across divisions, and redefine success. Project leads are allotted up to 20% of their time to work on their projects.

The author would like to thank the Innovation Program panel and the mentors for this project (Dr. Kathryn Loftis and Ms. Debra Patton) for their support. The author also acknowledges the helpful feedback on implementing and distributing R Shiny applications from the DAC Data Analytics Community of Practice.

1. INTRODUCTION

The Human Systems Integration (HSI) Metric Tradespace Exploration Environment (HMTee) provides a toolset to optimize system designs or requirements with respect to the domains of HSI. For the U.S. Army, these seven domains are as follows: Manpower, Personnel, Training, Human Factors Engineering (HFE), Safety and Occupational Health, Force Protection and Survivability, and Habitability. HMTee is implemented as a convenient R Shiny application and constitutes a digital reference for identifying quantitative guidelines and metrics for relevant HSI factors. It enables practitioners to visualize results of an analysis and produces visual evidence of performance simulations for decision-makers and for further trade-off analysis. It also records any assumptions, limitations, and performance metrics identified during investigation of a concept, requirement, or design, which provides an analysis snapshot for application to future systems or by other practitioners and/or researchers.

1.1 Background and Motivation

HSI analyses can provide estimates of human and system performance and answer key analytical questions. For instance, what is the system performance that results from HFE analyses that model physical accommodation or cognitive workload (across a range of candidate designs/variables)? How does modifying the operator’s skillsets or crew size (analyses within the Manpower, Personnel, and Training [MPT] domains) affect this performance? How might various remediations impact cost or risk to the program? HSI tools aid in the application of methods that ensure systems consider human limitations and capabilities across the spectrum of HSI domains (Human Systems Integration Guidebook, 2022).

Currently, HSI practitioners, analysts, or researchers do not have many suitable tools to weigh, explore, and visualize these competing factors to arrive at an optimal solution and provide appropriate evidence to decision-makers (e.g., program managers and other stakeholders). Moreover, practitioners do not have a way to readily share quantitative analyses, inputs, and assumptions for various factors under analysis with other practitioners for review, future use, and modification. From the perspective of HSI tool development, a single common interface or framework that provides customized functionality for HSI while still maintaining the flexibility to handle a variety of use cases does not exist.

1.2 What is an Exploration Environment?

The intent of the HSI Metric Tradespace Exploration Environment is to bring together existing tools and strategies and to establish a place where various metrics can be explored, visualized, optimized, integrated, and stored. The name of the project was carefully considered to describe the purpose of the tool while also bounding its scope. The tool is limited to analyses that can be conducted using quantitative metrics; analyses focusing on observations or qualitative data are not supported by this environment.

It is not the goal of the project to be an authoritative source or framework for all HSI analyses or all HSI assessments, but rather to provide a decision-making tool that integrates and builds on a variety of existing quantitative resources. While HSI appears in the project title, HMTee is not intended to support only formal HSI Assessments—it is intended to also support HFE research, requirements development, and early consideration of HSI issues in the acquisition time line before Milestone C. Future work is expected that will broaden the tool to include models across all seven HSI domains.

1.3 Overview

This technical note describes the purpose, approach, and guide for using HMTee. It introduces the HMTee paradigm as a framework for addressing the challenges inherent within generating and comparing quantitative measures of human performance. Another U.S. Army Combat Capabilities Development Command (DEVCOM) Analysis Center (known as DAC) technical note describes and documents the technical aspects of the tool and how to integrate new interaction models with it; this companion technical note is titled, *HSI Metric Tradespace Exploration Environment (HMTee) Technical Documentation* (Garneau, 2022).

2. HMTEE APPROACH

This section discusses the HMTee approach and describes the interaction model concept, along with a description of the interaction models built into HMTee version (v) 1.0.

2.1 Paradigm

HMTee presents a paradigm where humans are **parameterized** in terms that can be interpreted by an **interaction model** for a specific HSI/HFE consideration, subject to **system constraints**. This abstraction allows for a variety of human factors metrics to be considered alongside others in a consistent manner for visualization, optimization, and documentation. See Figure 1.

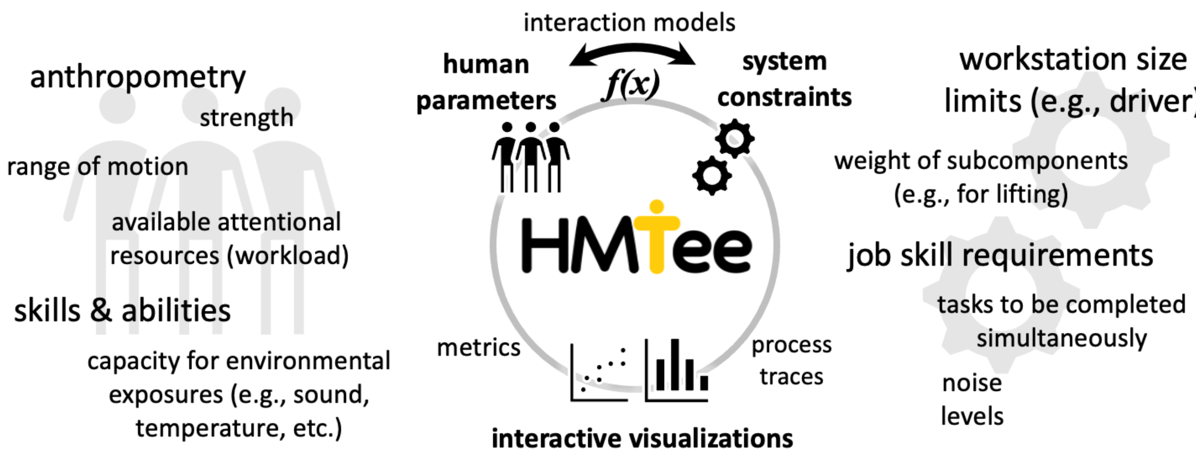

Figure 1. HMTee paradigm: Interaction models are situated between human parameters and system components

2.2 Interaction Models

Useful and accurate interaction models are key to the effective use of HMTee; the quality of resulting analyses will only be as good as the quality and breadth of the underlying interaction models. HMTee is designed to accept a range of interaction model types, from quantitative population-based simulations to simple equations or lookup tables. Figure 2 illustrates this continuum, noting that models employing more rigorous modeling techniques will yield better analyses with more analytical capabilities. Three models are included in the library of the initial version of HMTee (v1.0); these were chosen because they are representative of the continuum of interaction model fidelity that HMTee accepts. The Military Anthropometry Resource Companion (MARC) (1) and the Job Assessment Software System (JASS) (2) are discussed here; the Revised National Institute for Occupational Safety and Health (NIOSH) Lifting Equation

(3) interaction model is discussed in the accompanying HMTee documentation (Garneau, 2022) as an exemplar for integrating a new model.

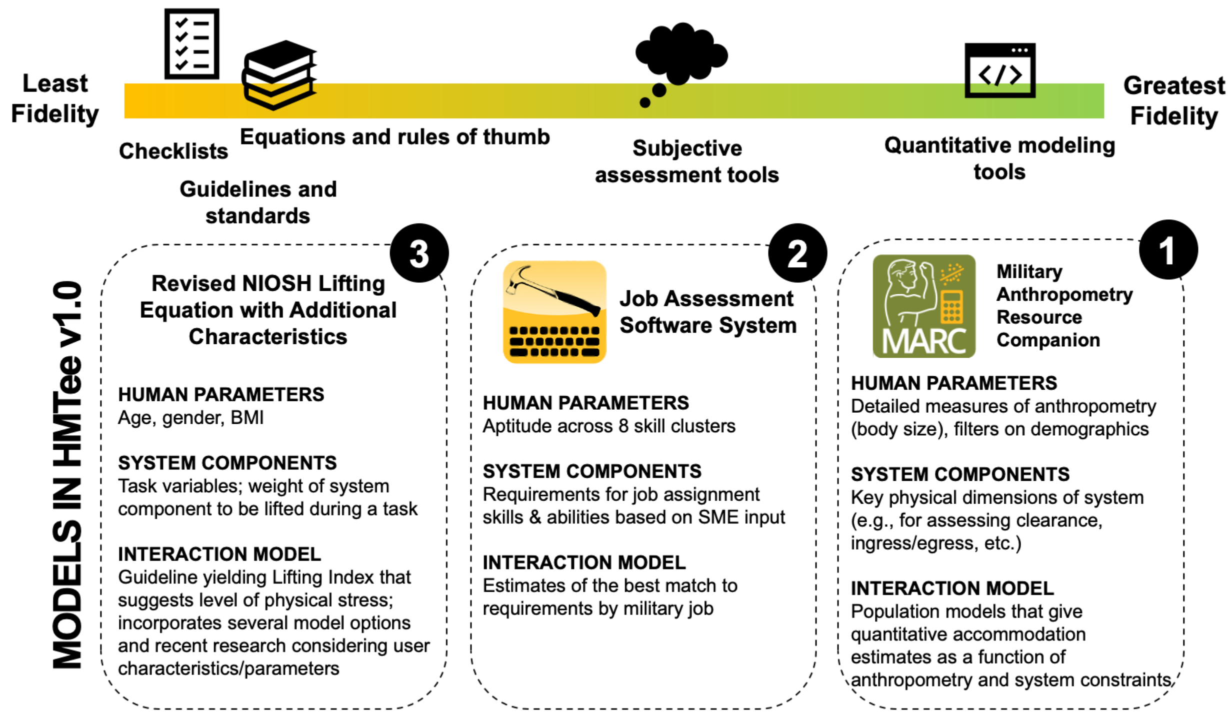

Figure 2. Continuum of interaction models supported by HMTee, with the examples found in v1.0

2.2.1 What is an Interaction Model?

The purpose of an interaction model in HMTee is to quantitatively describe the outcome of placing constraints on one or more system components that are mapped to human parameters. Interaction models are R functions with one or more inputs and one or more outputs, organized by the HSI domain to which they belong. At their most basic, interaction models need only include an outcome metric given a single input. At their most complex, interaction models may accept an array of system components and human parameters bounded by limits on each component, filters on several human characteristics, interactive model options, and vectors of output data that may be used for interactive graphing.

2.2.2 Military Anthropometry Resource Companion

MARC is an interactive analysis application that provides complete anthropometric (body size) data and related analytical tools (Garneau, 2017). MARC complements available guidance relevant to designing or evaluating an artifact or environment for physical accommodation (e.g., MIL-STD-1472, 2020). MARC may be used to explore anthropometric data and calculate percentiles for any given dimension and value, compare characteristics of available data sets, and get multivariate accommodation rates on the fly given certain constraints on anthropometry and demographics. MARC is developed by DAC and has been implemented as a standalone application and an R package called MARCR.

MARC capitalizes on the U.S. military's investment in large surveys of anthropometric data that have been conducted at various times in the last 50 years (primarily the 1988 U.S. Army Anthropometric Survey [ANSUR] [Gordon et al., 1989] and 2012 ANSUR II [Gordon et al., 2014] data sets). MARC enables various kinds of analysis for a variety of use cases, but essentially performs four types of calculations: (1) determination of the percentile associated with a specified value for a single dimension, (2) determination of the value associated with a specified percentile for a single dimension, (3) determination of the level of (percent) accommodation associated with specified limits on the values of multiple dimensions, and (4) determination of values associated with certain levels of accommodation for multiple dimensions. MARC accepts various filters on the demographics (e.g., age) and has options for combined gender, built-in plots, and so forth.

The MARCR package (included with the HMTee distribution) consists of four functions:

- `marc_names`, which returns available anthropometric dimension names when given a specified anthropometric database
- `marc_data`, which returns raw anthropometric data from either ANSUR or ANSUR II for the specified gender
- `marc_prctile`, which returns the percentile/value of a single specified measure with given parameters
- `marc_names`, which returns accommodation percentage given specified measure(s) and parameters

These functions are used in different ways in the HMTee interaction model (`marc.json`). MARC is included as a model for the HFE HSI domain in HMTee.

2.2.3 Job Assessment Software System

JASS is a computer-based survey tool used to define and measure human aptitudes required to do a job (Knapp and Tillman, 1998; Sargent et al., 2017). JASS permits evaluators to identify and rate the level of skills and abilities necessary to perform jobs and associated duties (on a scale of 1 to 7). As a test instrument, JASS provides a mechanism to elicit feedback from Soldiers and other subject matter experts on the relative importance of many different skills and abilities for high-level jobs and tasks performed by different specialties operating different systems.

The objective of any JASS analysis is to maximize overall performance of systems involving human personnel to avoid the use of underskilled personnel (leading to the failure of a system to perform at anticipated levels) or overskilled personnel (an inefficient use of human resources). There are 50 skills and abilities in JASS that are divided across 8 skill clusters. Sample applications include determining the impact of new systems, making the best use of existing skill sets, or recommending human factors remediation for job assignments with high skill demands. While the early versions of JASS were developed by the U.S. Army Research Institute for the Behavioral and Social Sciences (ARI) and then the U.S. Army Research Laboratory (ARL), DAC currently maintains the JASS application and a JASS module embedded in the Behavioral Observations Logging Toolkit (BOLT). DAC also maintains R scripts for JASS analyses via the JASSR package.

As part of HMTee, the `jass_match` function in the JASSR/job skills interaction model calculates the best match among military jobs in the Occupational Information Network (O*NET)[*] given the eight JASS cluster scores. Note that taken together, the JASS approach provides a data-driven, validated approach to determining required job skills. The `jass_match` functionality in the job skill interaction model (`jass.json`) is a simple demonstration of the integration of one component of a JASS analysis in the MPT HSI domain; it is not a representation of the complete, end-to-end JASS approach.

[*] Go to https://www.onetonline.org/.

3. USER'S GUIDE TO HMTEE

This section provides a guide for users getting started with HMTee. It is intended for all users of HMTee; developers looking to understand the HMTee approach to integrate new interaction models should see the companion technical note (Garneau, 2022).

3.1 Getting Started

HMTee is currently available via direct transfer of a zip file containing the complete set of files associated with HMTee. This file should be unzipped to a convenient location; the resulting directory will constitute the HMTee working directory.

Currently, HMTee requires installation of R and RStudio (future versions may be available at a hosted location without these requirements). Once installed, the HMTee working directory should be opened in RStudio and set as the current working directory. To start HMTee, open (double click) the `app.R` file in the working directory and click "Run" at the top of the code pane in RStudio. Note that it will be necessary to install HMTee's R package dependencies before running HMTee. RStudio typically presents a banner prompting installation of any required packages before running a Shiny app.

3.2 Interface Elements

The appearance and functionality of each component of HMTee is described in this section. The order of these sections roughly corresponds with the suggested order for configuring a new analysis in HMTee. Figure 3 shows the HMTee interface upon start-up.

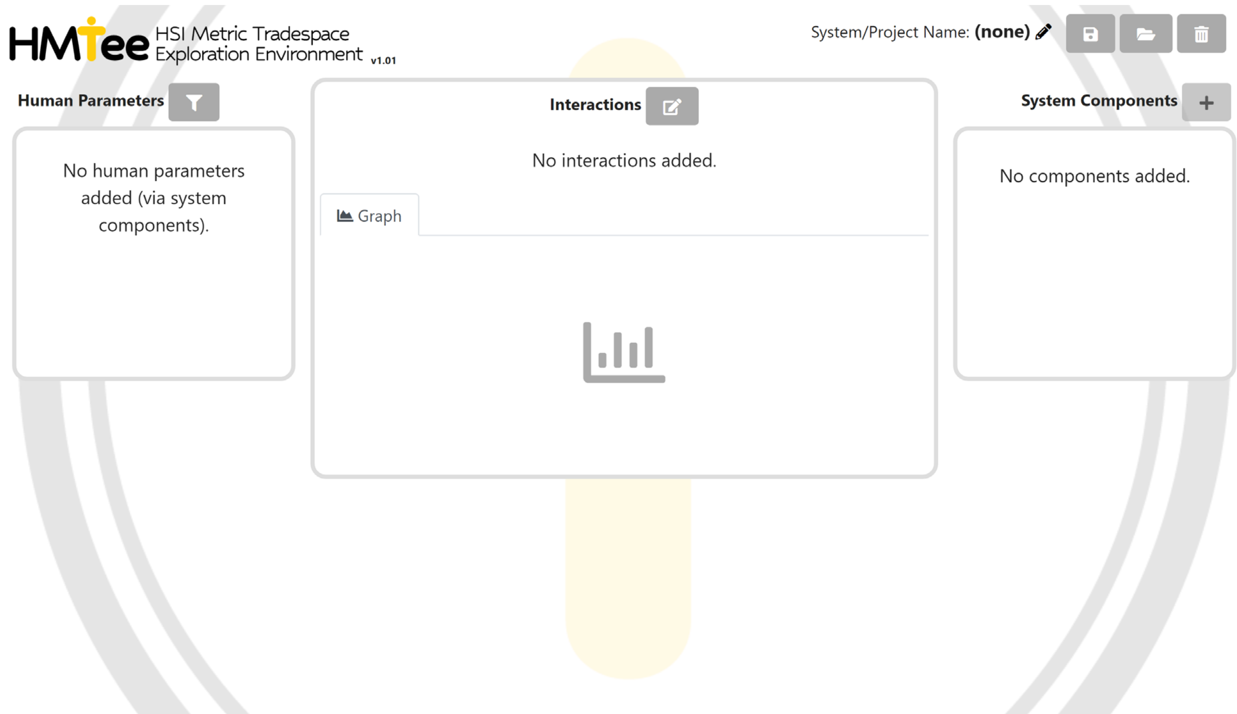

Figure 3. Full HMTee interface upon start-up; note that no models or settings have been configured

3.2.1 Action Bar

Users should start an HMTee analysis by naming their project by clicking the pencil icon next to "System/Project Name." Alternately, users may choose to open an existing analysis by clicking the open icon (see Section 3.2.2). To clear all analysis parameters and settings in HMTee, the user may click the trash can icon. See Figure 4.

Figure 4. Action bar buttons

3.2.2 Save/Load Modal

Users may choose to save their analysis to a file in the current working directory. Likewise, users may choose to load any analysis saved in the current working directory. In either case, the analysis is stored in a text file in JavaScript Object Notation (JSON) format with an ".hmt" extension. Any name may be chosen when saving a file; this field is prepopulated with "hmtee_" and a random number. See Figure 5.

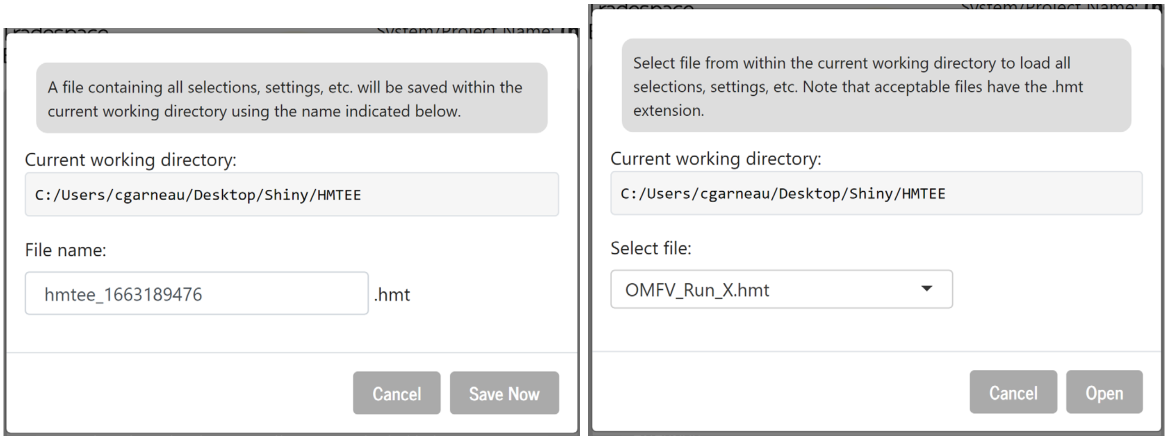

Figure 5. Save modal (left) and Load modal (right)

3.2.3 Interaction Selection Modal

The first step to start a new analysis is to click the edit button (paper-and-pencil icon) next to “Interactions.” The Interaction Selection modal will then appear (Figure 6) with tabs across the top for “Human Factors Engineering,” “Manpower, Personnel, & Training,” “Safety & Occupational Health,” “Force Protection,” “Habitability,” and “Meta Models.” Within each tab, a list of the currently configured/available models is shown with a checkbox next to each. Users may add or remove a model from the current analysis by checking or unchecking the box next to the model name.

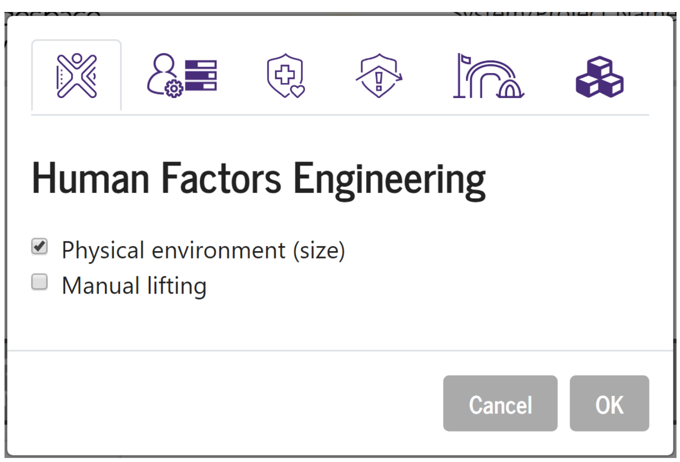

Figure 6. Interaction Selection modal with the “Human Factors Engineering” tab selected

3.2.4 Add System Component Modal

Users may add a new system component to an analysis by clicking the add button (plus icon) next to "System Components." A modal similar to Figure 7 will appear; upon selecting the "Interaction Model" for the component, the list of "Human Parameters" will populate. The user may name the component, then select the desired "Mapping." The mapping explicitly describes the way in which the system dimension relates to the human parameter. The properties of the component that will be mapped back to the parameter are available in the System Components pane (Section 3.2.5).

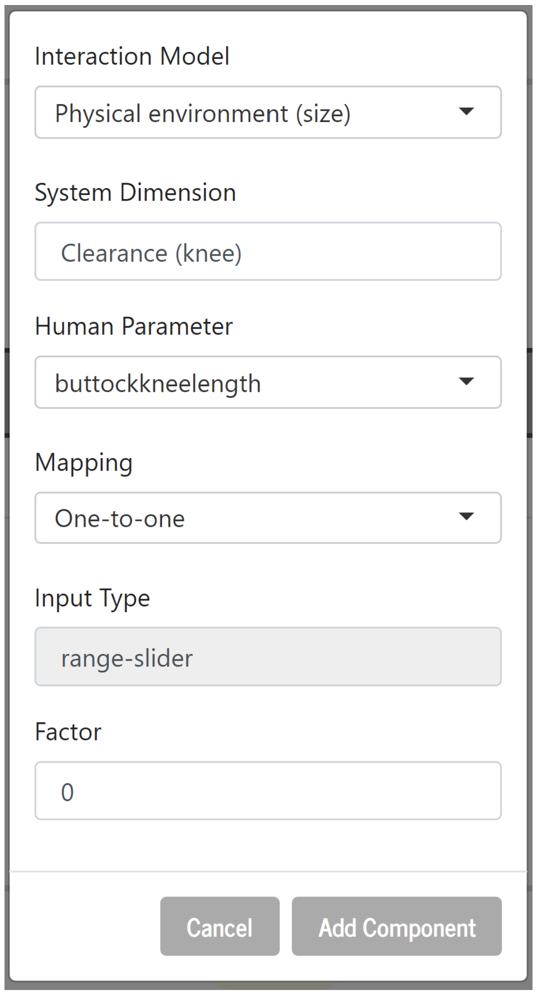

Figure 7. Add System Component modal

3.2.5 System Components Pane

The System Components pane (Figure 8) lists each of the configured system components, shows the human parameter onto which each is mapped, and indicates the mapping technique (“1:1”, offset value, etc.). Users may set limits on configured components by dragging the single-value sliders or two-value range sliders. Users may remove a component from an analysis by clicking the trash can icon; any settings for a deleted component will be cleared from HMTee.

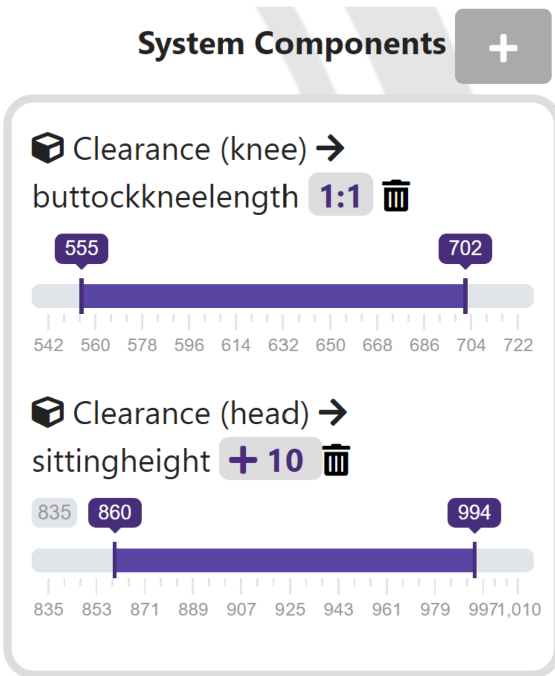

Figure 8. System Components pane with two components configured

3.2.6 Add Human Parameter Filter Modal

Users may add an available filter to an interaction model by clicking the add filter button (filter icon) next to “Human Parameters.” A modal similar to Figure 9 will appear; upon selecting the “Interaction Model” for the filter, the “Filter name,” “Comparator,” and “Filter value” fields will populate. Applied filters will affect the model by restricting the values of the human parameters that are included or accommodated. The “Comparator” field includes rational operators such as “==” (“is equal to”) or “>=” (“greater than or equal to”) and relates the indicated value to the filter name. For example, Figure 9 shows a filter wherein only individuals with an age greater than 24 will be included in the model.

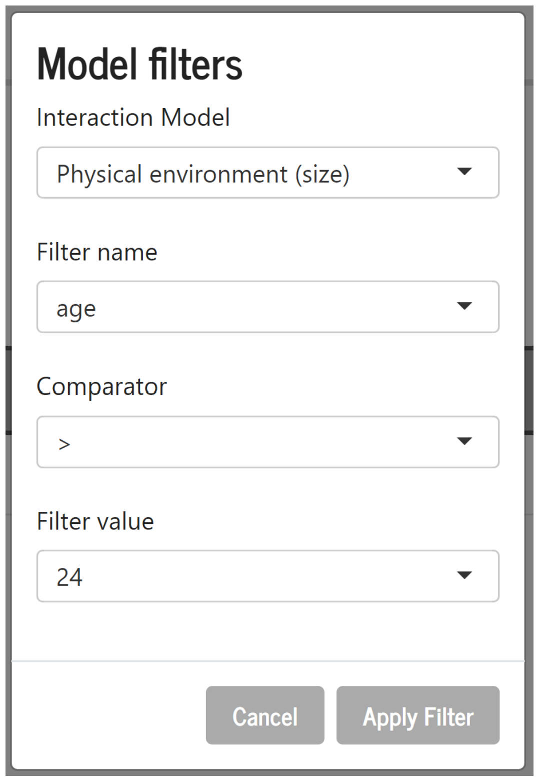

Figure 9. Add Filters modal

3.2.7 Human Parameters Pane

The Human Parameters pane (Figure 10) lists the human parameters for the model onto which each of the system components is mapped and indicates any filters that have been applied for the model. Parameters may only be added or removed from this pane by adding or removing the associated system component.

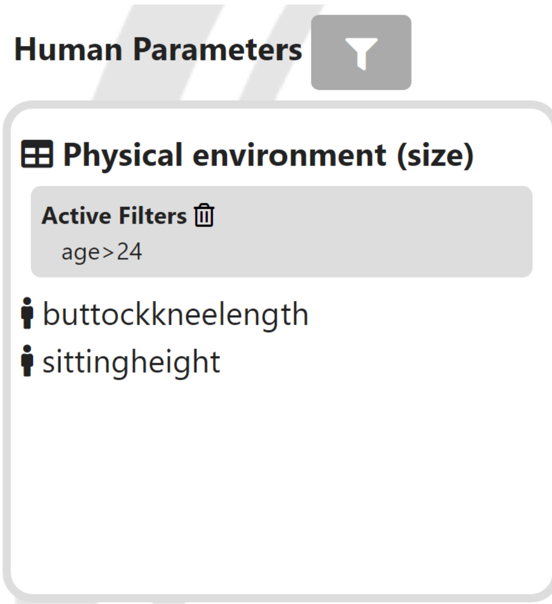

Figure 10. Human Parameters pane with two parameters mapped to two components for the "Physical environment (size) model"; one filter has also been applied

3.2.8 Interactions and Model Output Pane

The Interactions pane allows the user to interact with the model once the system components and filters have been set. The user may configure model options (Section 3.2.8.1), run models and view the session log (Section 3.2.8.2), and view or interact with various graphs (Section 3.2.8.3). See Figure 11.

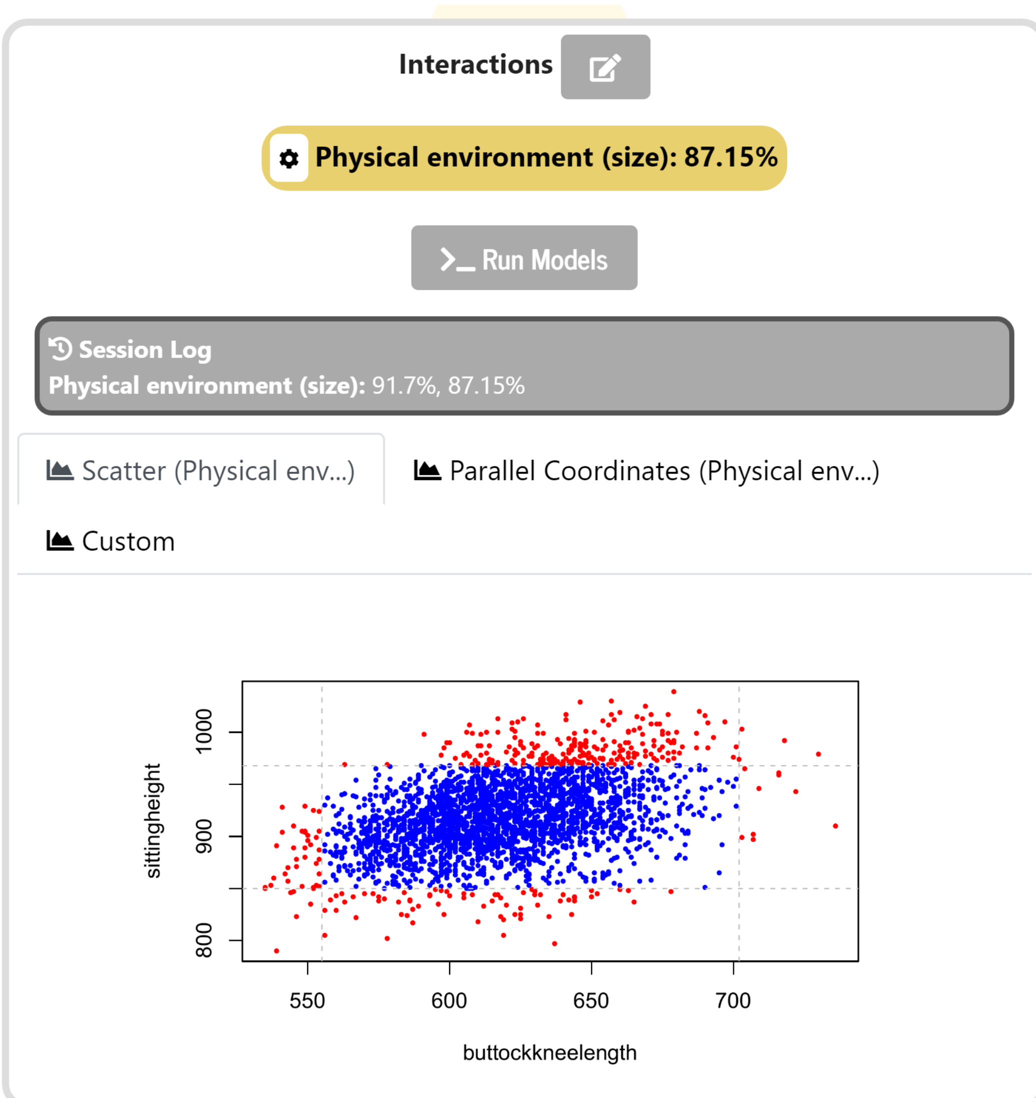

Figure 11. Interactions and Model Output Pane. Here, the "Physical environment (size)" model has been selected, configured, and run twice (as indicated by the Session Log). A pregenerated "Scatter" graph has been selected from the available graphing tabs.

3.2.8.1 *Model Options*

Users may configure model options by clicking the gear icon next to any active interaction model. A “Model options” modal similar to Figure 12 will appear (the options shown are specific to the selected model). Note that any selected/modified options will not take effect until the model is run again.

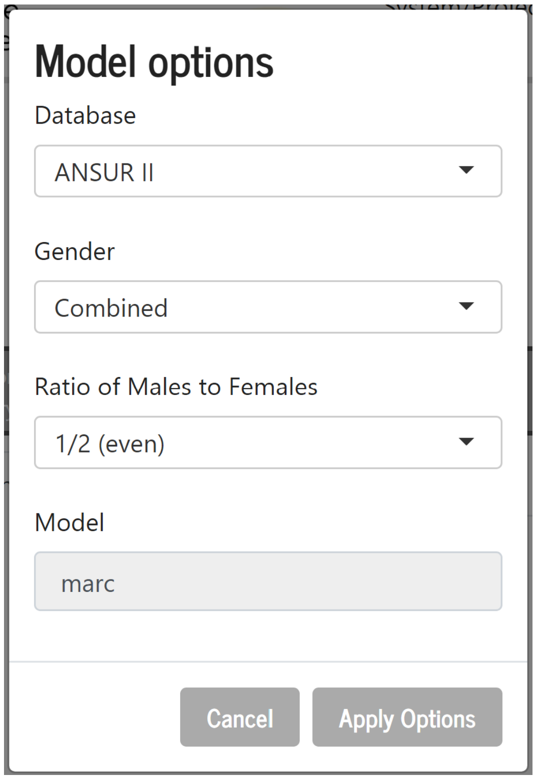

Figure 12. Model options modal

3.2.8.2 Model Execution, Output, and Session Log

Any active/selected interaction models are shown by a yellow chip (each model gets its own chip with its own options and output display). The output metric within the chip will update each time a model is run (when the "Run Models" button is clicked; see Figure 13). The "Session Log" stores a list of output metrics associated with each interaction model for the current session. Note that when an analysis is cleared or HMTee restarts, the session log data will be cleared (it is not persistent).

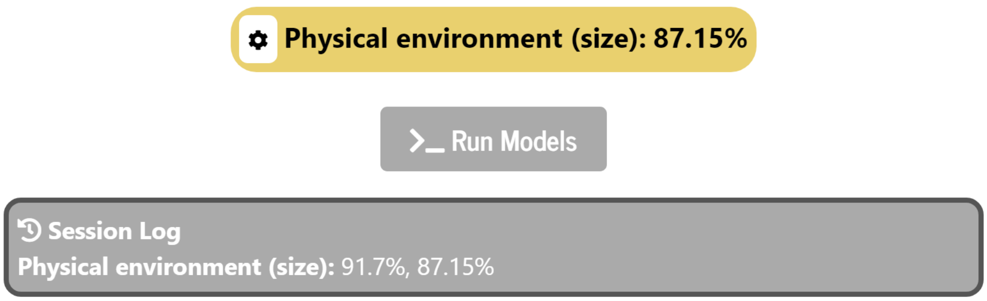

Figure 13. Interaction model results and session log

3.2.8.3 *Graphing*

Interaction models generally include one or more graph outputs. Graphs may be either pregenerated (i.e., a static plot image is generated when the model is run) or interactive (i.e., the user may select graph parameters and update the graph after the model has been run). An example of each type is shown in Figure 14 for the same model/data. Each available graph for the selected interaction model(s) are shown in their own tab. For pregenerated graphs, the tab is labeled with the type of graph (Scatter, Parallel Coordinates, etc.) and the model that created it. Interactive graphs are denoted by the “Custom” tab; the “Graph Type” is selected interactively, along with the graph parameters (e.g., x and y axes in Figure 14).

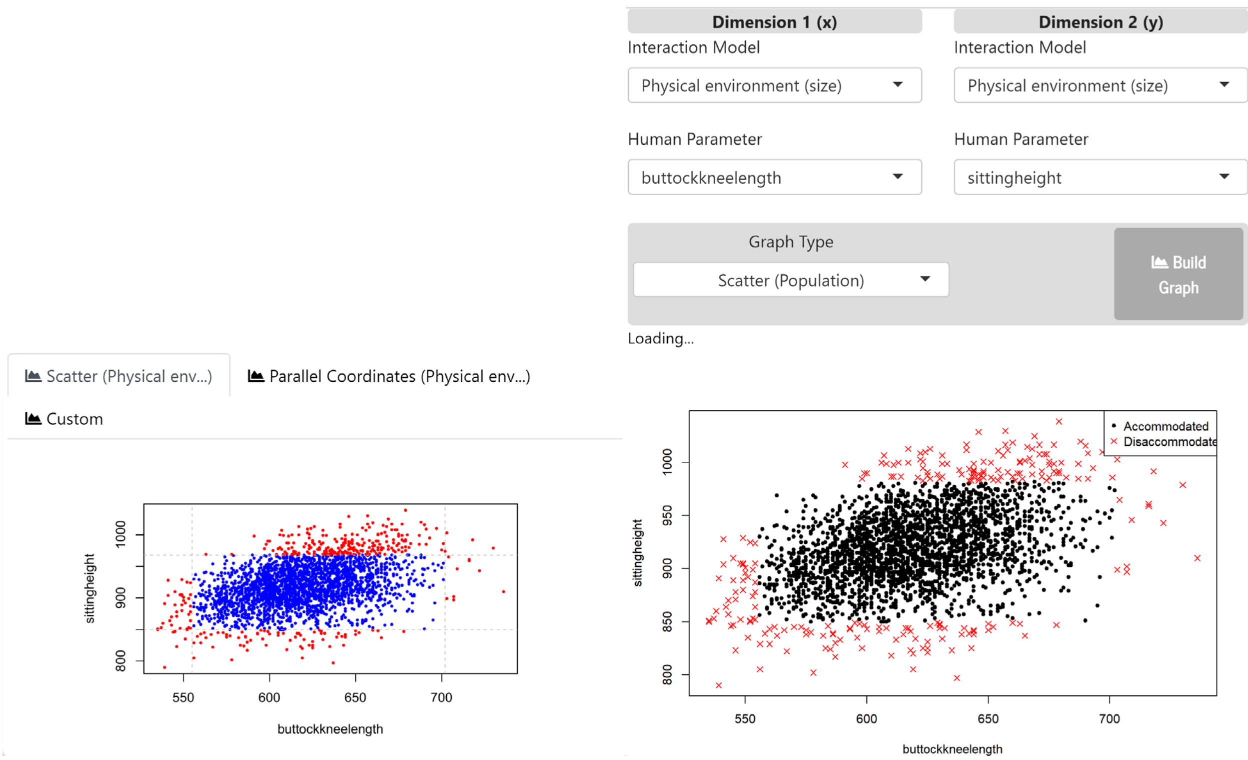

Figure 14. Graphing output for a pregenerated Scatter graph (left) and an interactive Custom graph (right)

4. CONCLUSION AND FUTURE WORK

HMTee provides a new paradigm for working with quantitative metrics in human factors and across the HSI domains. It provides a common environment that analysts or researchers may utilize to develop requirements, test ideas, evaluate systems, trade-off outcome metrics, and ultimately provide evidence for decision-makers across a range of relevant factors. The first version of the tool—developed as an easily modifiable R Shiny application—integrates three interaction models, allows for the generation of a variety of graphs, and permits an analyst to save or share their work for future use or for use by other analysts. This technical note provides a guide for the tool, and the companion technical note documents the technical approach and process for integrating new models (Garneau, 2022).

4.1 Future Work

HMTee was developed with expansion in mind—both in terms of the ability to integrate new models and in terms of additional development work to expand the functionality of the HMTee application itself. This section discusses the latter; it is not intended to be an exhaustive list of all possibilities but describes several areas of new development that were considered while developing HMTee v1.0 (but not completed given the time/ funding available).

4.1.1 Expanded Component-Parameter Mapping Types

HMTee currently includes three possible options for mapping a system component to a human parameter: (1) one-to-one, (2) one-to-one with offset, and (3) scaled. Future versions of HMTee should include additional options; in particular, there should exist a mechanism to map a component to a human parameter via a statistical model (e.g., regression equation).

4.1.2 Expanded Component Specification Input Types

HMTee currently includes two possible options for specifying input values for components: (1) single numerical value with lower and upper bounds (i.e., slider) and (2) numerical range with lower and upper bounds (i.e., dual/range slider). Future versions should include additional options, particularly for quantitative categorical data (i.e., drop-down menu) and numerical free response.

4.1.3 Meta Models and Output as an Input

Currently, interaction models specify outcome parameters via one or more system components mapped to human parameters. It would be beneficial in some cases to be able to specify an output metric that is dependent on one or more other output metrics or system components configured for other interaction models. As two examples, consider that (1) a reach analysis problem might depend on both range of motion data and physical body size data as inputs to an accommodation estimate, or (2) a task assignment problem might depend on aptitude to generate cognitive workload for a particular set of tasks.

4.1.4 Optimization and Trade-Off Features

HMTee v1.0 allows for tradespace exploration—simultaneously investigating multiple factors in the tradespace and visualizing outcome measures as a function of various human parameters and limits on the values of system components. Future work should investigate and implement optimization functionality wherein the output of one model (or the inputs to that model) linked to the output of another model (Section 4.1.3) is used to programmatically determine a globally optimal solution.

4.1.5 Expanded Graph Types

HMTee v1.0 will accept any pregenerated graph type—that is, graphs created within the configured interaction models. These graphs are displayed as prerendered images; while they update with changes to model inputs, it is not possible to interactively modify their configuration (change variables being plotted, modify graph type, etc.). Moreover, they are unable to integrate or graph any data outside of the model within which they are produced.

On the other hand, there is only one type of interactive graph currently supported in HMTee: a 2-D scatter plot. While this accommodates many types of data, additional graph options should also be included. For example, a bar chart would enable basic comparison of outcome metrics (perhaps across multiple runs of input variables), and interactive multidimensional graphing options like 3-D scatter or small multiples would facilitate data exploration.

4.1.6 Accommodating Complex Systems

Real systems often have a high number of attributes that will affect an analysis—there may be any number of physical dimensions of interest, certain tasks under investigation, user characteristics to consider (perhaps as filters), and so on. HMTee v1.0 will theoretically accept any number of system components, but the interface is not designed to facilitate easy navigation of more than about 10 system components across all interaction models. Future versions should consider how best to display and manipulate complex systems; possibilities include collapsible hierarchies, a filter mechanism, or search capability.

4.1.7 Expanded Export Options

HMTee allows its users to save a snapshot of their current analysis that includes the configured interaction models, system components and constraints, and any human parameters or filters applied. However, additional export options might facilitate integration with other analysis products (e.g., reports); for instance, HMTee could allow saving graphs to a file, generating tables of results, or creating Microsoft Excel spreadsheets with embedded data.

4.1.8 Enhanced Process Logging

To track and archive an analysis, HMTee currently provides a session log and save and load functionality. The session log (which clears with each new analysis) displays a list containing the outcome metric for each run of the configured model(s). This allows the analyst to conveniently compare outcomes when modifying input parameters. The ability to save and load an analysis allows an analyst to save their work for future modification and also provides other analysts with a snapshot of a particular solution or configuration of parameters. However, these features do not allow other analysts to understand the process by which an analyst arrived at a solution. HMTee could implement process logging whereby each action an analyst takes is stored for future replay. This would provide a full step-by-step account of the trial-and-error process of developing an acceptable solution set.

4.1.9 New Avenues for Distributing and Accessing HMTee

Currently, distribution is via direct transfer of the full set of files and subdirectories to the end user (e.g., via DOD SAFE) for execution on their machine. This scheme requires that the end user have R and R Shiny installed and then install all required R packages in their local installation. In the future, it would be beneficial to provide HMTee either via (1) standalone application with no dependencies, or (2) via a hosted location (e.g., an instance of RStudio Server).

4.2 Path Forward for Building the Interaction Model Library

The DAC Innovation Program provided a unique opportunity to develop the HMTee paradigm and implementation. However, it is often difficult to secure funding or to dedicate resources solely for design tool development. Waiting for similar resourcing to expand the library of interaction models in HMTee will likely delay new model development or lead to stagnation of the tool.

Instead, it is suggested that HMTee serve as a sort of repository for analytical work performed during future human factors/HSI projects. Typically, porting a model or analysis to R from another environment (e.g., MATLAB, Python, Excel) is straightforward due in large part to the huge number of open-source R packages available. This task could be completed by personnel in the organization familiar with R, or specified as a contract deliverable if the analysis work is done via contract. Once a model is ported to R, configuring it for use in HMTee requires just one more step to set a few parameters telling HMTee how to use the model as specified in the accompanying technical documentation (Garneau, 2022). Thus, if it can be ported to R, an analysis can become a part of the HMTee interaction model library and available for future use in similar projects or by other analysts. This approach would make HMTee a valuable tool for documenting institutional knowledge via archived processes and analyses and would mitigate knowledge loss when experts leave the organization.

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LIST OF ACRONYMS

2-/3-D	two-/three-dimensional
ANSUR	U.S. Army Anthropometric Survey
ARL	Army Research Laboratory
ARI	U.S. Army Research Institute for the Behavioral and Social Sciences
BOLT	Behavioral Observations Logging Toolkit
DAC	DEVCOM Analysis Center
DEVCOM	U.S. Army Combat Capabilities Development Command
DOD	Department of Defense
HMTee	Human Systems Integration Metric Tradespace Exploration Environment
HSI	Human Systems Integration
HFE	Human Factors Engineering
JASS	Job Assessment Software System
JSON	JavaScript Object Notation
MARC	Military Anthropometry Resource Companion
MPT	Manpower, Personnel, and Training
NIOSH	National Institute for Occupational Safety and Health
O*NET	Occupational Information Network
v	version

ORGANIZATION

DEVCOM Analysis Center
FCDD-DAH-C/C. Garneau
FCDD-DAH-C/A. Bodenhamer
FCDD-DAH-N/D. Patton
FCDD-DAG-S/K. Loftis
FCDD-DAW-J/A. Barnett
FCDD-DAW-W/S. Snead
FCDD-DAW-W/R. Bowers
FCDD-DAW-W/T. Myers
FCDD-DAW-W/A. Kulaga
FCDD-DAD-T/T. Stadterman
6896 Mauchly St.
Aberdeen Proving Ground, MD 21005-5071

DEVCOM Army Research Laboratory
FCDD-RLD-DCI/Tech Library
2800 Powder Mill Rd.
Adelphi, MD 20783-1138

Defense Technical Information Center
ATTN: DTIC-O
8725 John J. Kingman Rd.
Fort Belvoir, VA 22060-6218