Exertional Heat Strain Detection: Application of the Human Performance Model Based Systems Engineering System Architecture (MBSE-SA)

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Outline

- Introduction
- Overview of the Human Performance MBSE-SA
- Utilizing the Human Performance MBSE-SA for Wearable System Selection
- Performing a Cost Benefit Simulation for Wearable System Down-Selection
- Summary

US Military Health Concerns Have a Wide Impact

CNN

Hypoxia being investigated as potential factor in deadly plane crash, source says

By Pete Muntean and Elizabeth Wolfe, CNN
Updated 11:59 AM EDT, Tue June 6, 2023

Unintentional and Musculoskeletal Injuries: Greatest Health Threat to Military Personnel

Published March 14, 2000

JOHNS HOPKINS BLOOMBERG SCHOOL of PUBLIC HEALTH

NEWS

Military fights a deadly enemy: Heat

More U.S. troops are falling to heatstroke as the military struggles to balance training with rising temperatures.

July 23, 2019

11 student athletes treated for heat-related injuries at southern Minnesota cross country meet

WCCO NEWS

BY WCCO STAFF
SEPTEMBER 2, 2022 / 10:11 AM / CBS MINNESOTA

The New York Times

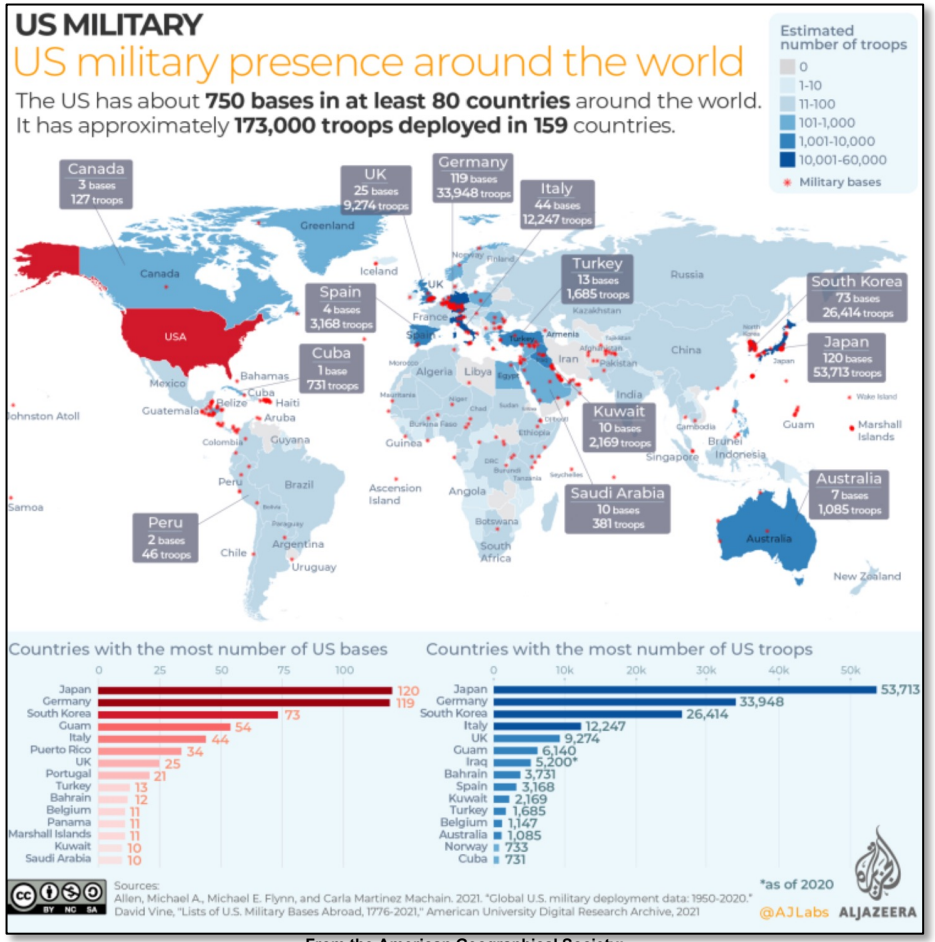
Fatigue and Training Gaps Spell Disaster at Sea, Sailors Warn

By Dave Philipps and Eric Schmitt
Aug. 27, 2017

VOA

January 06, 2022 7:21 AM
William Gallo

US Military COVID-19 Outbreak Spurs Tensions in Japan's Okinawa



From the American Geographical Society:
https://ubique.americangeo.org/map-of-the-week/map-of-the-week-mapping-the-global-u-s-military-bootprint/

Military health concerns impact both civilian health and geopolitical relationships pivotal to national security

Reactive Costs Are Very High – and Growing

Traumatic brain injury

Tinnitus/ hearing loss

Musculoskeletal Injury

PTSD

Personality disorders

Substance abuse

Example health issues leading to increased medical care and disability costs

Depression/ anxiety

Heat Stress

Chemical exposure

Environmental exposure

Infectious disease

Hypoxia

	2001*	2020**	% Change
# of living veterans	25.3M	18.5M	↓ -27%
Total federal budget	$2.7T	$5.3T	↑ 94%
VA budget *Largest shares: Health Care and Disability*	$65.3B	$259.1B	↑ 297%

Prevention

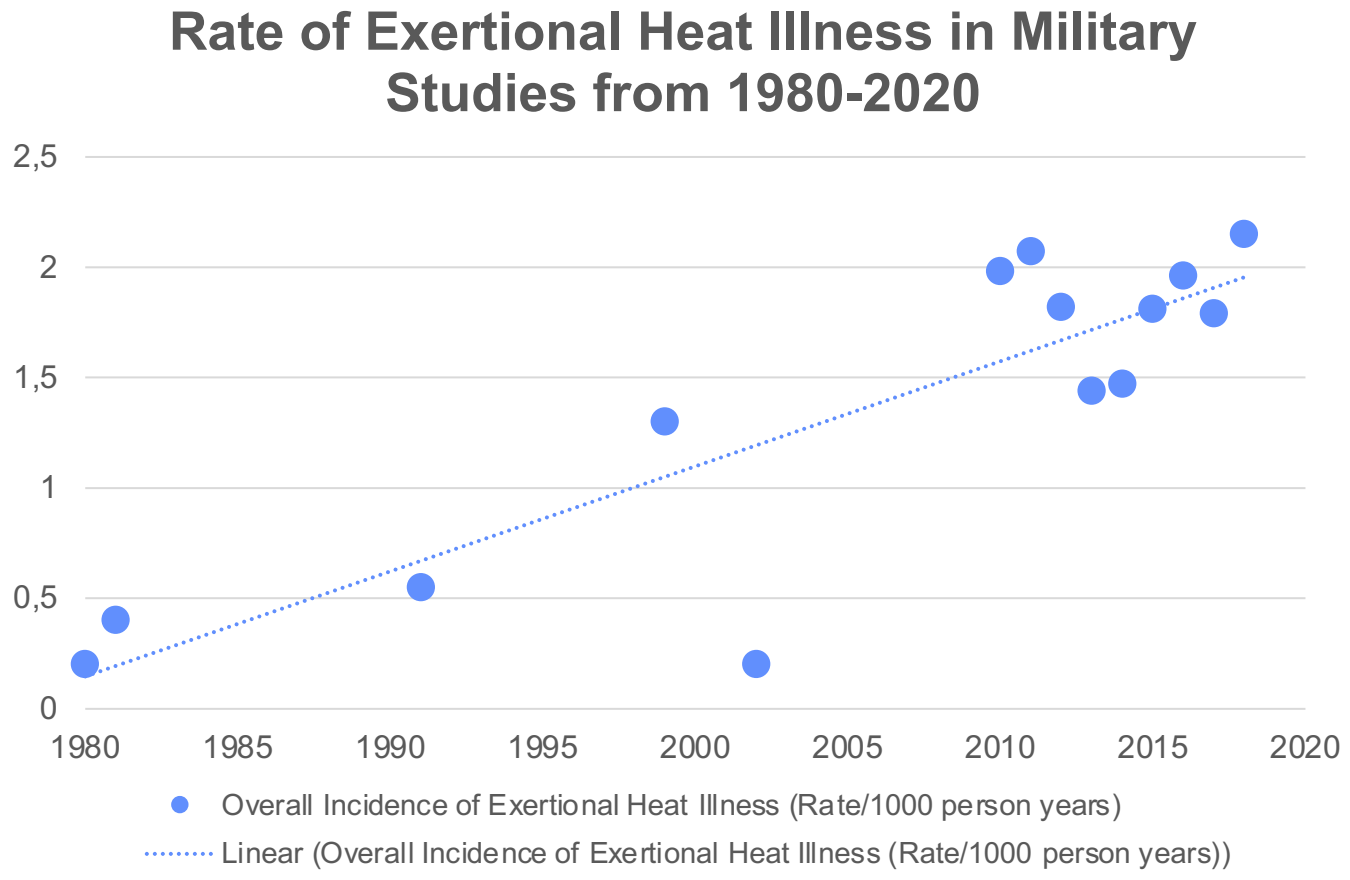
"An ounce of prevention is worth a pound of cure." – Benjamin Franklin

**All 2001 values adjusted for inflation through 2020 (factor of 1.46)*
***Excludes CARES Act funds*

PTSD: Post-Traumatic Stress Disorder
VA: Veterans Affairs

Exertional Heat Stress- an Increasing Problem

- **Each year more than 1,500 Soldiers develop an exertional heat illness (EHI) requiring medical attention and/or lost duty time (DCPH-A, 2023)**
- **In 2017, EHIs were responsible for more than 20,500 lost/limited duty days (DCPH-A, 2023)**
- **On average, 2-3 Soldiers die annually from heat illness (APHC, 2022)**
- **During the 2003 heatwave in Europe, more 70,000 people died (WHO, 2023)**
- **On average in the US, there are over 67,000 emergency department visits each year due to heat (CDC, 2023)**



EHI is an increasing problem that impacts both civilian & warfighter health

EHI: Exertional Heat Illness

What is Heat Stress?

Heat Exhaustion
- 100.5°F < Core Body Temp < 104°F
- Cramps
- Headache
- Nausea
- Dizziness, Unsteady Gait

Heat Stroke
- Core Body Temp < 104°F
- Convulsions and chills
- Vomiting
- Confusion, mumbling
- Loss of Consciousness

Hypernatremia
- History of large water consumption
- Convulsions
- Vomiting
- Confusion
- Clear Urine

Causes:
- **H**eat category
- **E**xertion level
- **A**cclimation
- **T**ime of exposure and rest period

Most vulnerable populations:
- Children
- Elderly
- Athletes
- Outdoor & manual workers

Heat stress is a life-threatening problem

An Ounce of Prevention: Wearable Monitoring Systems for Military Use

Use Cases

Basic Training

Desert Ruck March

Land Navigation

"requires …"

"requires …"

"requires …"

Alert Need

Heat Stress

"requires …"

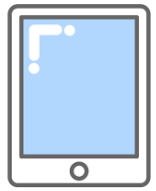
Real World Solution

	Generic Smart Phone
	Amazfit GTS 2e
	Ava Bracelet
	Fitbit Charge 4
	Fitbit Sense
	Oura Ring
	WHOOP 4.0
	HIPS

"requires …"

Communications

Visualization



Data Storage

Security

Selecting a wearable system that satisfies all trades requires an in-depth analysis

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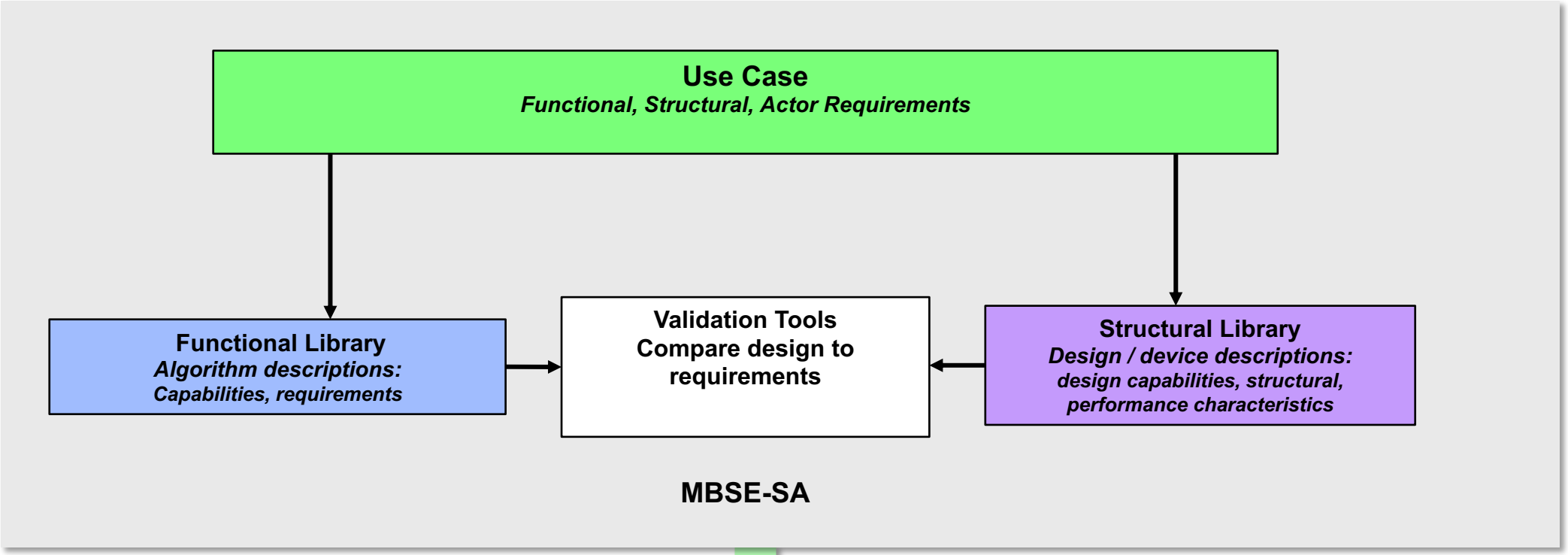
Introduction to the Human Performance MBSE-SA

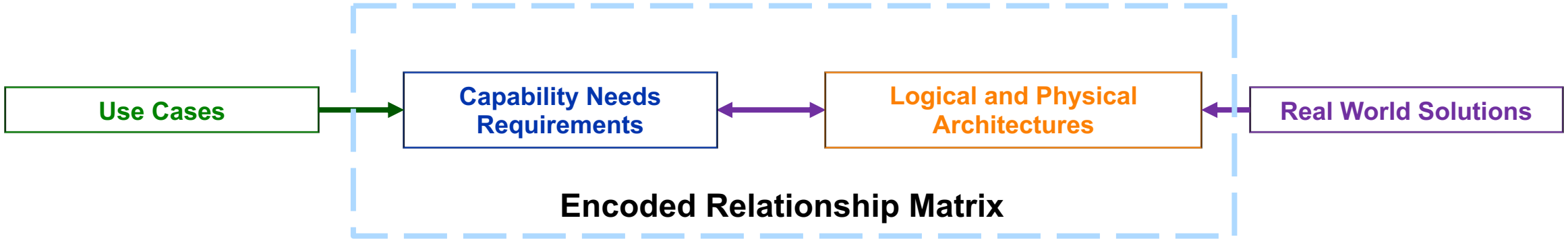


- Multiple views of system requirements
- Systems that meet use case requirements
- Gaps in current capabilities

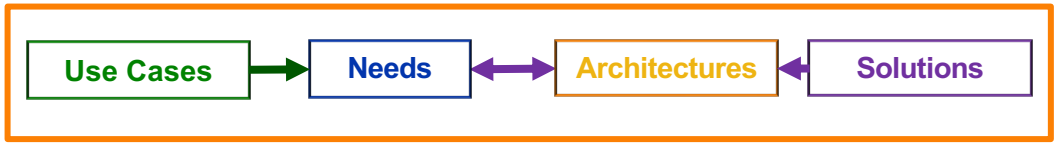
Human Performance MBSE-SA recommends wearable systems that are suitable for delivering relevant health information to end users

How the Human Performance MBSE-SA Works

- **Relationships within the model provide traceability between the use case needs and structural (system) capabilities**
  - **Identify existing system capabilities**
  - **Identify gaps and prioritize future research efforts**
  - **Detect areas for integration**
- **Relationship Options**
  - **DIRECT: Trace use case needs directly to the solution, similar to standard acquisition process**
  - **INDIRECT: Trace use case needs via capability requirement to solution capabilities**
    - **Benefit: technology agnostic architecture requirements, multiple solutions can address needs**



Use Case Relationship Example



- **Focus on capturing highly leveraged "scenarios" (aka capability requirements); use cases will be built from libraries as needed.**

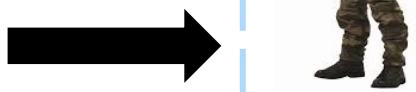
Use Cases

CBRND Training

Ebola Epidemic

Chemical Warfare

"requires a…"



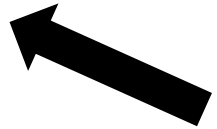
Hazmat suit

Hazmat suit threats

- Chem bio detection
- Decontamination
- Heat stress
- Musculoskeletal
- Cognitive fatigue
- Hypoxia

Encoded Relationship Matrix

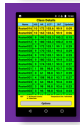
"provides …"



Real World Solutions

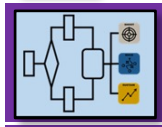
Environmental chem bio sensors

Personal contamination alerts



Heat stress alerts, algorithms, and measures

MSI alerts, algorithms, and measures



Cognitive fatigue alerts, algorithms and measures

Performance readiness metrics

Hypoxia alerts, algorithms, and measures

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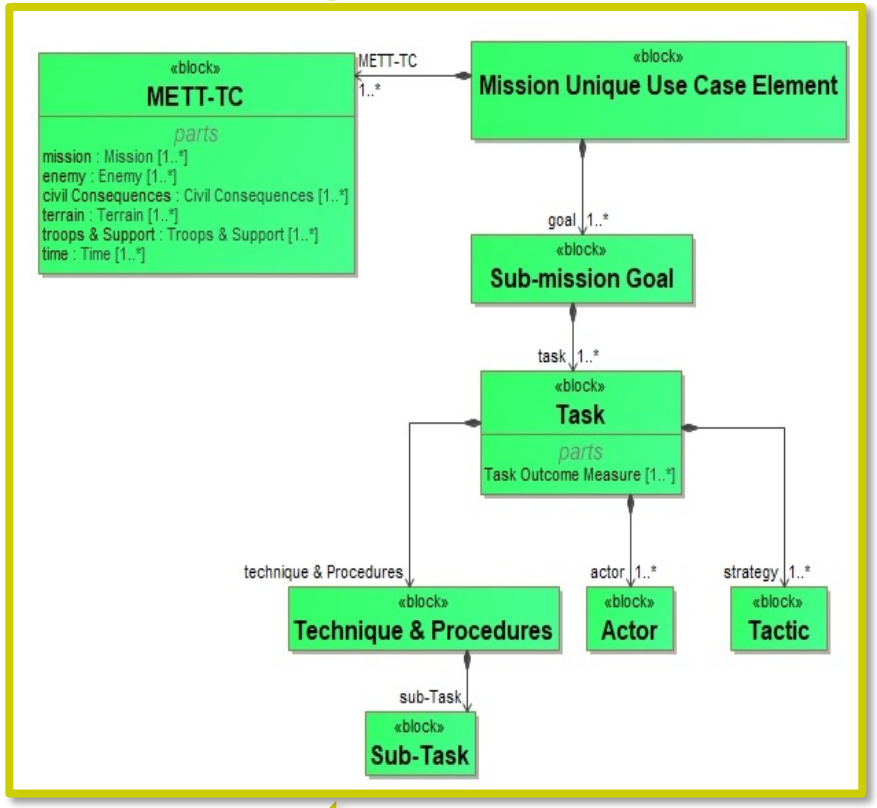
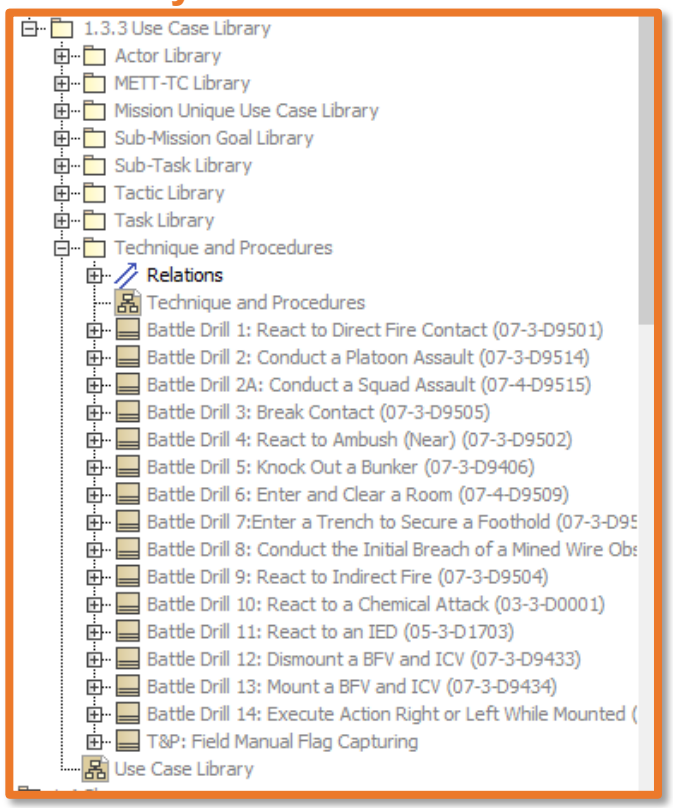
Different Aspects of the Human Performance MBSE-SA

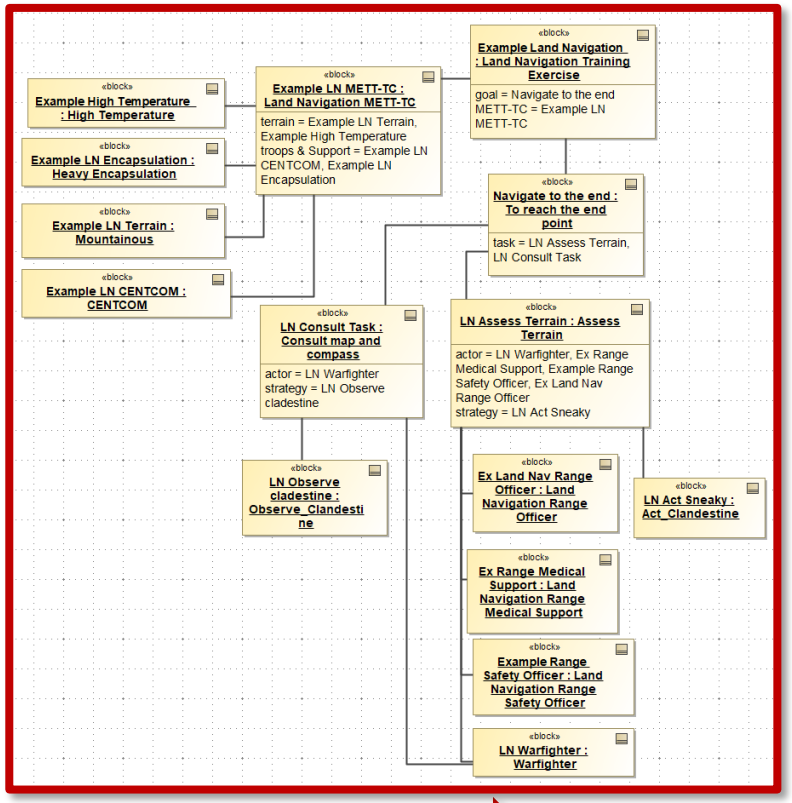
Conceptual Architecture



Physical Architecture



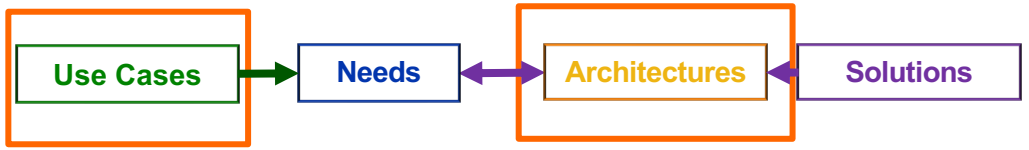
Instance Library



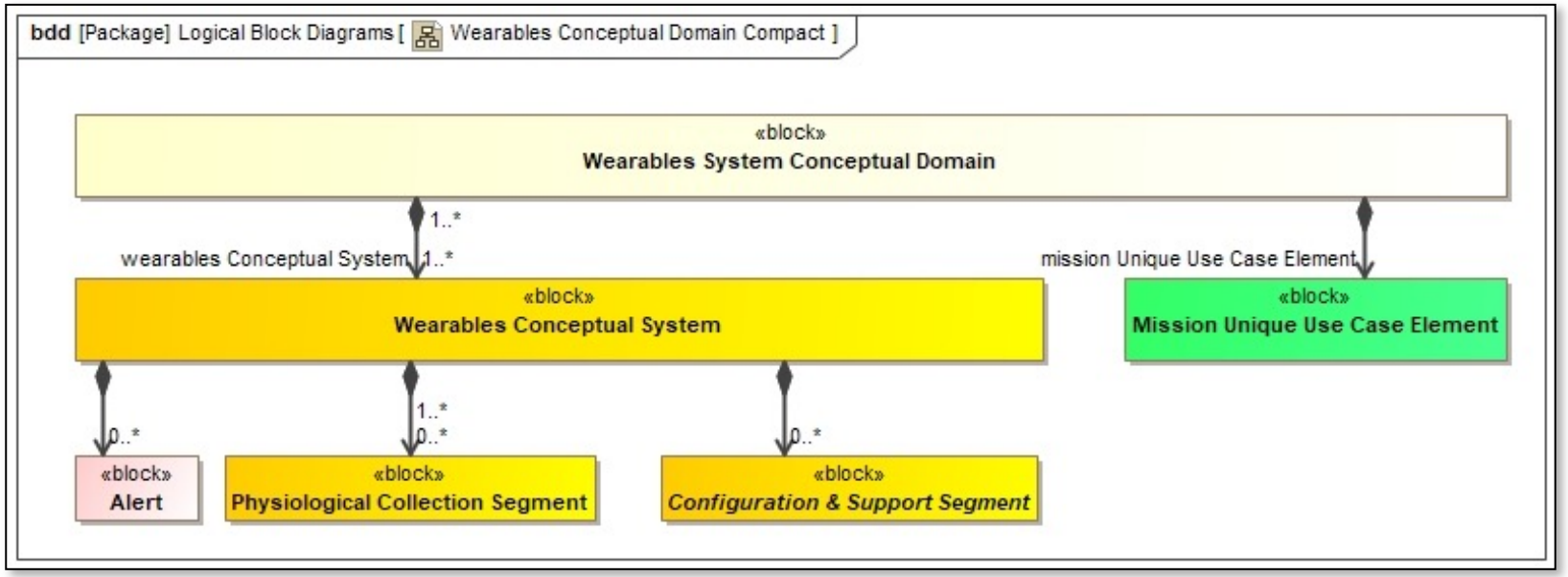
Generalized → Specific

Human Performance MBSE-SA supplies a reusable common framework to assess the compatibility and capabilities of real-world systems

Conceptual Architecture

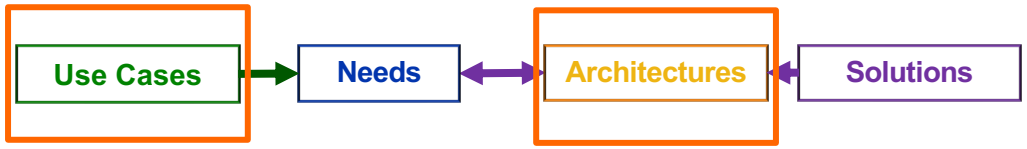


- **Alert Branch**: Encompasses abstract functions that make up the health alerts that a realized system could generate (such as a heat stress alert)
- **Wearables Conceptual System Branch**: Defines abstractions of realized or proposed devices and sensors
- **Mission Unique Use Case Element Branch**: Includes abstractions needed to define use cases whose requirements may be met by a structural system

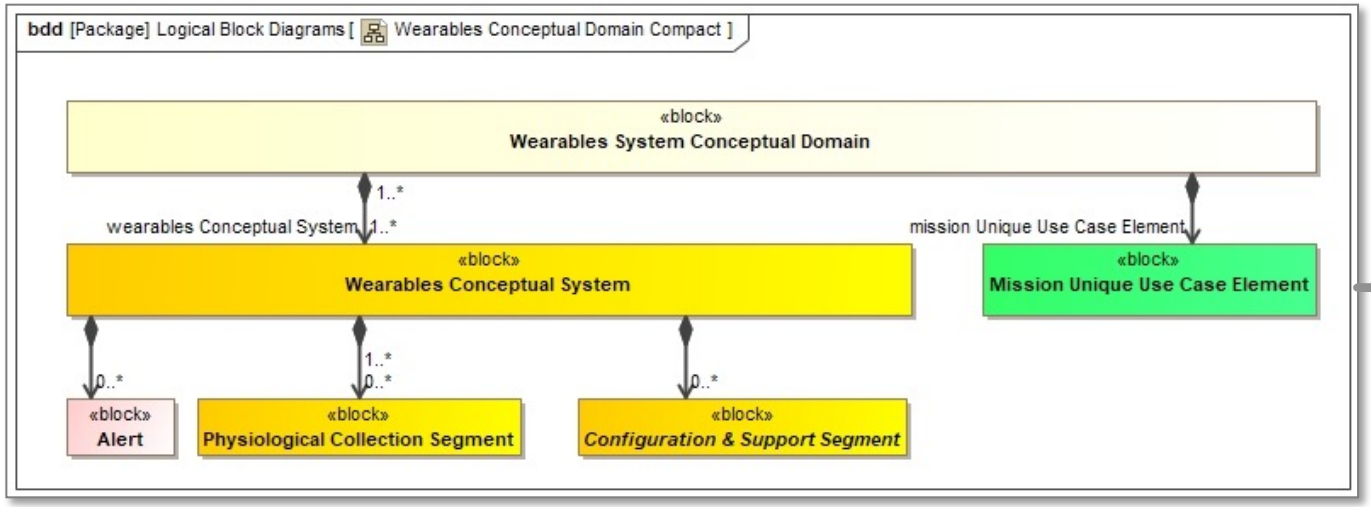


Conceptual Architecture generically describes and relates alerts, wearable systems, and military use cases in a consistent way

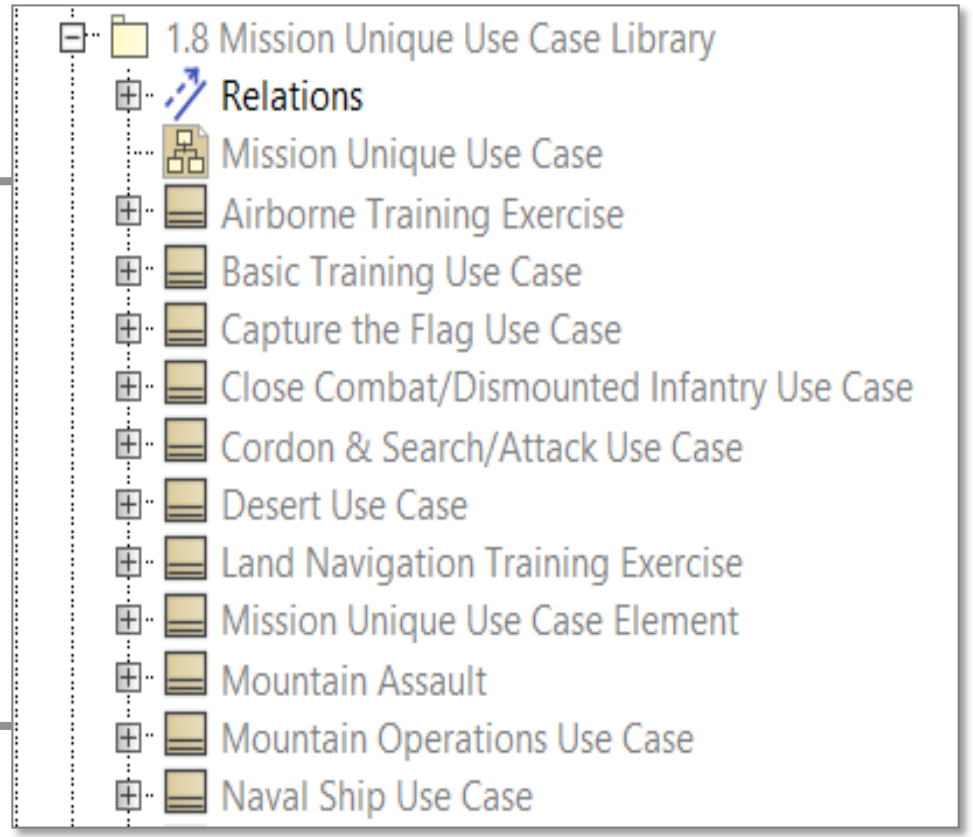
Physical Architecture



Conceptual Architecture



Physical Architecture for Use Case Branch

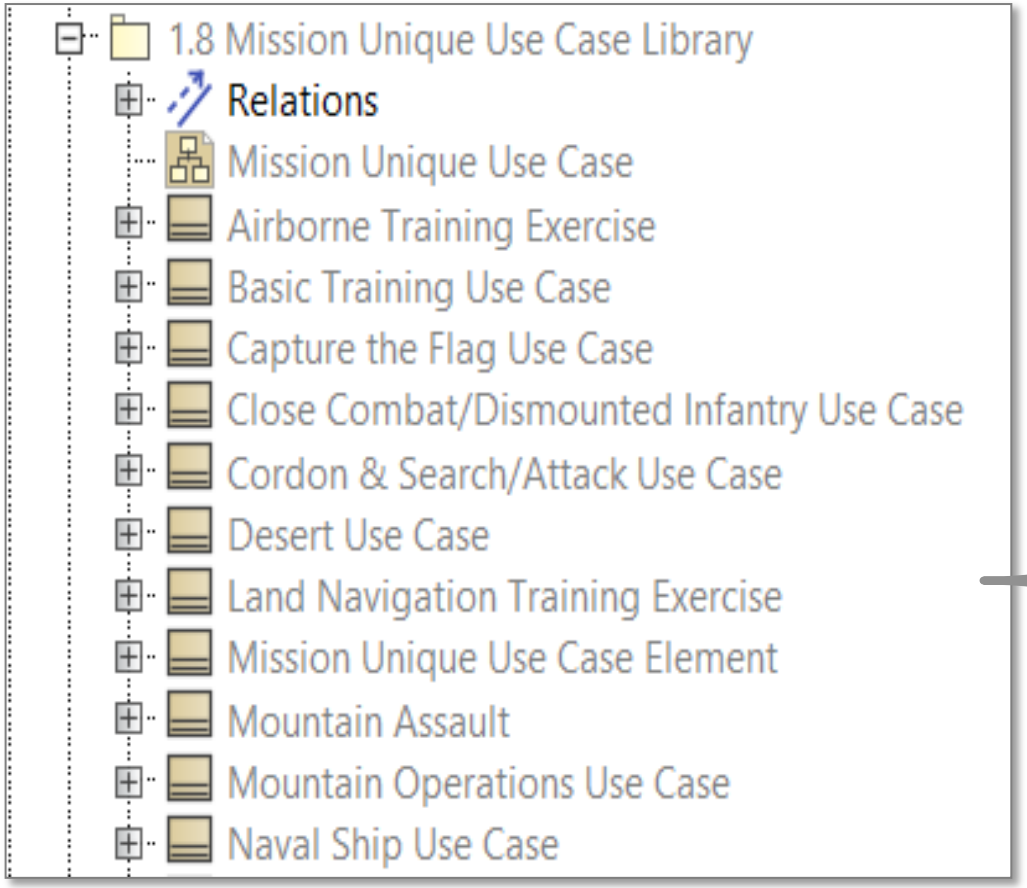


Physical Architecture contains the building blocks in which more specific use cases, systems, and alerts can be defined

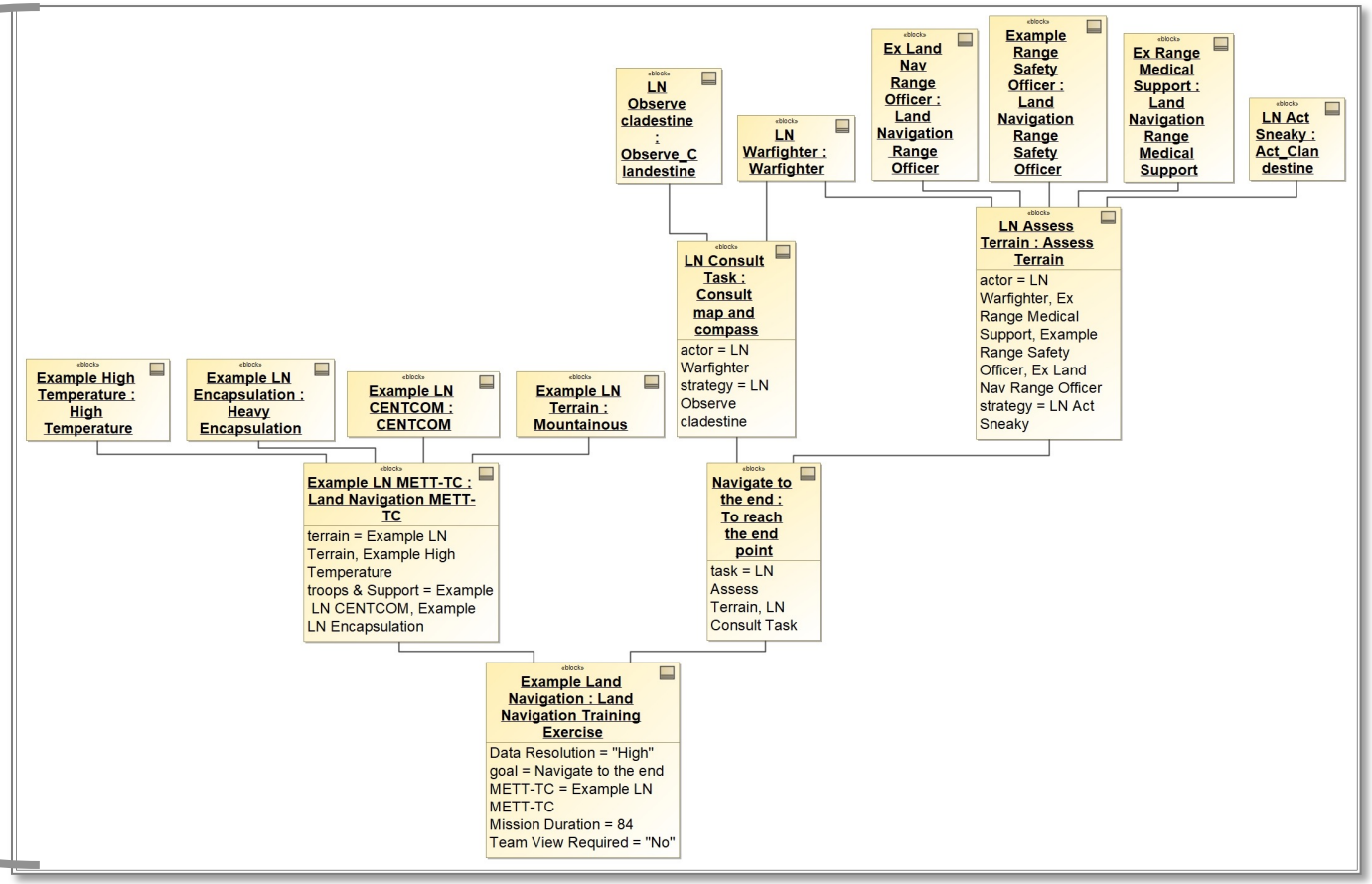
Instance Library

Use Cases → Needs ↔ Architectures ← Solutions

Physical Architecture for Use Case Branch



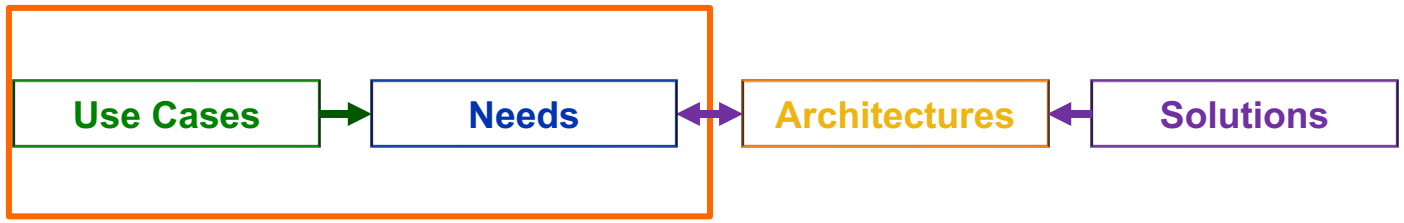
Instance Model for Example Land Navigation Use Case



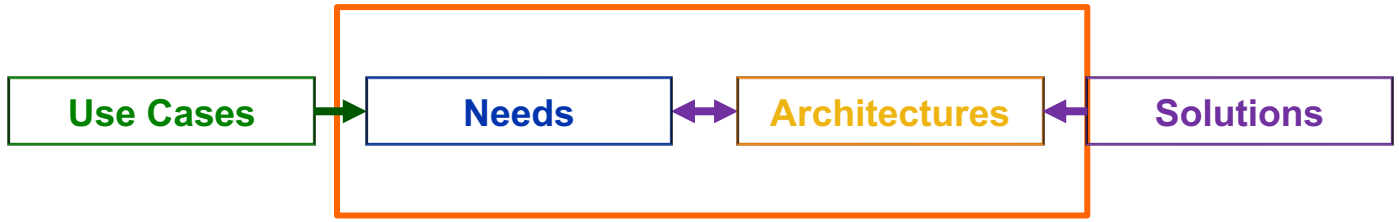
Instance Library represents specific real-world alerts, wearable systems, and military use cases

Using the Model to Identify Systems to Use Cases with Heat Stress Concern

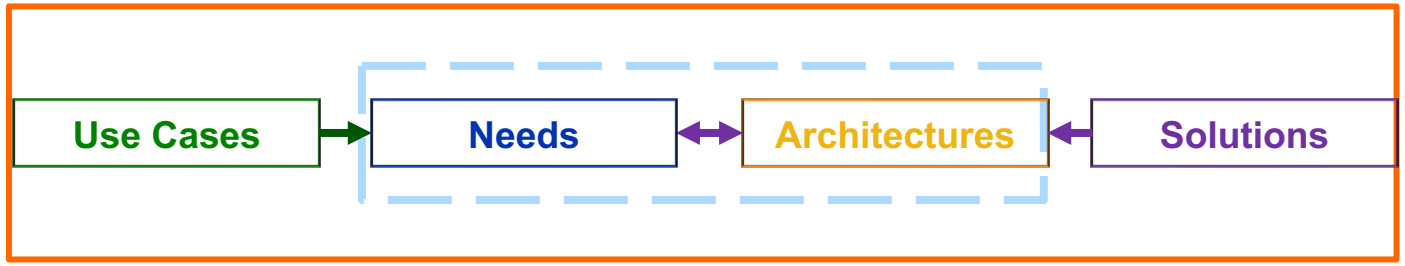
Apply the conceptual architecture to identify use cases that require a heat stress alert



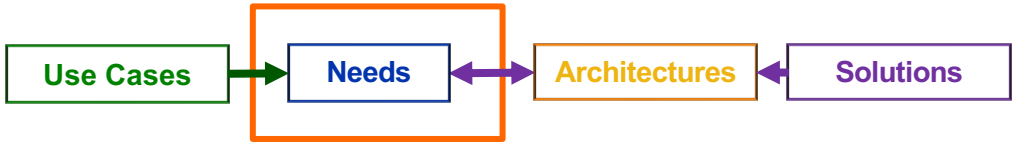
Apply the conceptual architecture to identify wearable systems with a heat stress alert



Compare the previously identified wearable systems to determine the best system for each use case



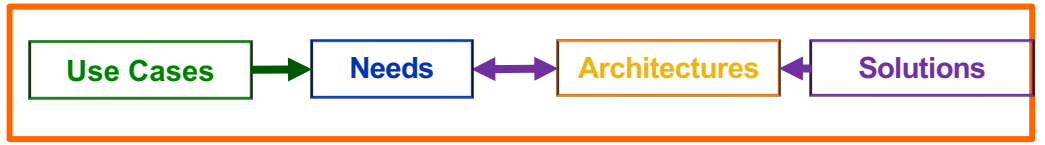
Applying the Conceptual Architecture: Capability Needs

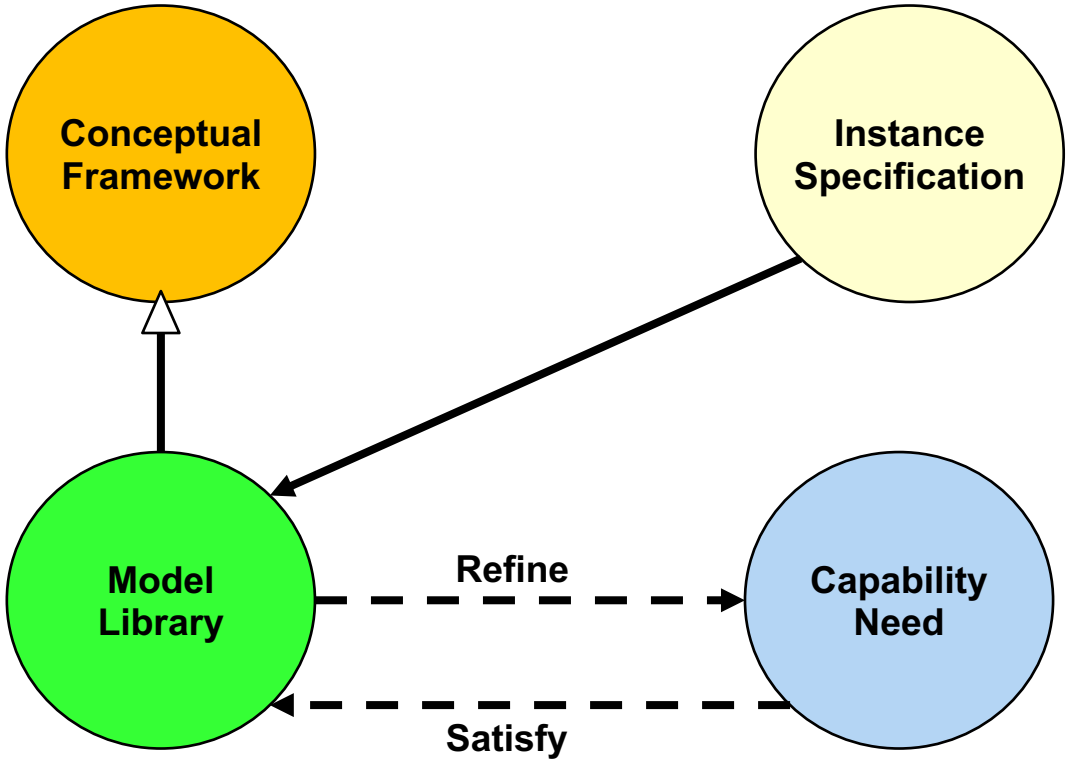


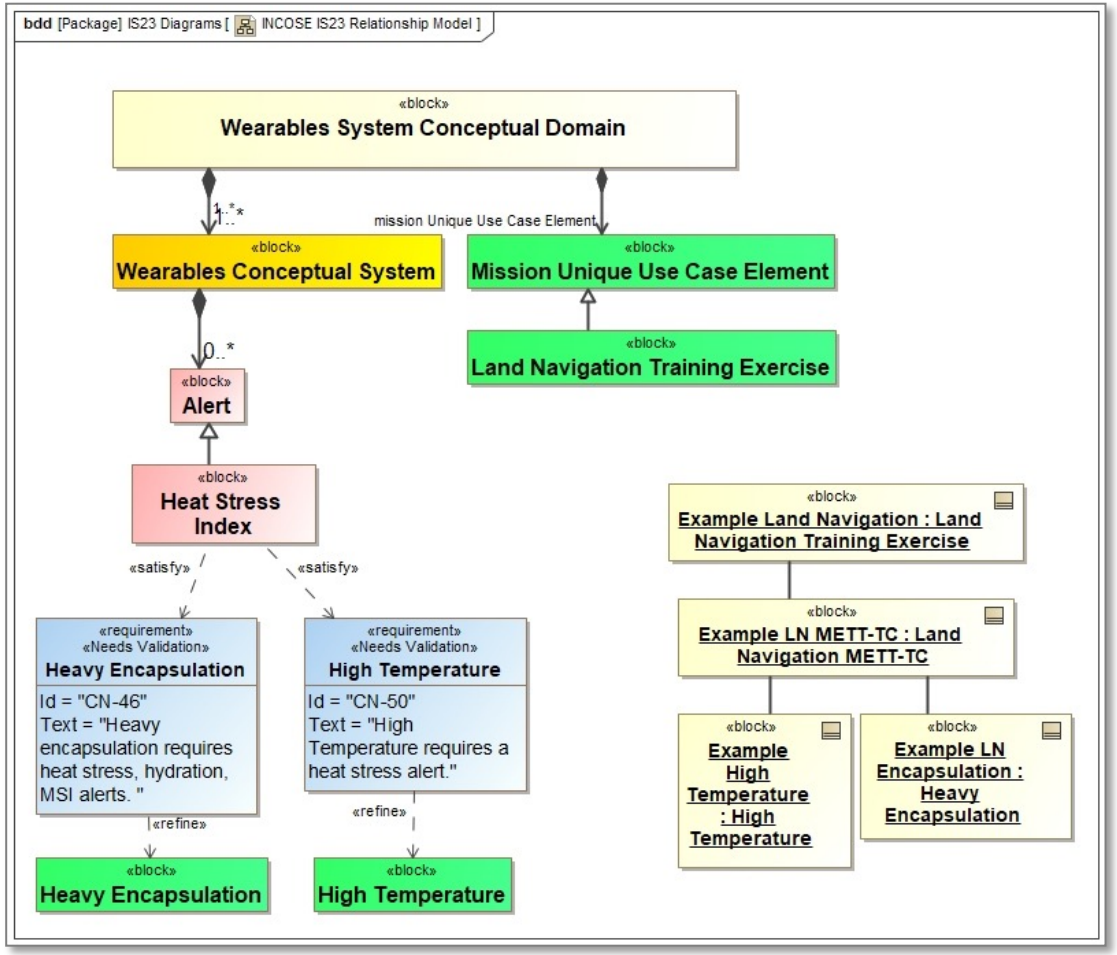
#	Name	Satisfied By	Refines	Text
6	Beginner Experience Level	Heat Stress Alert Movement Alert Hydration Alert Cognitive Readiness Ale	Beginner Warfighter	Beginner warfighter requires alertness, hydration, movement alert and heat stress alert. Recruits had the highest incident rate of exertional heat stress injury.
11	Heat Acclimatization	Heat Stress Alert	New Location for Troops	Not being acclimated to a climate can lead to heat stress.
12	Heat Alert for Airborne Phase I exercise	Heat Stress Alert	Airborne Training Immediate Leader Airborne Training Medical Support Airborne Training Jump Safety Officer	Jump safety, immediate leader, and medical support all require heat monitoring
13	Heavy Encapsulation	Hydration Alert Heat Stress Alert Musculoskeletal Injury A	Heavy Encapsulation	Heavy encapsulation requires heat stress, hydration, MSI alerts.
16	High Humidity	Hydration Alert Heat Stress Alert	High Humidity	High humidity requires hydration and heat stress alert. Humid environments have a high rate of exertional heat stress injuries.
17	High Temperature	Heat Stress Alert	High Temperature	High Temperature requires a heat stress alert.
35	Road March	Hydration Alert Location Alert Movement Alert Heat Stress Alert	Road March	Road March requires HSI alert, movement alert, location alert, hydration alert, cognitive alert. Road marches with loads had the highest rate of EHI at Fort Benning between 2017 and 2021.
40	Training Environment	Heat Stress Alert Cardiovascular Alert Emotional State Alert Hydration Alert Metabolic State Alert Sleep Health Alert Wellness Status Alert Musculoskeletal Injury A	Training Area	When training, it is important to consider the overall health of the warfighter in order to prevent unnecessary injuries.
55	Recent Febrile Illness	Acute COVID Infection A Post COVID Infection Al Heat Stress Alert	Recent Illness or Immunization	Recent febrile illness or immunization leaves a person at higher risk for an exertional heat stress event.
56	Combat Task and Heat Injury	Heat Stress Alert	Combat Tasks	Combat-related occupations had the highest rate of EHI across the DoD in 2021 (4x higher than other occupations).

Capability Needs relate Physiological Alerts to Use Case Physical Library elements

Applying the Conceptual Architecture: Relationship Model



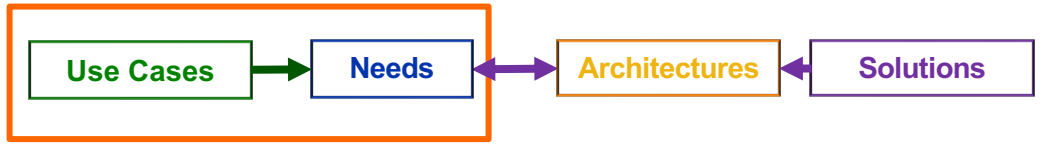


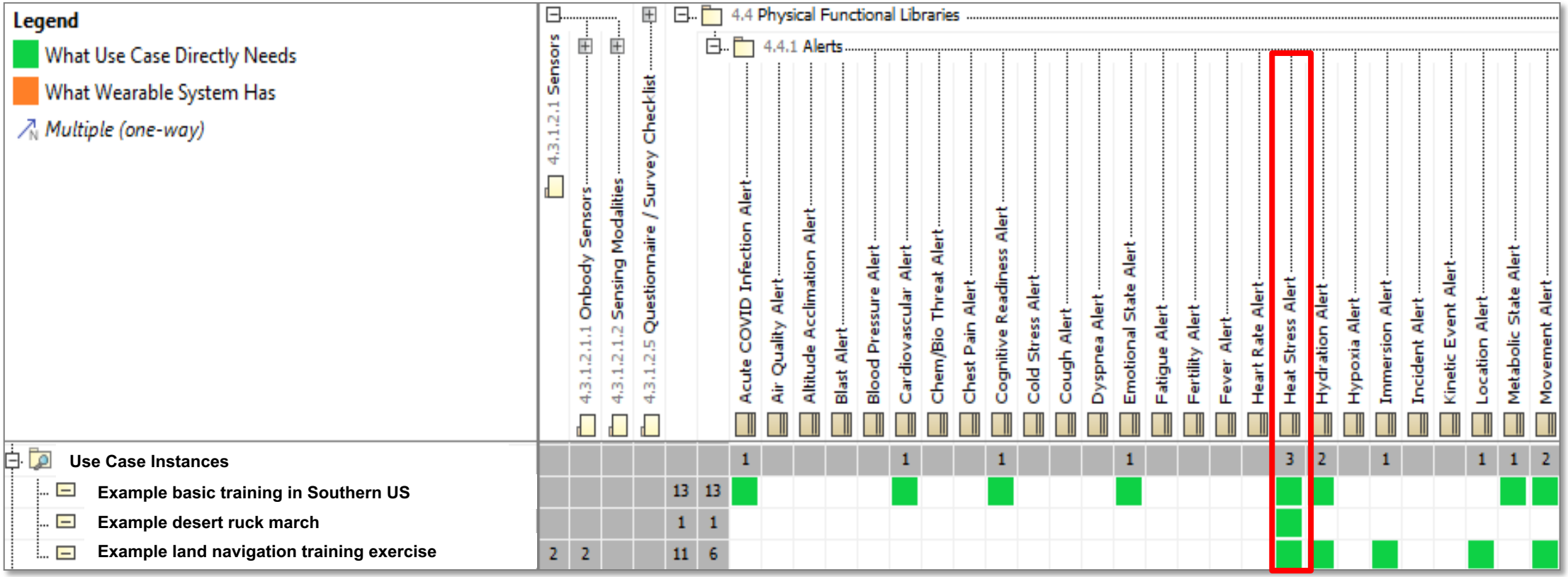


A Relationship Model allows for analyses to be automatically performed among the three different branches

METT-TC: Mission, Enemy, Terrain and Weather, Troops and Support, Time Available, and Civil Considerations

Military Use Cases Requiring Heat Stress Alert

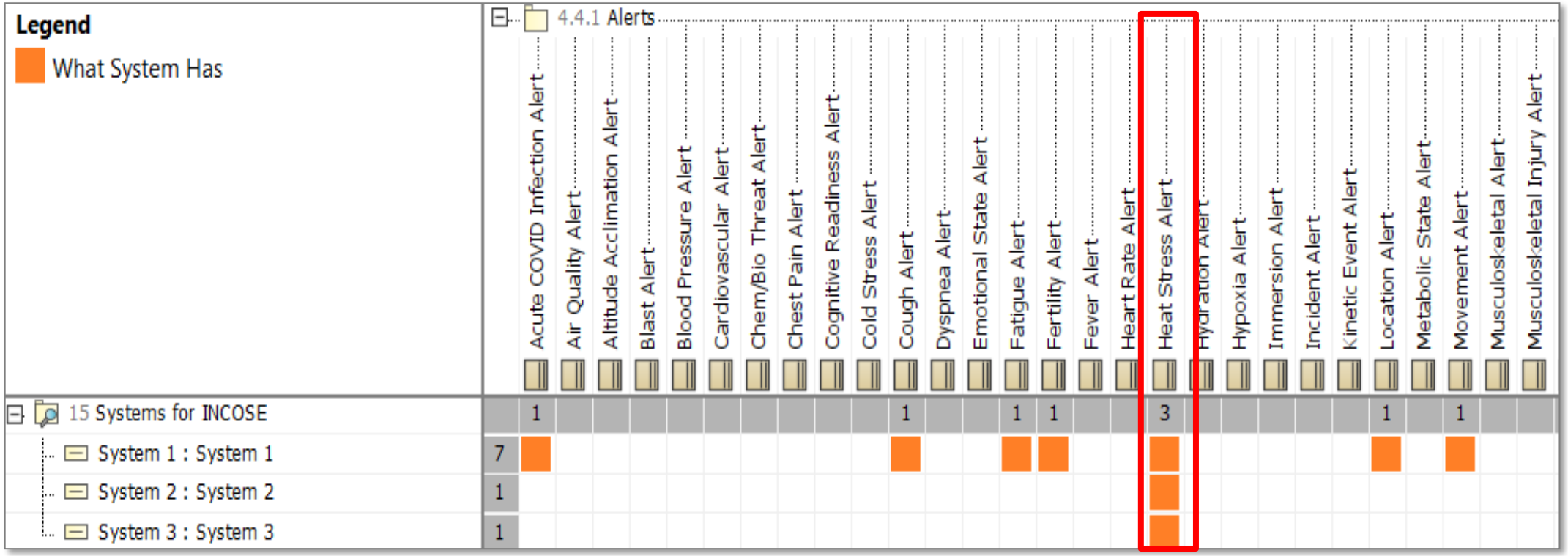




Dependency Matrix reveals three Use Cases which require a Heat Stress Alert

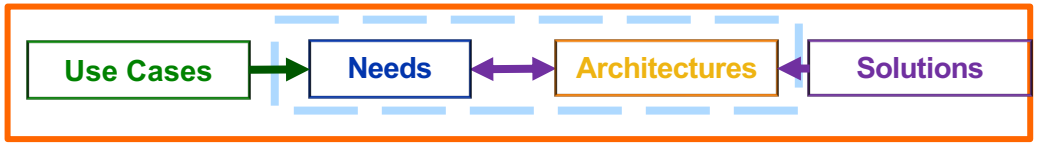
Wearable Systems With Heat Stress Alert Functionality

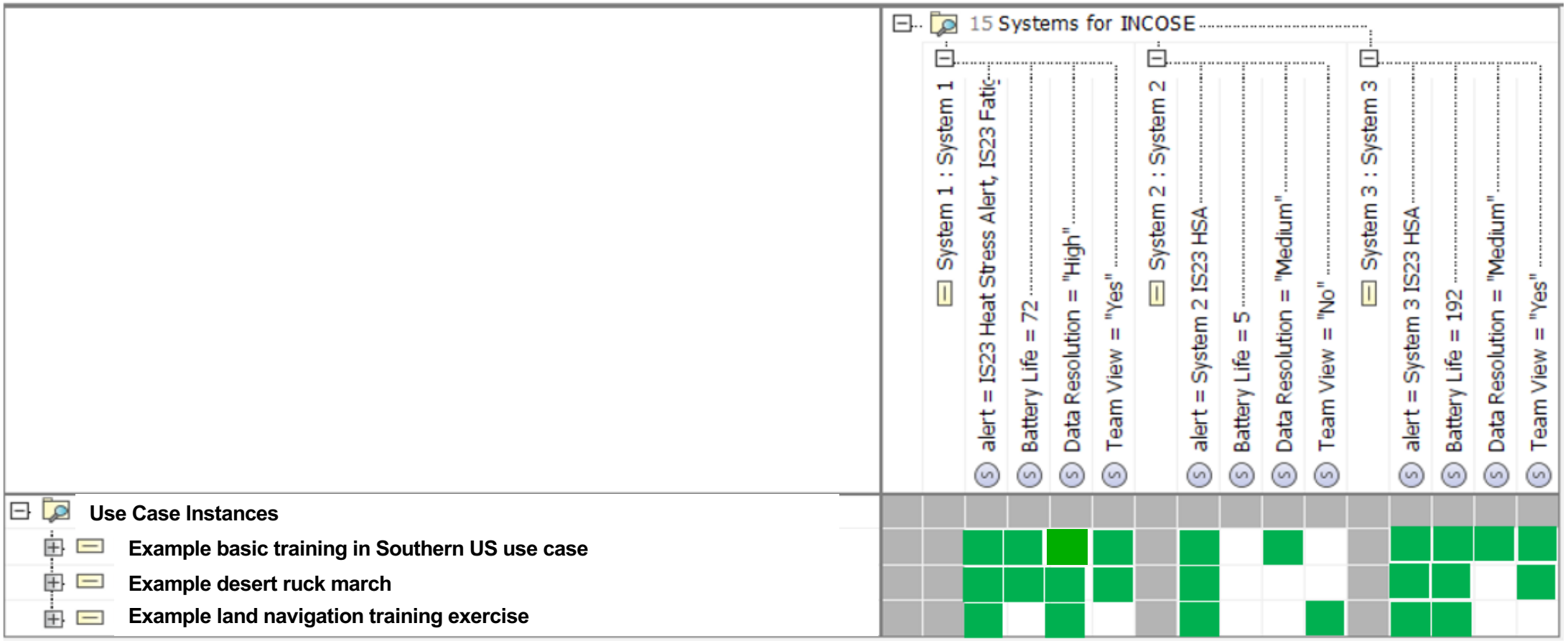
Use Cases → Needs ↔ Architectures ← Solutions



Dependency Matrix reveals three Wearable Systems which provide a Heat Stress Alert

Determining Best Wearable System for Use Case





System 1 meets the requirements for Basic Training and Desert Ruck March, while System 3 meets the requirements for Basic Training. However, how does system cost factor in?

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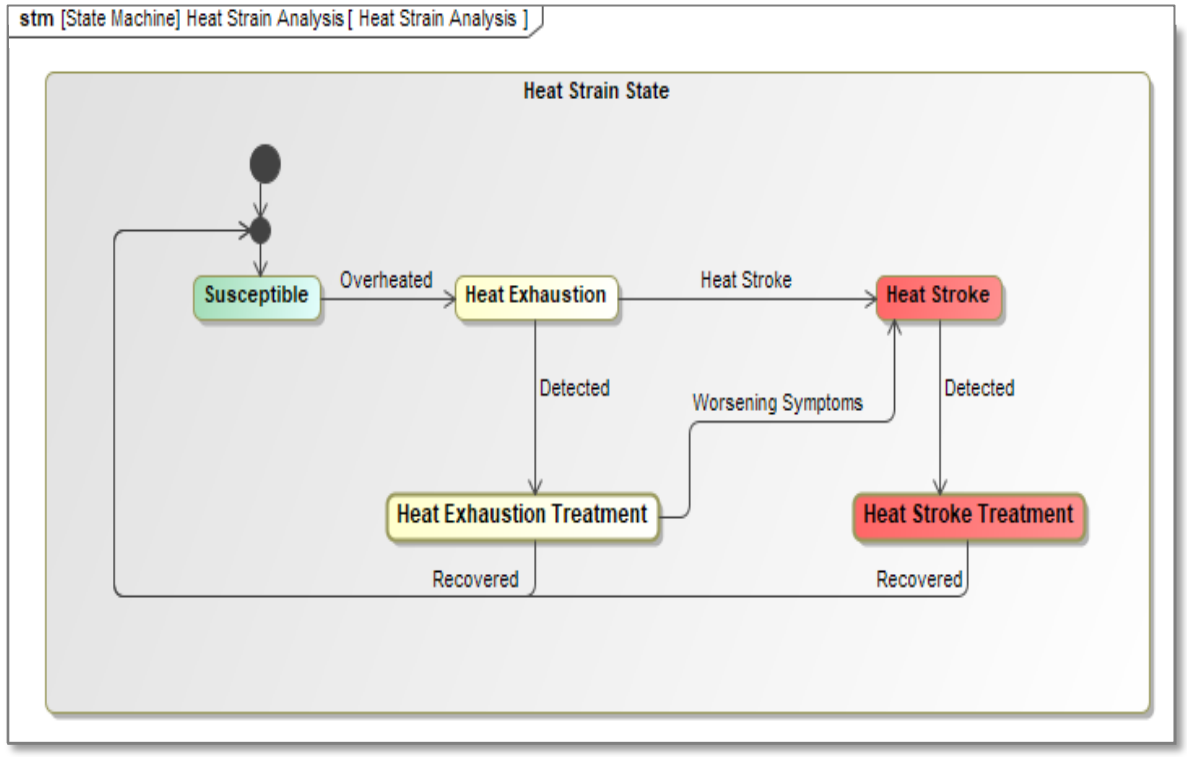
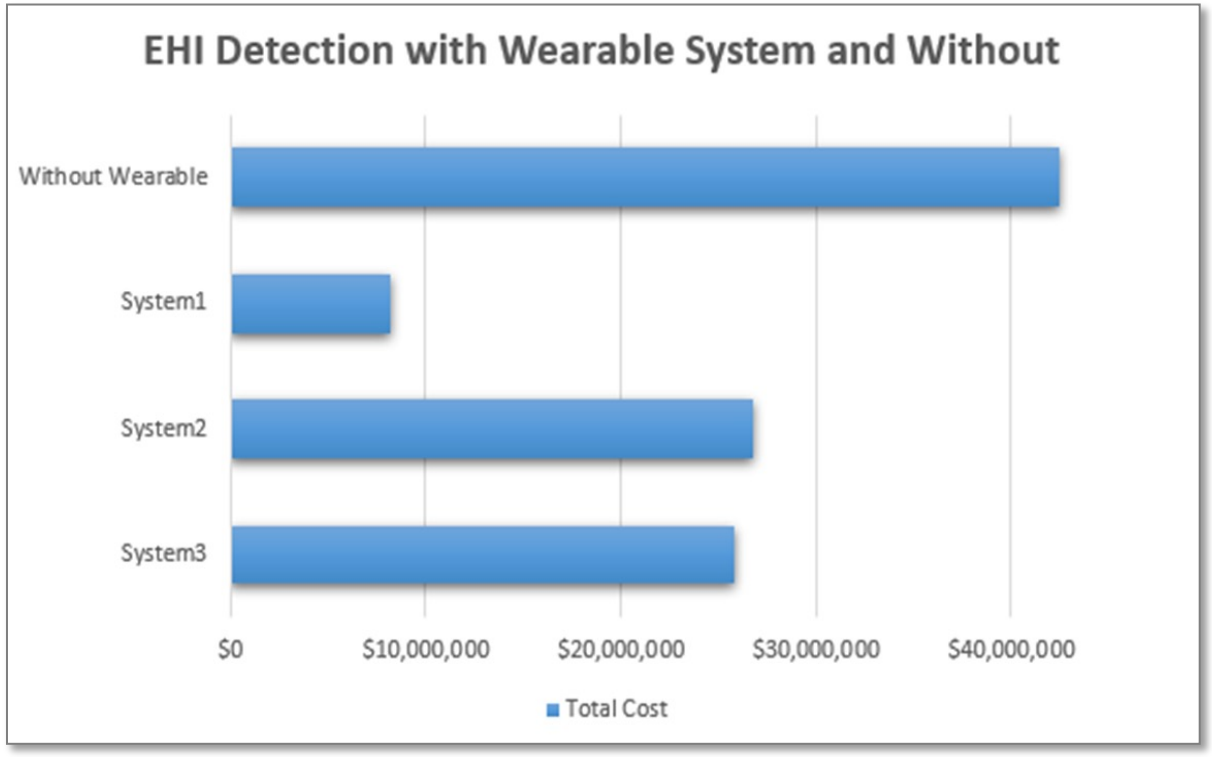
Heat Strain Cost Analysis Simulation





Cost-benefit simulation within the MBSE-SA takes into account wearable system costs and healthcare costs

Simulation Construction Process

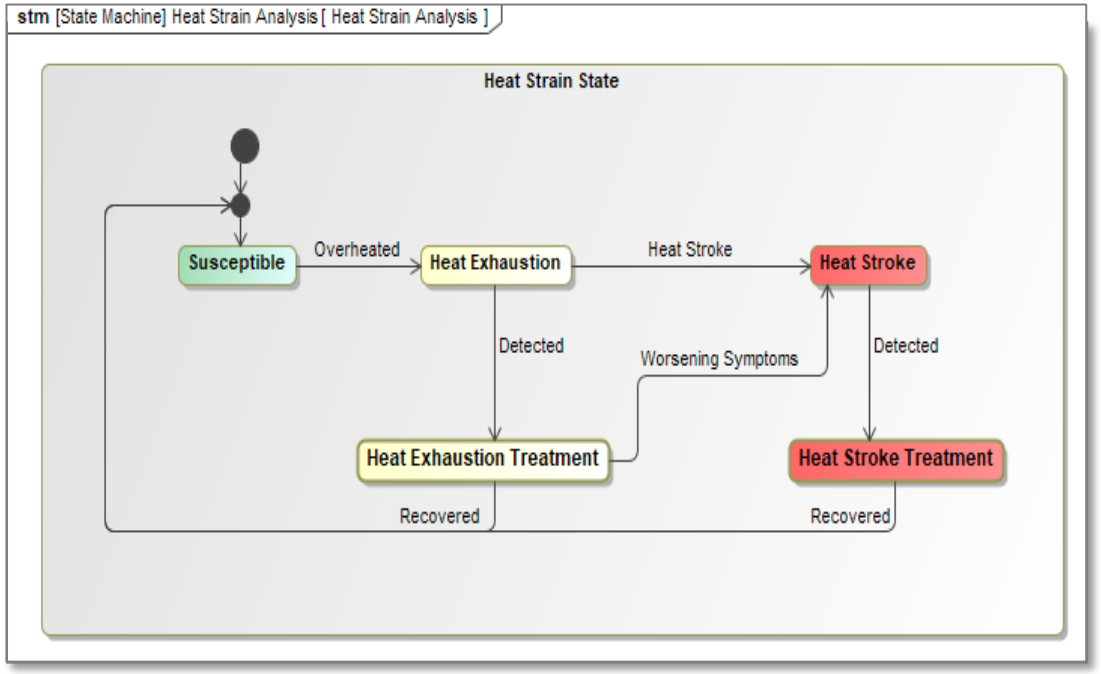
Build
- Build machine based on problem states

Elaborate
- Elaborate with associated health costs

Assess
- Assess potential wearable systems

Input
- Input wearable system characteristics

Run
- Run simulation



Simulation Construction Process- Build

Build
- **Build machine based on problem states**

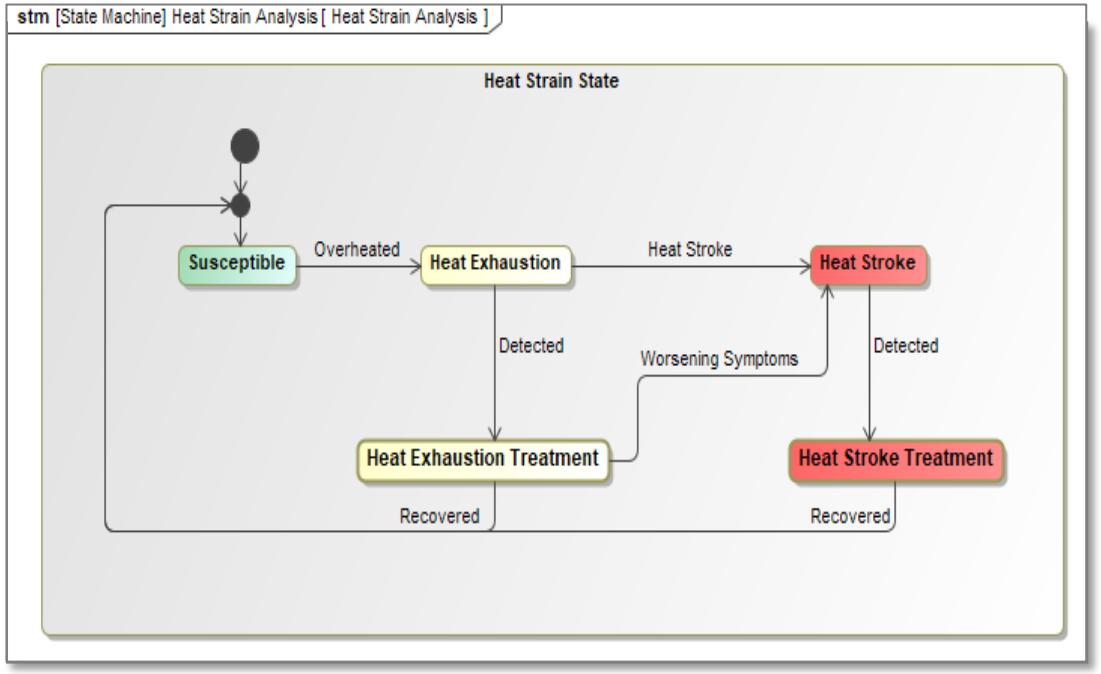
Elaborate
- Elaborate with associated health costs

Assess
- Assess potential wearable systems

Input
- Input wearable system characteristics

Run
- Run simulation

- **What is the progression of the medical condition in question?**



Simulation Construction Process- Elaborate

Build
- Build machine based on problem states

Elaborate
- Elaborate with associated health costs

Assess
- Assess potential wearable systems

Input
- Input wearable system characteristics

Run
- Run simulation

- **Be sure to include direct and indirect costs**

TABLE 2. Medical encounters and direct care costs associated with heat illness, U.S. Army, 2016–2018

Heat illness	Care location	Total heat encounters	% total encounters	Total direct care cost	% total direct care cost	Per encounter cost
Any heat illness[a]	All	13,087	100.0	$7,321,719	100.0	$559
Heat exhaustion	All	9,074	69.3	$3,720,542	50.8	$410
	Inpatient	186	2.0	$761,413	20.5	$4,094
	Outpatient	8,888	98.0	$2,959,129	79.5	$333
Heat stroke	All	4,013	30.6	$3,601,177	49.2	$897
	Inpatient	344	8.6	$2,563,740	71.2	$7,453
	Outpatient	3,669	91.4	$1,037,436	28.8	$283

[a]Includes heat exhaustion and heat stroke.

Simulation Construction Process- Assess

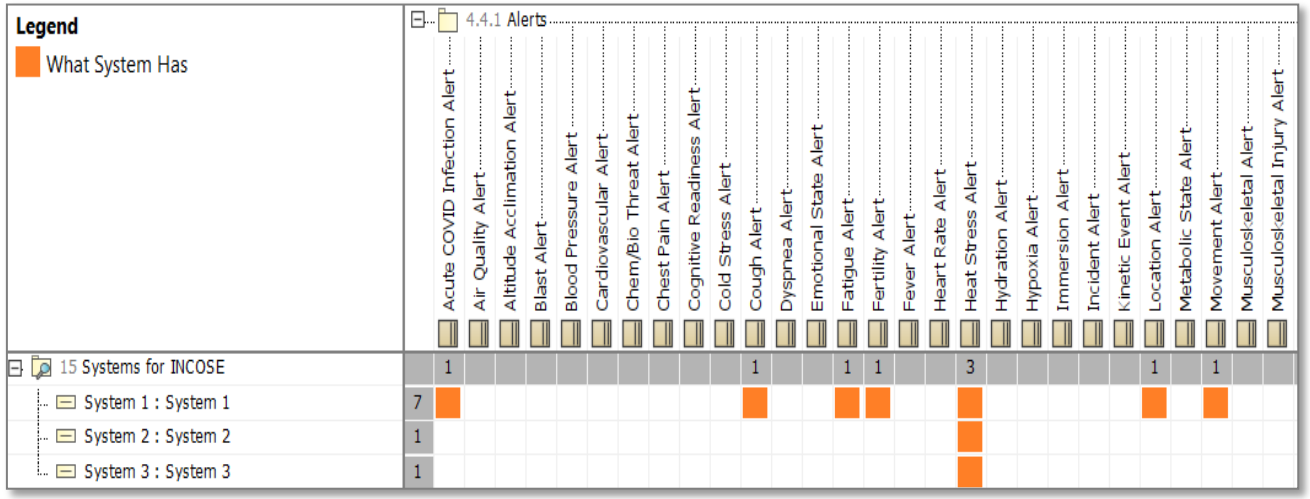
Build
- Build machine based on problem states

Elaborate
- Elaborate with associated health costs

Assess
- **Assess potential wearable systems**

Input
- Input wearable system characteristics

Run
- Run simulation



Simulation Construction Process- Input

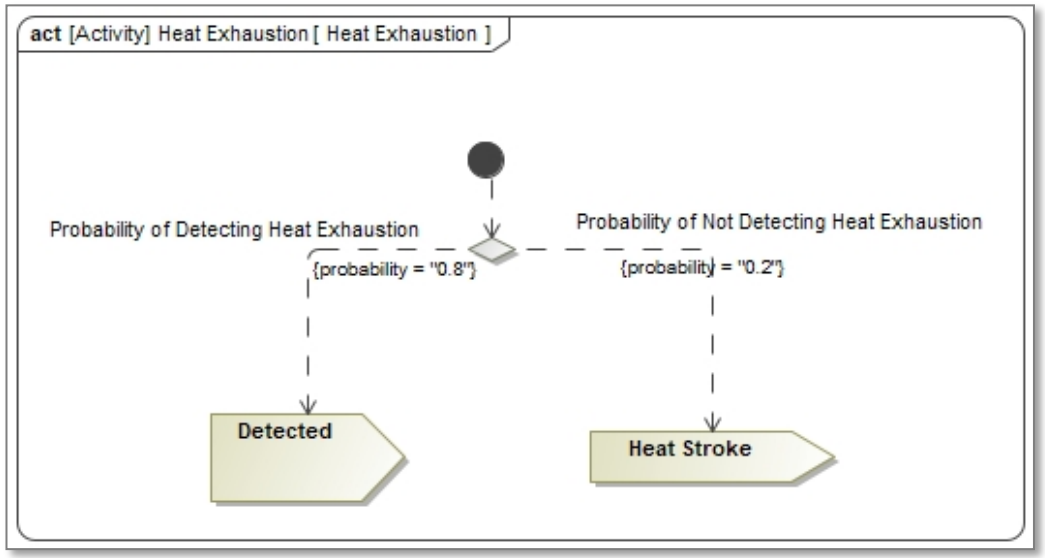
Build
- Build machine based on problem states

Elaborate
- Elaborate with associated health costs

Assess
- Assess potential wearable systems

Input
- Input wearable system characteristics

Run
- Run simulation



- **What is the probability of detection and the probability of false alarm for the system?**
- **How many wearable systems do you need?**

Simulation Construction Process- Run

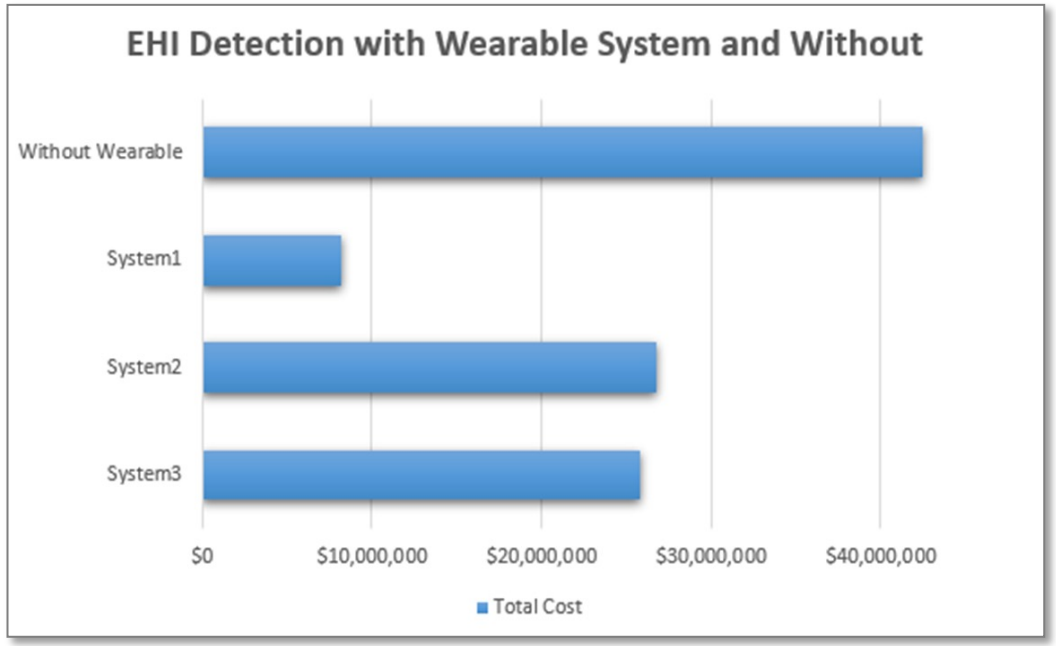
Build
- Build machine based on problem states

Elaborate
- Elaborate with associated health costs

Assess
- Assess potential wearable systems

Input
- Input wearable system characteristics

Run
- Run simulation



While this graph looks at one ailment, the cost-benefit of wearable systems is further enhanced when looking at multi-illness detection

Comparing Wearable System Functionality to Cost

Basic Training

	Battery	Resolution	Team View	Cost-Benefit
System 1	G	G	G	Best
System 2	Y	G	R	Good
System 3	G	G	G	Good

Desert Ruck March

	Battery	Resolution	Team View	Cost-Benefit
System 1	R	G	G	Best
System 2	R	Y	R	Good
System 3	G	Y	G	Good

While System 1 has the lowest overall cost, its important to consider how a wearable system operates in many different use cases

Summary

- Exertional heat illness is an increasing problem that impacts both civilian & warfighter health
- A Cost-Benefit Simulation added to the MBSE-SA can compare the cost of a wearable system against the costs of a physiological event or several physiological events
- The Human Performance MBSE-SA helps in selecting a wearable system that satisfies the tradeoff between cost, functionality and use case suitability that is essential for heat illness prevention

- Future efforts include developing tools that enable DoD leaders and mission planners to:
  - Perform analyses across a range of missions
  - Identify opportunities for mission improvement