Department of Defense Guidance

Integrating Sustainability into DoD Acquisitions

Version 2.0 – Draft

May 2014

Integrating Sustainability into DoD Acquisitions

Executive Summary

This draft guidance introduces the concept of a Sustainability Analysis. It provides detailed guidance on how to complete such an analysis and how to use the results to better inform tradeoff, design, and supportability decisions. Subject to final approval, this guidance can be used on a trial basis by all Departments and Agencies within the Department of Defense (DoD).

Sustainability is the capacity to endure. The environmental-related term "sustainability" is often defined as a durable and self-sufficient balance between social, economic, and environmental factors. In the context of the DoD acquisition process, and for the purpose of this guidance, sustainability means wisely using resources and minimizing corresponding mission, human health, and environmental impacts and associated costs during the life cycle.

The DoD acquires weapons systems, equipment, and platforms (hereafter referred to as "systems") that must be made more sustainable to meet mission requirements well into the future while reducing life cycle costs (LCCs). Systems often need to be sustained for up to 30 years or more while consuming resources that are costly and in many cases dwindling. The DoD term "sustainment" is used by acquisition and logistics professionals to describe the support needed to operate and maintain a system over its lifetime. Acquisition personnel must fully understand life cycle impacts and the costs of systems; otherwise, they could inadvertently "push downstream" significant impacts and associated costs to the DoD operational, logistics, and installations management communities. For example, energy-efficient systems are often procured up front to reduce life cycle energy costs; however, there is an entire class of costs that are typically excluded from current LCC estimates during acquisition. Thus, opportunities are missed to minimize these costs during acquisition. Some examples of life cycle costs related to material design choices and chemicals used during sustainment include investments in personal protective equipment (PPE) and engineering controls, hazardous waste management, water use, environmental differential pay, and medical monitoring.

A Sustainability Analysis allows for more robust and informed trade space and supportability analyses. To improve visibility into traditionally hidden sustainability-related costs, this guidance outlines a streamlined process for estimating life cycle impacts (impacts to human health, resource availability and the environment) and monetizing those impacts so that they can be included in LCC analyses. Most importantly, the Sustainability Analysis is an "overlay" on performance—it allows the analyst to identify the most sustainable alternative among those that can meet performance requirements, as defined by the Initial Capabilities Document (ICD), the Capability Development Document (CDD), or performance specifications.

The Sustainability Analysis is derived from the standardized ISO 14040 Life Cycle Assessment (LCA) framework and existing life cycle costing guidance. It is tailored to enhance insights on sustainability, integrate with existing DoD-required analyses, and reduce the data requirements of a traditional LCA. By using open-source, peer-reviewed scoring and cost factors, the Sustainability Analysis alleviates the data collection burden associated with traditional LCA and life cycle costing methods, striking an appropriate balance between accuracy and ease of use.

This guidance describes how a Sustainability Analysis, used in early conceptual and design decisions, can help design more sustainable systems – systems that use fewer resources over the life cycle; have reduced impacts on mission, human health, and the environment; and typically result in lower life cycle costs.

This process is composed of five steps: (1) define the scope of the analysis, (2) develop a life cycle inventory, (3) estimate life cycle impacts, (4) estimate sustainability-related life cycle costs, and (5) synthesize results and iterate as necessary. Incremental to, and in support of, existing cost and performance analyses, the Sustainability Analysis ensures greater visibility of a system's hidden LCCs early in the acquisition process. These steps are summarized below:

STEP 1: Define the Scope of the Analysis. The first step of the Sustainability Analysis guides analysts to establish the functional unit and system boundary for the chosen alternatives. The functional unit defines the capability of each alternative in comparable units. These are typically established by the capability requirements documented in the Initial Capabilities Document (ICD), the Capability Development Document (CDD) for a system, or in a specification for a component. For example, when comparing two aircraft wing designs an analyst would compare them based on one or more common performance parameters such as wing span limits, payload, or other requirements as specified in the ICD or CDD. Design alternatives may include choices among materials which could have different impacts and costs during sustainment activities. Next, the analyst defines the system boundary by completing a Life Cycle Activity Profile, which is a process that streamlines data collection by identifying which activities will be included in the analysis across manufacturing, operation, sustainment, and decommissioning. Properly establishing the system boundary for all considered alternatives ensures comparability among alternatives and eliminates the need to collect data for any activities that are likely immaterial or identical among the alternatives.

STEP 2: Develop a Life Cycle Inventory (LCI). The second step of the Sustainability Analysis guides the analyst in developing an LCI of all relevant system inputs (resources) and outputs (emissions) that fall within the boundary established in **STEP 1.** The inventory is then translated into impacts to resource availability (affecting the mission), human health, and the environment. To facilitate the development of the inventory, this document offers guidance for establishing data requirements for each inventory element.

STEP 3: Estimate Life Cycle Impacts. The third step of the Sustainability Analysis guides the analyst in completing a life cycle impact assessment (LCIA). To significantly reduce the analytical burden of the Sustainability Analysis, the guide simplifies the translation of the inventory to impacts by using pre-defined scoring factors.

STEP 4: Estimate Sustainability-related Life Cycle Costs. The fourth step instructs the analyst on how to use the results in **STEPs 2&3** to identify (1) internal costs that are likely to be paid by the DoD over the system's lifetime and (2) external costs that society will bear outside the of the DoD. In this step, analysts will uncover a system's hidden costs by identifying the costs associated with risk mitigation required as a result of the life cycle impacts identified in **STEP 3**. These costs can include activities such as engineering controls, personnel protection equipment, permitting, and waste management. The analysis can also help uncover any contingent costs that may occur in the future in the absence of risk mitigation (e.g., medical costs, resource unavailability, material substitution testing). For external costs, costing factors provided in Appendix I can be used to simplify the translation of impacts identified in **STEP 3** to costs borne by society (e.g., the value of lost productivity, human and ecosystem health

degradation, reduced resource availability). *This step is incremental to and in support of the cost element structures used in traditional LCC analyses.*

STEP 5: Synthesize Results and Iterate. The fifth step guides the analyst on how to synthesize, view, and interpret the results. Analysts can use the results to identify the most sustainable alternative.

The benefits to completing a Sustainability Analysis can be realized even if an analyst discovers that sufficient data do not exist to complete all five steps of the analysis. Simply going through the process can create awareness of life cycle impacts and their related costs, inform alternatives selection, and drive research and development efforts for high-cost activities.

The methods presented here support multiple government policies and initiatives. Executive Order (E.O.) 13514—*Federal Leadership in Environmental, Energy and Economic Performance* (October 5, 2009) establishes an integrated strategy for sustainability in the federal government. In accordance with the E.O., the DoD developed a Strategic Sustainability Performance Plan (SSPP) that the DoD updates annually. The SSPP includes DoD goals for efficiency and reductions in energy, water, solid waste, and the use of hazardous chemicals and materials. Further, reducing LCC by acquiring more sustainable systems directly supports the Better Buying Power[1] initiative and "designing for affordability" goal established by the Under Secretary of Defense (Acquisition, Technology, & Logistics). In summary, results from a Sustainability Analysis can help acquisition officials make more informed design, logistics, and sustainment decisions towards meeting the above goals.

All comments (recommendations, additions, and deletions) and any pertinent, beneficial document information may be addressed to Office of the Deputy Under Secretary of Defense (Installations & Environment), Science & Technology Directorate, 4800 Mark Center Drive, Box 56, Suite 16G14, Alexandria, VA 22350 or e-mailed to paul.j.yaroschak.civ@mail.mil.

[1] ODUSD I&E Policy Memorandum, "Better Buying Power 2.0: Continuing the Pursuit for Greater Efficiency and Productivity in Defense Spending", issued November 13, 2012.

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Sustainability Analysis Overview

In this guidance, a Sustainability Analysis is introduced as the recommended approach for assessing a system's resource consumption and resulting impacts—internally to DoD and externally. The purpose of the Sustainability Analysis is to compare two or more systems, sub-systems, or components with the same performance requirements on the basis of resource consumption, emissions, and the associated life cycle impacts. The intent is for this guidance to be incorporated into the DoD Integrated Defense Acquisition, Technology, and Logistics Life Cycle Management System. Results can be presented visually in various types of charts that illustrate the relative differences in impact. The results of a Sustainability Analysis can be used to better inform alternatives analyses, system design, supportability, and life cycle cost (LCC) estimates.

The Sustainability Analysis evaluates sustainability-related impacts for three categories of interest to the DoD:

- **Resource Availability (affecting the mission)**: Includes impacts to resource reserves that, if depleted or unavailable, could negatively affect the ability of defense personnel to complete the mission
- **Human Health**: Includes health impacts to defense personnel or surrounding communities that could increase internal or external costs
- **Environmental Health**: Includes impacts to natural cycles (e.g., the earth's hydrological cycle), ecosystems, or wildlife that could increase internal or external costs

The Sustainability Analysis is derived from the standardized ISO 14040 Life Cycle Assessment (LCA) framework[2] and existing life cycle costing guidance. It is tailored to enhance insights on sustainability, integrate with existing DoD-required analyses, and reduce the data requirements of a traditional LCA. The Sustainability Analysis includes a series of steps that inventory a system's resource requirements throughout its life cycle; model the system's resulting life cycle impacts; and compare those impacts to the life cycle impacts associated with all other alternatives being evaluated. The Sustainability Analysis framework also adds a final step of estimating related costs. The Sustainability Analysis framework demonstrated below in Figure 1 is structured to help analysts quickly construct a model of cause-effect relationships by identifying all inputs (e.g., energy, chemicals and materials (C&M), water, and land) entering the system and the resulting impacts and costs to the mission, human health, and the environment that are associated with the emissions generated from the use of those inputs.

The acquisition process includes the critical step of determining a system's total LCC; however many sustainability-related costs (e.g. energy for sustainment activities, water consumption, medical monitoring, waste disposal) are often not fully accounted for in the cost estimates completed during the acquisition process. The Sustainability Analysis presented in this guidance fills this gap, allowing for more robust and informed trade space and supportability analyses by enabling analysts to assess mission, human health, and environmental impacts and their resulting costs for an entire system, subsystem, component, process, or activity. This method complements existing cost guidance by addressing costs often excluded in the current acquisition cost structure (see Appendix L for additional information). It also retains the basic concepts of a traditional ISO 14040 Life Cycle Assessment, a standard for estimating impacts to human health and the environment,[3] but differs in that it reduces the

[2] For more information on LCA, analysts should see ISO 14040 and ISO 14044. For guidance on how to comply with these standards, analysts are advised to review the European Commission Joint Research Center ILCD handbook. This document is available at http://lct.jrc.ec.europa.eu.

[3] See ISO (the International Organization for Standardization) 14040.

time, resources, and data needed to conduct the assessment. The method in this guidance was specially developed for the DoD acquisition process.

By relying less on user input and more on models that accurately estimate life cycle impacts, the Sustainability Analysis alleviates the data collection burden associated with traditional LCA and life cycle costing methods. The Sustainability Analysis does not require analysts to quantify resulting system outputs (e.g., emissions) for activities or processes that occur within the system boundary (**STEP 1**). Chemical and material inputs present an exception since they require users to develop chemical emission profiles for industrial processes that consume those inputs (see Appendix F). The streamlined nature of this method means that analysts only need to record the inputs needed by the system across its life cycle where they differ between alternatives.[4] The inventory of these inputs includes the type, source, quantity, and cost of resources consumed to produce, operate, sustain, and dispose of the system.

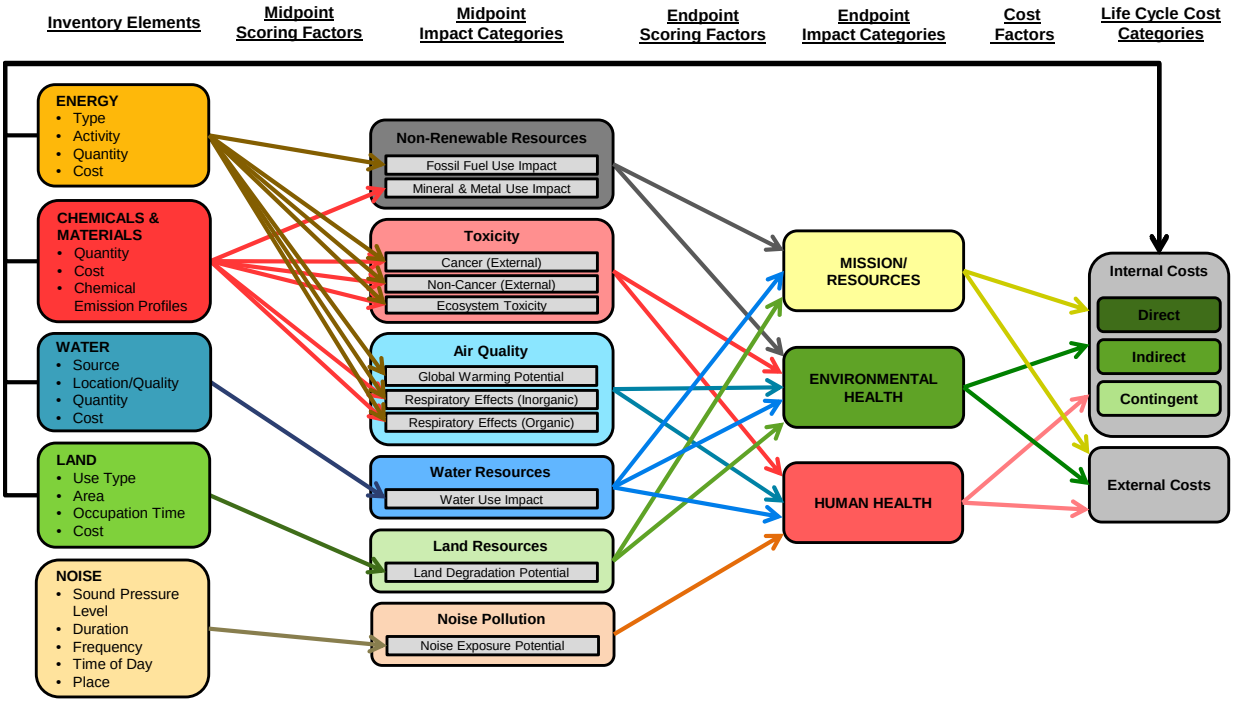

Figure 1. Sustainability Analysis framework overview

The Sustainability Analysis captures a greater scope of life cycle impacts and associated costs than traditional risk assessment and life cycle costing methods because the models used in the Sustainability Analysis are more inclusive of all activities and processes that occur throughout the system's life cycle. The methods and models presented in this guidance employ well-researched life cycle impact assessment (LCIA) methods to estimate two types of impacts: (1) *upstream* supply chain impacts that are embedded in the resources, components, and parts procured by the DoD and its prime contractors throughout the system's life cycle and (2) *downstream* impacts that are directly caused by the consumption of resources during the manufacturing, operation, sustainment, and disposal of the system. Summarized in Figure 2, these impacts are explained in detail below.

[4] Noise is also considered in a Sustainability Analysis. Unlike resources that are consumed by the system (energy, chemicals, materials, water, and land), noise is an output that results from the production, operation, and sustainment of the system.

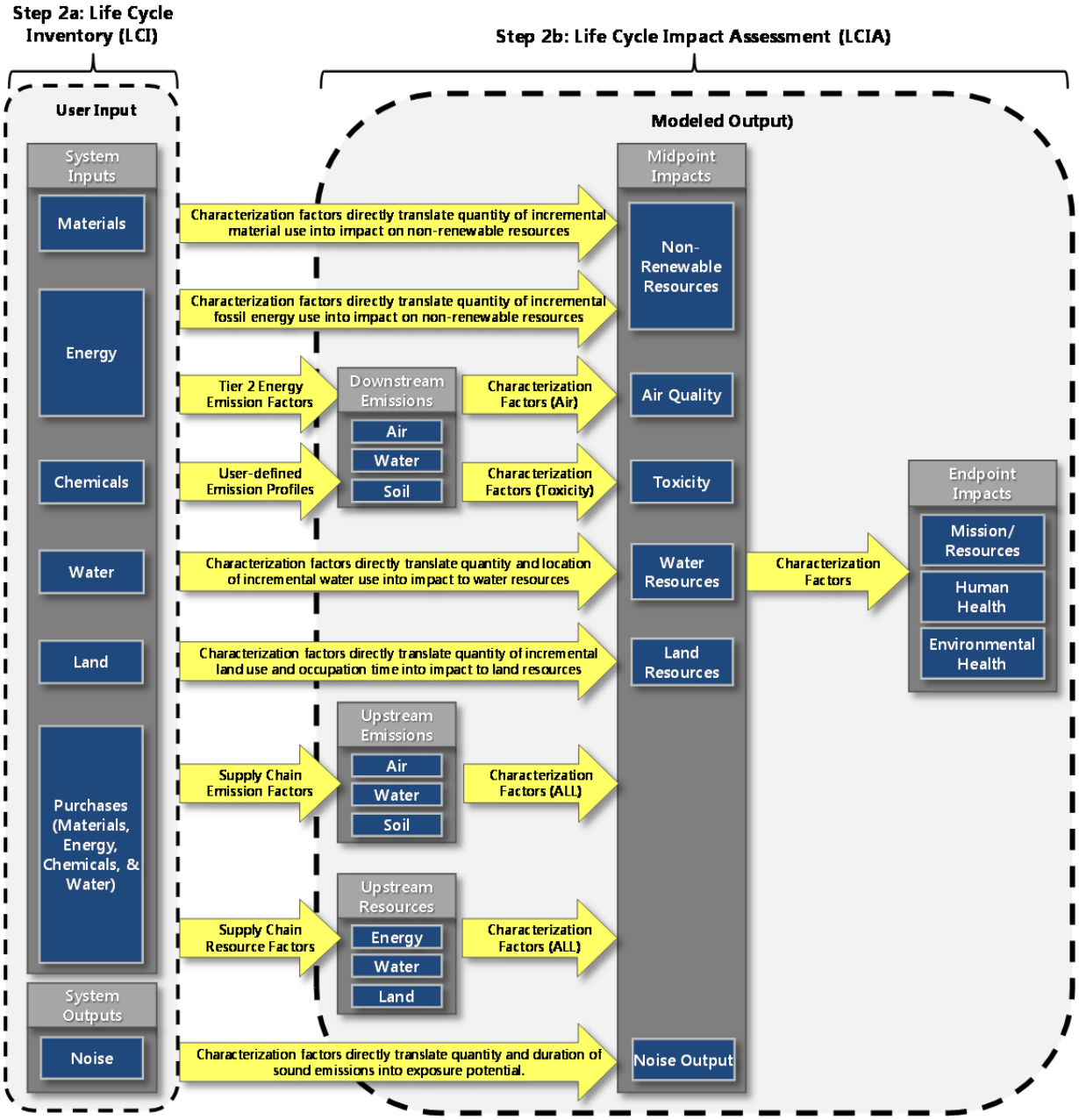

Figure 2. Process flow diagram for Sustainability Analysis methodology

- **Upstream impacts:** Procuring resources (energy, chemicals, materials, water, and land), components, and parts for use in a system has embedded impacts as a result of the activities and processes that occur throughout the many tiers of DoD's supply chain (e.g., raw material acquisition; material processing; and part or component production). Given an integrated worldwide economy, it is impossible to trace the resource consumption and resulting impacts associated with each direct and indirect DoD supplier using traditional LCA methods. The Sustainability Analysis uses well-established Economic Input-Output (EIO) LCA methods to translate procurement costs into estimates for upstream resource consumption and resulting impacts to resource availability, human health, and environmental health. More specifically, to quickly capture the upstream impacts of a system using readily available procurement data, the Sustainability Analysis methodology provides

analysts with upstream scoring factors that represent an industry segment's average quantity of resources consumed and emissions per dollar spent within that industry.

- **Downstream impacts**: Activities during the manufacturing, operation, sustainment, and disposal of the system require additional resource consumption, which affects resource availability, human health, and the environment. As Figure 2 demonstrates, the Sustainability Analysis uses downstream scoring factors to quickly translate the inputs into estimated system outputs using standardized emission factors. It then characterizes those outputs into well-established impact categories. Finally, it quantifies the magnitude of impact within each category by using standardized impact characterization factors derived from risk assessment and LCIA methodologies. While the downstream component of Sustainability Analysis is not as robust as traditional LCA methods, it requires considerably less data and time to produce results. Figure 2 summarizes the Sustainability Analysis methodology in terms of general data requirements (user input) and data transformations and results (modeled output).

A Sustainability Analysis can be used to compare the overall sustainability of alternatives for acquisition-related activities such as Analysis of Alternatives (AoAs), Business Case Analyses (BCAs), trade studies for major design elements, Preliminary Design Reviews (PDRs), Supportability Analyses (SAs), and Life Cycle Sustainment Plans (LCSPs). Sustainable alternatives meet all performance requirements outlined in the Initial Capabilities Document (ICD), the Capability Development Document (CDD), or performance specifications; minimize impacts to the resource availability, human health, and the environment; and minimize LCCs (see Figure 3). More information on how a Sustainability Analysis fits into the current acquisition process can be found in Appendix B.

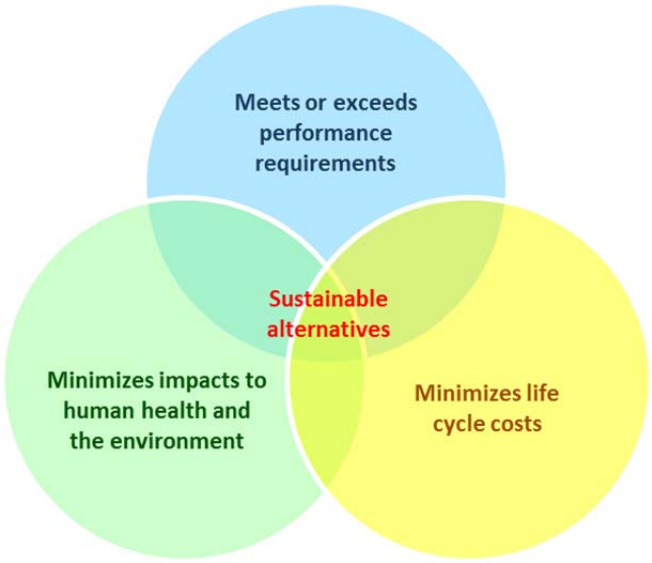

Figure 3. Key elements of sustainable alternatives

Sustainability Analysis Step-by-Step

The Sustainability Analysis process outlined in this guidance has five main steps:

1) Define the scope of the analysis
2) Develop a life cycle inventory
3) Estimate life cycle impacts
4) Estimate sustainability-related life cycle costs
5) Synthesize results and iterate as necessary

These steps were developed to streamline the process of collecting data and accurately estimating a system's life cycle impacts and associated LCC. This guidance document also provides, by reference, a tool that automates the Sustainability Analysis calculations (Appendix A). An effort is underway to provide this tool in a user-friendly, web-based format.

Step 1: Define the Scope of the Analysis

1a. Define the Functional Unit

Step 1a outlines a process for defining the unit of measure that will be used to compare alternatives.

Key Steps

- Define the functional unit, which is the required capability of each alternative in comparable units (e.g., payload, tensile strength, corrosion protection).
- Establish how many systems/components are required in each alternative to meet the functional unit (e.g., two small helicopters or one larger helicopter can satisfy the same mission/functional unit; two layers of coating X or one layer of coating Y can satisfy the same corrosion protection over a specified area and period of time).

Discussion

The functional unit defines the identified functions (performance characteristics) of a system. The primary purpose of a functional unit is to provide a common reference to ensure that, when comparing alternatives in the sustainability analysis, the same performance requirements are evaluated.

Comparability of results is particularly critical when assessing different system platforms. The functional unit is a common unit of measure that (1) provides a reference for the system inputs and outputs, (2) assures equivalence, (3) allows for meaningful comparisons between alternative systems, and (4) identifies elements that all of the alternatives in the study have in common. Analysis results will be presented relative to the functional unit (e.g. kilograms of carbon dioxide equivalents per hour or gallons of fuel per defined mission).

Both the time and number of activities (e.g. mission tasks) needed to fulfill a desired capability are potential elements of the functional unit. Examples that demonstrate a time-based and mission-based functional unit are as follows:

- **Time example:** The functional unit must meet a capability over a 50-year period. Alternative X is expected to have a lifespan of 25 years, while Alternative Y is expected to have a life span of 50 years. Thus, two units of Alternative X are needed to meet the minimum capability requirements, while only one unit of Alternative Y is needed. In this example, one unit of Alternative Y may have greater impacts over its life cycle compared to one unit of Alternative X. However, when considering that two units of Alternative X are needed to meet the functional unit, the cumulative impacts of selecting Alternative X may be greater than the impacts of Alternative Y.

- **Mission task example:** The defined functional unit is to transport 100 combat vehicles 200 miles. In this example, Alternative X has half the transport capacity of Alternative Y, implying that Alternative X must complete twice the number of trips as Alternative Y in order to fulfill the capability. Alternative Y may be less fuel-efficient than Alternative X. However, since Alternative X has to complete twice the number of trips as Alternative Y, the impacts of the two materiel solutions may favor Alternative Y over Alternative X.

The functional unit should be defined by the minimal performance requirements needed to properly meet the stated capability, as outlined in Integrated Capabilities Document (ICD), the Capability Development Document (CDD), or a specific component performance requirement or specification. The functional unit is the same for all evaluated alternatives.

Superstructure Alternatives Example

Throughout this guidance document, each step of the Sustainability Analysis process is illustrated using a hypothetical example. In this example, two material alternatives for a noncombat ship's superstructure are compared. It is assumed that both alternatives, superstructure made either from composite material or steel, meet all performance requirements. For **STEP 1a**, the illustrative functional unit for the superstructure is the transport of an additional 220 passenger cabins over the ship's expected life of 30 years, assuming that the ship will be in transit 270 days a year. In this example it is assumed that both alternatives would carry an identical passenger load and that no armoring is needed. Both material choices are expected to last the required 30 years without replacement.

1b. Define the System Boundary

STEP 1b outlines a process for quickly defining which activities will be included in the analysis while also eliminating any activities that are likely immaterial or identical between the alternatives.

Key Steps

- Define the system by identifying all subsystems, components, parts, and resource inputs ("system elements") that are necessary to fulfill the capability of the functional unit. All stages of the system's life cycle (i.e., production, operation, sustainment and disposal) should be considered.
- List any elements of a parent system whose activities could be affected by the alternatives being considered. For example, two alternative weapon systems designs that have a difference in weight may cause a weapons platform (parent system) to consume more fuel. This difference in the parent system's fuel consumption should be included in the boundary of the Sustainability Analysis.
- Determine if any of the identified system elements are equivalent across all of the selected alternatives. System elements qualify as equivalent when both of the following conditions are met: (1) the elements meet identical specifications and (2) the number of units needed per function is equal. All equivalent system elements should be removed from the analysis since they "cancel out one another" and justification for the exclusion should be documented.
- Complete a Life Cycle Activity Profile to identify high-impact activities that are associated with each inventory element (energy, water, C&M, land and noise). See Appendix D for additional guidance.
- Group activities by system element. Depending on the system boundary, it may be more appropriate to group system elements and associated activities at the level of the parent system. See Table 1 for an example.
- Iterate these steps to identify any additional support systems that are required to fulfill the life cycle activities or mitigate risk associated with those activities. For example, an alternative that requires the use of hazardous materials may require supporting systems (e.g., facility controls, PPE, waste disposal services) to mitigate health- and environmental-related risks.

Discussion

The system boundary defines all system elements that should be included in the Sustainability Analysis and all associated activities that would differ between the alternatives being evaluated. The system boundary should include all incremental materiel—systems, components, subcomponents—and resource inputs needed to fulfill the capability gap specified by the ICD, CDD, or performance criteria. The system boundary should be the same for all alternatives.

It is up to the analyst to determine which processes, products, infrastructure, and activities should be included in the analysis depending on the scale of the system being evaluated, the availability of data, and the objectives of the analysis. To assist with this process, the Life Cycle Activity Profile (see Appendix D) should be completed for each alternative to identify high-impact activities (largest drivers of impacts and associated costs) for each inventory element. A justification should be provided if any the following are excluded from the study boundary: (1) key processes, products, infrastructure, and activities that significantly influence the assessment or (2) any life cycle stages from production through disposal.

Superstructure Alternatives Example

Table 1 provides an illustrative system boundary for an analysis of two material alternatives. The initial identification of key systems and activities associated with the superstructure's use requires the system boundary to extend to the ship's (parent system) operation to ensure a fair comparative analysis. In this example, the difference in density between the two alternatives causes the ship's weight to vary, which ultimately leads to a difference in fuel consumption during operation. This material choice directly influences the ship's fuel efficiency, and therefore the difference in fuel combustion should be included in the boundary. Note that all other activities and inputs associated with a ship's superstructure are assumed to be equivalent for both alternatives and are therefore excluded from this example system boundary.

Table 1. System boundary example

Ship's Life Cycle Stage	System Element	System Activity	Support System	Support Activity	Include in Composite Alternative?	Include in Steel Alternative?
Production	Support & Exterior facing	Metal working	Personal Protective Equipment (PPE)	Replacement and waste disposal	YES	YES
		Thermoforming	Facility air filtration	Replacement and waste disposal	YES	NO
			New thermo-forming facility	Construction	YES	NO
		Waste disposal	No support system	No support activity	YES	YES
	Coating	Application (interior & exterior)	PPE	Replacement and waste disposal	YES	YES
			Facility air filtration	Replacement and waste disposal	YES	YES
		Waste disposal	No support system	No support activity	YES	YES
	Insulation	Installation	PPE	Replacement and waste disposal	YES	YES
Operation	Ship fuel	Combustion	Fuel delivery system	Delivery of fuel to system	YES	YES
Sustainment	Support & Exterior facing	Cleaning	Power washer	No support activity	YES	NO
	Coating	Removal (exterior)	PPE	Replacement and waste disposal	NO	YES
			Facility air filtration	Replacement and waste disposal	NO	YES
		Application (exterior)	PPE	Replacement and waste disposal	NO	YES
			Facility air filtration	Replacement and waste disposal	NO	YES
		Waste disposal	No support system	No support activity	NO	YES
Disposal	Support & Exterior facing	Metal Scrapping	No support system	No support activity	YES	YES

Step 2: Develop a Life Cycle Inventory (LCI)

2a. Develop an Inventory of Procurement Costs

STEP 2a provides guidance on how to develop a life cycle inventory (LCI) of procurement costs for each alternative. Procurement costs are those costs associated with the procured items and services that fall within the system boundary established in **STEP 1**.

Key Steps

- Identify all procured items (e.g., resource inputs, equipment, controls) and services (e.g., waste management, construction, etc.) needed for the system elements and activities (system boundary) identified in **STEP 1**.
- Review data availability for each data element identified above and document the format and sources for such data in accordance with the guidance provided in Appendix E.
- Calculate the total LCC of each procured item or service identified above. The total LCC of a specified inventory element is calculated by multiplying the total quantity of the item or service procured by the cost per unit. If procurement is expected to occur over time, the cost per unit should be discounted to 2013 dollars (all upstream scoring factors in Appendix I are indexed to 2013 dollars). NOTE: Analysts may also need to index procurement costs to the year in which the analysis is completed to accurately complete **STEP 4** (additional information is provided in **STEP 4**).

Discussion

Procurement cost data are used to calculate all upstream impacts and inform LCC estimates (see **STEP 4**). The example below in Table 2 illustrates how the collected data are organized to facilitate the Sustainability Analysis. Additional details on the data requirements for procured items and services can be found in Appendix F.

Sources of the data may include, but are not limited to (1) purchase records from similar existing systems and legacy systems, (2) sustainment data for operation and maintenance of similar existing systems and legacy systems, (3) an estimated bill of materials informed by initial designs or technology development activities, (4) use of inputs from initial tests during technology development, and (5) estimates (engineering, parametric, etc.) of input use or consumption during all appropriate life cycle stages. Additional guidance on data collection can be found in Appendix E.

Superstructure Alternatives Example

Table 2 below provides an example inventory of procurement costs for both superstructure alternatives. In this example, a new thermoforming facility is required for the composite alternative to mold the composite material during production. For this example, the new facility is assumed to be built on 0.92 acres of temperate broadleaf forest. Note that the life cycle stage, system, and activities listed should be the same for each inventory and match that of the system boundary established in Table 1.

Table 2. Procurement cost inventory example

Ship's Life Cycle Stage	System Element	System Activity	Procured Item/Service	Unit	Price ($/unit)	Composite Total Spend ($)	Steel Total Spend ($)
Production	Coating	Application	Electricity (CT)	kWh	6.0000E-02	$8,507	$13,610
			Primer	gallon	1.5593E+02	$3,230	$109,507
			Paint	gallon	2.0600E+02	$8,533	$289,335
			PPE	#	1.4924E+02	$2,484	$22,273
			Air Filter	#	4.3643E+02	$3,928	$137,476

Table 2 (continued). Procurement cost inventory example

Ship's Life Cycle Stage	System Element	System Activity	Procured Item/Service	Unit	Price ($/unit)	Composite Total Spend ($)	Steel Total Spend ($)
Production	Coating	Waste Disposal	Air Filter Hazardous Waste	lbs	1.1800E+00	$537	$18,201
			PPE Hazardous Waste	lbs	1.1800E+00	$46	$1,554
			Hazardous Wastewater	gallon	3.1700E+00	$0	$0
	Insulation	Installation	PPE	#	1.2762E+02	$637	$5,714
			Mineral Wool	kg	9.0000E-02	$42,552	$4,500
	Support & Exterior facing	Metal Working	Electricity (CT)	kWh	6.0000E-02	$803	$27,221
			Steel (low alloy)	kg	7.9000E-01	$54,984	$1,619,500
			Aluminum (virgin)	kg	1.6950E+00	$0	$525,450
			PPE	kg	9.2730E+01	$926	$8,303
			Water (US, quality & source unspecified)	gallon	2.5300E-03	$41	$533
		Thermoforming	Electricity (CT)	kWh	6.0000E-02	$55,198	$0
			Glass fiber	kg	1.7500E+00	$972,300	$0
			Polyester resin, unsaturated	kg	3.5000E+00	$1,260,000	$0
			Epoxy resin	kg	3.0000E+00	$180,600	$0
			Polyurethane, rigid foam	kg	2.5000E+00	$675,625	$0
			Air Filter	#	4.3643E+02	$185,483	$0
			Thermoforming Facility (including equipment)	sqft	4.2000E+02	$1,680,000	$0
			Water (US, quality & source unspecified)	gallon	2.5300E-03	$124	$0
		Waste Disposal	Hazardous Wastewater	gallon	3.1700E+00	$207,128	$667,507
			Hazardous Wastewater Permit	gallon	1.0000E+00	$65,340	$210,570
Operation	Ship Fuel	Combustion	Residual Fuel Oil (No. 6)	gallon	3.7800E+00	$5,908,768,657	$6,951,492,537
Sustainment	Coating	Application	Electricity (VA)	kWh	7.0000E-02	$0	$15,411
			Primer	gallon	1.5593E+02	$0	$1,263,944
			Paint	gallon	2.0600E+02	$0	$3,339,537
			Air Filter	#	4.3643E+02	$0	$549,903
			Air Filter	#	4.3643E+02	$0	$3,537,568
			PPE Suites	#	1.4924E+02	$0	$408,679
		Removal	Electricity (VA)	kWh	7.0000E-02	$0	$20,034
			Stripper	gallon	5.3000E+01	$0	$1,277,191
			PPE	#	1.4924E+02	$0	$408,679
			Water (US, quality & source unspecified)	gallon	3.6700E-03	$0	$13,807,110
		Waste Disposal	Air Filter Hazardous Waste	lbs	1.1800E+00	$0	$91,007
			PPE Hazardous Waste	lbs	1.1800E+00	$0	$7,769
			Hazardous Wastewater	gallon	3.1700E+00	$0	$11,926,032
		Waste Disposal	Hazardous Wastewater Permit	gallon	1.0000E+00	$0	$3,762,155

Table 2 (continued). Procurement cost inventory example

Ship's Life Cycle Stage	System Element	System Activity	Procured Item/Service	Unit	Price ($/unit)	Composite Total Spend ($)	Steel Total Spend ($)
Sustainment	Support & Exterior facing	Cleaning	Water (US, quality & source unspecified)	gallon	3.6700E-03	$18,593,138	$0
			All-Purpose Cleaner	gallon	8.5133E+00	$14,376,789	$0
Disposal	Support & Exterior facing	Metal Scrapping	N/A	N/A	N/A	N/A	N/A

2b. Develop an Inventory of System Inputs and Outputs in Physical Units

STEP 2b provides guidance on how to develop a life cycle inventory (LCI) of system inputs (energy, C&M, water, and land requirements) for each alternative. It also provides guidance on how to develop an inventory for two types of outputs (chemical and noise emissions) that cannot be automated using downstream scoring factors. All data collected should be directly tied to all activities that fall within the system boundary established in **STEP 1**. Data elements in this step are recorded in physical units and include additional data attributes as specified in Appendix F.

Key Steps

- Identify all energy, C&M, water, and land inputs needed by the system elements and activities (system boundary) identified in **STEP 1**. All relevant inputs over the system's life cycle, as specified in the Life Cycle Activity Profile, should be considered. These data may overlap with data collected in **STEP 2a**; however, in **STEP 2b** the physical quantities are of interest. Identify all noise and chemical emissions that occur within the system boundary established in **STEP 1**. All relevant outputs over the system's life cycle, as specified in the Life Cycle Activity Profile, should be considered.
- Review data availability for each data element identified above and document the format and sources for such data in accordance with the guidance provided in Appendix E.
- For energy, C&M, water, and land inputs, estimate the total quantity consumed per functional unit, as shown in Tables 3, 4, 5, and 6. Specific data requirements for each inventory element are provided in Appendix F.
- Also quantify chemical emissions to air, soil, and water associated with those inputs and the stated activity as illustrated in the Emissions Profile portion of Table 7. These quantities should represent emissions to the environment immediately outside of the facility taking into account facility controls and filtration. To avoid double counting, any chemical releases that are included in a managed waste stream should not be counted as a chemical emission and instead should inform waste management costs. Waste management should be included as a system element within the established system boundary. Specific data requirements for chemical emissions are provided in Appendix F.
- For noise, record or estimate the sound pressure level, in decibels (dB), and duration of all noise emissions at the source of such emissions during processes that occur within the system boundary. Then convert sound pressure level and duration into sound energy, recorded in Joules (J). Also record the octave band of the noise as well as the time of day and location for which the emission occurs (as shown in example Table 8). Specific data requirements and unit conversions for noise emissions are provided in Appendix F.

Discussion

Data collected, in terms of physical units, for all system inputs and outputs are used to calculate all downstream impacts and inform life cycle impact assessments (see **STEP 3**). Tables 3-8 illustrate how the

collected data can be organized to facilitate the Sustainability Analysis. Additional details on the data requirements for each item can be found in Appendix F.

Most of the data collected for procured items will contain quantities (physical units) used by the system. However, some data elements that fall within the system boundary (e.g., chemical and noise emissions) will require additional investigation. Some of the following techniques may be useful to fulfill the inventory data requirements: (1) collect and use system-specific data, (2) use data or modeled relationships from legacy systems as proxy estimates for system-specific data elements, and (3) develop proxy estimates for system-specific data elements from qualitative assessments (see Appendix E for additional guidance). When system-specific data are not available or too costly and time consuming to collect, consider using proxy data from legacy systems, components, or parts that have similar functions and performance expectations. Legacy data are often derived from models (e.g., engineering and parametric) that may need to be adjusted before they are used as proxy data inputs into the analysis. When adjustments in modeled data are required, document any assumptions and make sure they are consistent across evaluated alternatives.

Expert judgment should be used to determine which C&Ms are to be included in the analysis including available information on whether a chemical or material is potentially hazardous to human health or the environment. C&Ms that have high emission control or waste management costs, are at risk of supply disruption, or are critical to the system should always be considered. Focus efforts towards identifying high-impact emissions not expected to be captured by facility equipment and emitted into the external environment. It may be useful to use mass balance analysis or to reference safety data sheets (SDS) to estimate the quantities of chemicals embedded in procured materials and chemical compounds that may be released during industrial processes. Although not exhaustive, Appendix I provides analysts with a list of chemical emissions that should be considered when collecting data. Quantity data should be recorded in units of mass, as specified in Appendix I. If an inventory element is not listed in Appendix I, this does not imply that it is not relevant to the estimation of emissions.

For energy, the scoring factors that will be used in **STEP 3** estimate both the emissions associated with the energy use and then the impact of those emissions. This simplifies the data collection requirements; estimates for energy emissions are not necessary.

Superstructure Alternatives Example

Tables 3 through 8 below provide example inventory data for energy, C&M, water, and land inputs, and chemical and noise outputs. All data elements in this example meet the requirements established in Appendix F. Tables 3 through 8 should be completed for each alternative across the system boundary to facilitate comparisons. In this example, most entries in the tables below contain quantity data obtained from Table 1; however, some data elements (e.g., chemical emissions profile and noise emissions) required additional investigation. The listed life cycle stage, system elements, and activities are the same for each inventory and match that of the system boundary established in Table 1. Where relevant, the items in Tables 3 through 8 overlap with costs identified in Table 2; this is by design.

Table 3. Energy inventory example

Ship's Life Cycle Stage	System Element	System Activity	Fuel	Activity	Unit	Composite Quantity	Steel Quantity
Operation	Support & Exterior facing	Metal working	Residual Fuel Oil (No. 6)	Ship combustion	gallon	1.563E+09	1.839E+09
Production	Support & Exterior facing	Metal Working	Electricity (United States)	CT (average)	kWh	1.3380E+04	4.5368E+05
		Thermoforming	Electricity (United States)	CT (average)	kWh	9.1997E+05	0.0000E+00
	Coating	Application	Electricity (United States)	CT (average)	kWh	1.4178E+05	2.2684E+05
Sustainment	Coating	Application	Electricity (United States)	VA (average)	kWh	0.0000E+00	2.2015E+05
		Removal	Electricity (United States)	VA (average)	kWh	0.0000E+00	2.8620E+05

Table 4. Chemicals inventory example (only coating processes shown in example)

Ship's Life Cycle Stage	System Element	System Activity	Chemical/Material	Unit	Composite Quantity	Steel Quantity
Production	Coating	Application	1-Butanol	kg	4.2106E+01	1.4277E+03
			Acetone	kg	4.4714E+01	1.5161E+03
			Benzyl alcohol	kg	6.9900E+00	2.3702E+02
			Chromium VI	kg	9.3543E+00	3.1718E+02
			Xylene	kg	1.4479E+01	4.9096E+02
Sustainment	Coating	Application	1-Butanol	kg	0.0000E+00	6.9282E+03
			Acetone	kg	0.0000E+00	7.3572E+03
			Benzyl alcohol	kg	0.0000E+00	1.1501E+03
			Chromium VI	kg	0.0000E+00	1.5392E+03
			Xylene	kg	0.0000E+00	2.3824E+03
		Removal	Benzyl alcohol	kg	0.0000E+00	2.8979E+05
			D-Limonene	kg	0.0000E+00	2.4149E+04

Table 5. Water inventory example

Ship's Life Cycle Stage	System Element	System Activity	Source	Location	Quality	Unit	Composite Quantity	Steel Quantity
Production	Support & Exterior facing	Thermoforming	Unspecified	United States	Unspecified	gallon	4.1328E+01	5.3274E+02
		Metal Working	Unspecified	United States	Unspecified	gallon	1.2398E+02	0.0000E+00
Sustainment	Coating	Removal	Unspecified	United States	Unspecified	gallon	0.0000E+00	1.3807E+07
	Support & Exterior facing	Cleaning	Unspecified	United States	Unspecified	gallon	1.8593E+07	0.0000E+00

Table 6. Land inventory example

Ship's Life Cycle Stage	System Element	System Activity	Land Use Type	Occupation Time (yrs)	Area per Functional Unit (m2)[5]		Area*time (m2a)	
					Composite	Steel	Composite	Steel
Production	Support & Exterior facing	Thermoforming	Industrial area, unspecified (temperate broadleaf forest)	30	3.72E+02	0.00E+00	1.11E+04	0.00E+00

Table 7. Chemical emissions inventory example

Ship's Life Cycle Stage	System Element	System Activity	Fate	Emission	Unit	Composite Quantity	Steel Quantity
Production	Coating	Application	Air	1-Butanol	kg	5.2633E-01	1.7847E+01
				Acetone	kg	5.5892E-01	1.8952E+01
				Benzyl alcohol	kg	8.7374E-02	2.9627E+00
				Chromium VI	kg	1.1693E-01	3.9648E+00
				Xylene	kg	1.8099E-01	6.1370E+00
			Water	1-Butanol	kg	1.5790E+00	5.3540E+01
				Acetone	kg	1.6768E+00	5.6856E+01
				Benzyl alcohol	kg	2.6212E-01	8.8881E+00
				Chromium VI	kg	3.5078E-01	1.1894E+01

[5] To keep this hypothetical example simple, it is assumed that only one ship will be acquired to meet the functional unit; thus allocating all incremental land use associated with the thermoforming facility to one superstructure. In most cases, an acquisition will compose multiple units of the system of interest, and in such cases the incremental land use must be allocated across those units. See Appendix F for more information.

Table 7 (cont.). Chemical emissions inventory example

Ship's Life Cycle Stage	System Element	System Activity	Fate	Emission	Unit	Composite Quantity	Steel Quantity
Production	Support & Exterior facing	Metal Working	Air	Arsenic	kg	3.1891E+00	1.5457E-01
				Cadmium	kg	1.2536E+00	4.9773E-02
				Mercury	kg	5.0953E-03	1.3748E-02
				Methane	kg	3.9056E+02	4.8774E+02
				Particulates, < 2.5 um	kg	8.6150E+01	1.7115E+02
				Sulfur dioxide	kg	4.1548E+02	6.0581E+02
				Zinc, ion	kg	4.0778E+01	1.0281E+02
			Water	Arsenic, ion	kg	5.9843E-01	1.1822E+00
				Chromium VI	kg	1.2845E+00	3.2887E+00
				Vanadium, ion	kg	7.4730E+00	1.0485E+00
		Thermoforming	Air	Arsenic	kg	8.6225E+00	4.1790E-01
				Cadmium	kg	2.6640E+00	1.0577E-01
				Mercury	kg	3.1299E-02	8.4453E-02
				Methane	kg	3.5150E+03	4.3896E+03
				Particulates, < 2.5 um	kg	2.0102E+02	3.9934E+02
				Sulfur dioxide	kg	4.7780E+03	6.9669E+03
				Zinc, ion	kg	1.1025E+02	2.7796E+02
			Water	Arsenic, ion	kg	4.8418E+00	9.5652E+00
				Chromium VI	kg	7.2787E+00	1.8636E+01
				Vanadium, ion	kg	9.9284E+01	1.3930E+01
Sustainment	Coating	Application	Air	1-Butanol	kg	0.0000E+00	8.6602E+01
				Acetone	kg	0.0000E+00	9.1965E+01
				Chromium VI	kg	0.0000E+00	1.9239E+01
				Benzyl alcohol	kg	0.0000E+00	1.4377E+01
				Xylene	kg	0.0000E+00	2.9780E+01
			Water	1-Butanol	kg	0.0000E+00	2.5981E+02
				Acetone	kg	0.0000E+00	2.7589E+02
				Benzyl alcohol	kg	0.0000E+00	4.3130E+01
				Chromium VI	kg	0.0000E+00	5.7718E+01
				Xylene	kg	0.0000E+00	8.9340E+01
		Removal	Air	Benzyl alcohol	kg	0.0000E+00	3.6224E+03
				D-Limonene	kg	0.0000E+00	3.0186E+02
			Water	Benzyl alcohol	kg	0.0000E+00	1.0867E+04
				D-Limonene	kg	0.0000E+00	9.0559E+02

Table 8. Noise inventory example

Ship's Life Cycle Stage	System Element	System Activity	Level of Noise Output (dB)	Attenu-ations from Protection (dB)	Sound Energy (J)	Octave Band of Noise	Time	Place	Include in Comp.?	Include in Steel?
Production	Coating	Application	87	10	72	Unspecified	Day	Industrial	NO	YES
Sustainment	Support & Exterior facing	Cleaning	84	10	434	Unspecified	Day	Industrial	YES	NO
	Coating	Removal	90	10	361	Unspecified	Day	Industrial	NO	YES
		Application	87	10	720	Unspecified	Day	Industrial	NO	YES

Step 3: Estimate Life Cycle Impacts

3a. Translate the LCI into Midpoint Impacts

STEP 3a uses the inventory results of **STEP 2** and converts them into midpoint impacts associated with non-renewable resources, toxicity affecting human health or the environment, air quality, water resources, land resources, and noise pollution (see Figure 2 in the overview). There are two approaches for assessing impacts based on the gathered inventory data. The first approach uses the automated tool as described in Appendix A. This approach vastly simplifies the analysis effort. The second approach assesses impacts manually by using the scoring factors provided in Appendix I. Guidance on how to use the scoring factors and manually calculate midpoint impacts is provided below.

Key Steps

- Identify the appropriate midpoint scoring factor from Appendix I for each item in the LCI. Procurement cost data are used to calculate upstream (e.g., supply chain of procured items and services) midpoint impacts and physical data are used to calculate downstream (e.g., direct manufacturing, use, maintenance, disposal) impacts. For upstream scoring factors, match each procured item or service to the industry sector listed in Appendix I that best represents the sector from which the item or service was supplied. Downstream scoring factors are grouped according to inventory element and spread across multiple tables within Appendix I.
- Calculate the resulting upstream midpoint impacts by multiplying the procurement cost for each applicable inventory element by the appropriate upstream scoring factor in Appendix I (see Table 9).
- Likewise, calculate the resulting downstream midpoint impacts by multiplying the inventory quantity for each applicable inventory element by the appropriate downstream scoring factor in Appendix I (see Table 10).
- Aggregate results within each midpoint category (see Table 11).

Discussion

The inventory data are translated into a set of upstream and downstream midpoint impacts using scoring factors provided in Appendix I.

Midpoint impacts are the relative impacts at a common midpoint along the cause-effect chain that model emissions to the environment, their transport and fate through environmental media, exposure, and effects. As shown in Figure 2 the use of resources (system inputs) can negatively impact availability of non-renewable resources, air quality, water, and land resources, and result in adverse impacts to human health or the environment. Similarly, noise emissions can result in noise pollution and chemical emissions can result in degradation of air, water, and soil quality. Using midpoint impacts reduces the complexity of the life cycle modeling, simplifies communication of results, and provides a higher level of confidence in the results. Estimating impacts at midpoint can inform environment, health, and safety requirements (e.g., personal protective equipment, permitting, emissions reporting) that are likely to have associated LCC that may not have been captured in **STEP 2a**. There are disadvantages associated with midpoint impact characterization. Using midpoint results makes comparing the importance or magnitude of impacts across midpoint impact categories difficult because those impacts are measured in different—and incomparable—units. Also, valuation of midpoint impacts is difficult because the costs of such impacts are abstract (e.g., what is the cost of emitting a specified quantity of pollution into the air or water?). These limitations result in the need to characterize the impact at the endpoint of the cause-and-effect chain (see **STEP 3b**).

Additional information for each midpoint impact category, as well as step-by-step instructions for completing midpoint scoring factor calculations, can be found in Appendix G.

Superstructure Alternatives Example

Tables 9 and 10 provide examples of how the inventory data from **STEP 2** align with scoring factors from Appendix I to facilitate calculation of midpoint impacts. Here, by way of example, only the scoring factors for global warming potential are shown, however the process is the same for all other midpoint impact categories. Table 11 shows aggregated results for the superstructure alternatives across all midpoint impact categories.

Table 9. Calculation of global warming potential (GWP) from procurement inventory data

Inventory Element	Procured Item/ Service	Matching Scoring Factor Description	NPV of Procurement Cost (2013 $)		GWP Midpoint Scoring Factor (kg CO2eq/ 2013 $)	Total GWP (kg CO2eq)		Source in Appendix I
			Composite	Steel		Composite	Steel	
C&M	Air Filter	Air purification and ventilation equipment manufacturing	$189,411	$4,224,947	7.3651E-01	1.3950E+05	3.1117E+06	Table 1
	Air Filter Hazardous Waste	Waste management	$537	$109,208	2.9969E-01	1.6087E+02	3.2728E+04	Table 1
	Aluminum (virgin)	Alumina refining and primary aluminum production	$0	$525,450	1.7256E+00	0.0000E+00	9.0672E+05	Table 1
	Epoxy resin	Plastics material and resin manufacturing	$180,600	$0	1.1060E+00	1.9974E+05	0.0000E+00	Table 1
	Glass fiber	Other plastics product manufacturing	$972,300	$0	6.9991E-01	6.8052E+05	0.0000E+00	Table 1
	Hazardous Wastewater	Waste management	$207,128	$12,593,540	2.9969E-01	6.2074E+04	3.7741E+06	Table 1
	Mineral Wool	Mineral wool manufacturing	$42,552	$4,500	1.2441E+00	5.2938E+04	5.5984E+03	Table 1
	Paint	Paint and coatings	$8,533	$3,628,872	6.7027E-01	5.7193E+03	2.4323E+06	Table 1
	Polyester resin, unsaturated	Plastics material and resin manufacturing	$1,260,000	$0	1.1060E+00	1.3936E+06	0.0000E+00	Table 1
	Polyurethane, rigid foam	Urethane and other foam product (except polystyrene) manufacturing	$675,625	$0	9.7986E-01	6.6202E+05	0.0000E+00	Table 1
	PPE	Surgical supplies	$926	$8,303	4.0862E-01	3.7837E+02	3.3929E+03	Table 1
	PPE Hazardous Waste	Waste management	$46	$9,323	2.9969E-01	1.3733E+01	2.7939E+03	Table 1
	PPE Suites	Surgical supplies	$3,121	$845,345	4.0862E-01	1.2753E+03	3.4542E+05	Table 1
	Primer	Paint and coatings	$3,230	$1,373,452	6.7027E-01	2.1646E+03	9.2058E+05	Table 1
	All-Purpose Cleaning Solution	Soap and cleaning compound manufacturing	$14,376,789	$0	6.2275E-01	8.9532E+06	0.0000E+00	Table 1
	Steel (low alloy)	Iron and steel mills and ferroalloy manufacturing	$54,984	$1,619,500	2.4906E+00	1.3695E+05	4.0336E+06	Table 1
	Stripper	Inorganic chemicals	$0	$1,277,191	1.1165E+00	0.0000E+00	1.4260E+06	Table 1

Table 9 (continued). Calculation of global warming potential (GWP) from procurement inventory data

Inventory Element	Procured Item/ Service	Matching Scoring Factor Description	NPV of Procurement Cost (2013 $)		GWP Midpoint Scoring Factor (kg CO2eq/ 2013 $)	Total GWP (kg CO2eq)		Source in Appendix I
			Composite	Steel		Composite	Steel	
Energy	Electricity (CT)	Power Generation	$8,507	$49,055	9.0080E+00	7.6627E+04	2.2933E+05	Table 1
	Electricity (VA)	Power Generation	$56,001	$27,221	7.8928E+00	4.4200E+05	2.3506E+05	Table 1
	Residual Fuel Oil (No. 6)	Petroleum Fuel	$5,908,768,657	$6,951,492,537	3.7349E+00	2.2069E+10	2.5963E+10	Table 1
Land	Thermoforming Facility (including equipment)	Nonresidential manufacturing structures	$1,680,000	$0	4.9064E+05	4.9064E+05	0.0000E+00	Table 1
Water	Water (US, quality & source unspecified)	Water, sewage and other systems	$18,593,303	$13,807,643	5.8685E+07	5.8685E+07	4.3580E+07	Table 1

Table 10. Calculation of GWP from physical inventory data

Inventory Element	Activity/ Emission	Unit	# of units		GWP Midpoint Scoring Factor (kg CO2eq/unit)	Total GWP (kg CO2eq)		Source in Appendix I
			Composite	Steel		Composite	Steel	
C&M	Methane	kg	3.9056E+03	4.8774E+03	2.7500E+01	1.0740E+05	1.3413E+05	Table 3
Energy	Electricity (CT)	kWh	1.0751E+06	6.8052E+05	7.8064E-02	8.3928E+04	5.3124E+04	Table 2
	Electricity (VA)	kWh	0.0000E+00	5.0635E+05	1.3155E-01	0.0000E+00	6.6608E+04	Table 2
	Residual Fuel Oil (No. 6)	gallons	1.5632E+09	1.8390E+09	1.2014E+01	1.8780E+10	2.2095E+10	Table 2

Table 11. Aggregation of midpoint impacts

Impact Category	Impact Unit	Aggregated # of impact units	
		Composite	Steel
Fossil Fuel Use Impact	MJ deprived	5.60131E+11	6.5875E+11
Mineral & Metal Use Impact*	kg deprived	0.0000E+00	0.0000E+00
Global Warming Potential	kg CO2eq	2.2140E+10	2.6024E+10
Respiratory Effects (Inorganic)	kg PM2.5eq	4.2203E+07	4.9643E+07
Respiratory Effects (Organic)	kg NMVOCeq	5.3061E+08	6.2413E+08
Water Use Impact	m3 deprived	3.3986E+09	2.5673E+09
Land Degradation Potential	ha.yr arable eq	3.1746E+04	0.0000E+00
Cancer (External)	CTUh	1.1015E+01	1.4755E+01
Non-Cancer (External)	CTUh	4.3487E+02	5.2761E+02
Ecosystem Toxicity	CTUe	4.8205E+05	5.8098E+05

*The beta version of this guidance document does not currently include scoring factors for Mineral & Metal Use Impact.

3b. Translate the LCI into Endpoint Impacts

STEP 3b uses the inventory results of **STEP 2** and converts them into endpoint impacts associated with resource availability, human and environmental health (see Figure 2 in the overview). There are two approaches for assessing impacts based on the gathered inventory data. The first approach uses the automated tool as described in Appendix A. The second approach assesses impacts manually by using the scoring factors provided in Appendix I. Guidance on how to use the scoring factors and manually calculate endpoint impacts is provided below.

Key Steps

- Identify the appropriate endpoint scoring factor for each item in the inventory from Appendix I. Procurement cost data are used to calculate upstream (e.g., supply chain of procured items and services) endpoint impacts and physical data are used to calculate downstream (e.g., direct manufacturing, use, maintenance, disposal) impacts. For upstream scoring factors, match each procured item or service to the industry sector listed in Appendix I that best represents the sector from which the item or service was supplied. Downstream scoring factors are grouped according to inventory element and spread across multiple tables within Appendix I.
- Calculate the resulting upstream endpoint impacts by multiplying the procurement cost for each applicable inventory element by the appropriate upstream scoring factor in Appendix I (see Table 12).
- Likewise, calculate the resulting downstream endpoint impacts by multiplying the inventory quantity for each applicable inventory element by the appropriate downstream scoring factor in Appendix I (see Table 13).
- Aggregate results within each endpoint category (see Table 14).

Discussion

The inventory data are translated into a set of upstream and downstream endpoint impacts using scoring factors provided in Appendix I.

Endpoint impacts represent the damage caused to resource availability, human health, and the environment. Endpoint impacts have real costs that can be quantified and tied to system-level activities (see **STEP 4**). Endpoint impacts can also affect the DoD's mission. For example, depleting fossil fuel resources today affects future missions because current consumption of nonrenewable resources reduces the availability of those resources in the future.

Using endpoint scoring factors requires additional modeling assumptions, such as fate and transport of emissions and probability of exposure, and can result in increased uncertainty in the results. Life cycle costs can be more easily assigned to endpoint impacts making these impacts more understandable for decision makers. Endpoint impact characterization can also be a powerful life cycle costing tool for estimating hidden mission, human health, and environmental costs (see **STEP 4** for a more detailed explanation).

Additional information for each endpoint impact category, as well as step-by-step instructions for completing endpoint scoring factor calculations, can be found in Appendix H.

Superstructure Alternatives Example

Tables 12 and 13 provide examples of how the inventory data from **STEP 2** align with scoring factors from Appendix I to facilitate calculation of endpoint impacts. Here, by way of example, only the scoring factors for human health degradation are shown, however the process is the same for all other endpoint impact categories. Table 14 shows aggregated results for the superstructure alternatives across all endpoint impact categories.

Table 12. Calculation of DALYs from procurement inventory data

Inventory Element	Procured Item/Service	Matching Scoring Factor Description	NPV of Procurement Cost (2013 $)		Human Health Endpoint Scoring Factor (DALY/ 2013 $)	Total Human Health Impact (DALY)		Source in Appendix I
			Composite	Steel		Composite	Steel	
C&M	Air Filter	Air purification and ventilation equipment manufacturing	$189,411	$4,224,947	7.8073E-06	1.4788E+00	3.2986E+01	Table 1
	Air Filter Hazardous Waste	Waste management	$537	$109,208	1.9004E-06	1.0201E-03	2.0754E-01	Table 1
	Aluminum (virgin)	Alumina refining and primary aluminum production	$0	$525,450	2.9410E-05	0.0000E+00	1.5454E+01	Table 1
	Epoxy resin	Plastics material and resin manufacturing	$180,600	$0	6.7784E-06	1.2242E+00	0.0000E+00	Table 1
	Glass fiber	Other plastics product manufacturing	$972,300	$0	5.2333E-06	5.0883E+00	0.0000E+00	Table 1
	Hazardous Wastewater	Waste management	$207,128	$12,593,540	1.9004E-06	3.9363E-01	2.3933E+01	Table 1
	Mineral Wool	Mineral wool manufacturing	$42,552	$4,500	8.7421E-06	3.7200E-01	3.9340E-02	Table 1
	Paint	Paint and coatings	$8,533	$3,628,872	8.3687E-06	7.1409E-02	3.0369E+01	Table 1
	Polyester resin, unsaturated	Plastics material and resin manufacturing	$1,260,000	$0	6.7784E-06	8.5408E+00	0.0000E+00	Table 1
	Polyurethane, rigid foam	Urethane and other foam product (except polystyrene) manufacturing	$675,625	$0	6.6534E-06	4.4952E+00	0.0000E+00	Table 1
	PPE	Surgical supplies	$926	$8,303	3.7040E-06	3.4298E-03	3.0756E-02	Table 1
	PPE Hazardous Waste	Waste management	$46	$9,323	1.9004E-06	8.7083E-05	1.7717E-02	Table 1
	PPE Suites	Surgical supplies	$3,121	$845,345	3.7040E-06	1.1560E-02	3.1312E+00	Table 1
	Primer	Paint and coatings	$3,230	$1,373,452	8.3687E-06	2.7027E-02	1.1494E+01	Table 1
	All-Purpose Cleaning Solution	Soap and cleaning compound manufacturing	$14,376,789	$0	6.0329E-06	8.6734E+01	0.0000E+00	Table 1
	Steel (low alloy)	Iron and steel mills and ferroalloy manufacturing	$54,984	$1,619,500	1.2009E-05	6.6030E-01	1.9449E+01	Table 1
	Stripper	Inorganic chemicals	$0	$1,277,191	2.6432E-05	0.0000E+00	3.3759E+01	Table 1
Energy	Electricity (CT)	Power Generation	$8,507	$49,055	5.5755E-04	4.7428E+00	3.1564E+00	Table 1
	Electricity (VA)	Power Generation	$56,001	$27,221	7.2612E-06	4.0663E-01	2.7850E+00	Table 1
	Residual Fuel Oil (No. 6)	Petroleum Fuel	$5,908,768,657	$6,951,492,537	1.1912E-05	7.0383E+04	8.2804E+04	Table 1
Land	Thermoforming Facility (including equipment)	Nonresidential manufacturing structures	$1,680,000	$0	4.9064E+05	4.5392E+00	0.0000E+00	Table 1
Water	Water (US, quality & source unspecified)	Water, sewage and other systems	$18,593,303	$13,807,643	5.8685E+07	1.0522E+02	7.8141E+01	Table 1

Table 13. Calculation of DALYs from physical inventory data

Inventory Element	Activity/ Emission	Unit	# of units		Human Health Endpoint Scoring Factor (DALY/ 2013 $)	Total Human Health Impact (DALY)		Source in Appendix I
			Composite	Steel		Composite	Steel	
C&M	1-Butanol, Air	kg	5.2633E-01	1.0445E+02	1.1870E-07	6.2475E-08	1.2398E-05	Table 3
	1-Butanol, Water	kg	1.5790E+00	3.1335E+02	1.0100E-07	1.5948E-07	3.1648E-05	Table 3
	Acetone, Air	kg	5.5892E-01	1.1092E+02	2.3090E-08	1.2905E-08	2.5611E-06	Table 3
	Acetone, Water	kg	1.6768E+00	3.3275E+02	1.5800E-08	2.6493E-08	5.2574E-06	Table 3
	Arsenic, Air	kg	1.1812E+01	5.7246E-01	4.9230E-02	5.8149E-01	2.8182E-02	Table 3
	Arsenic, ion, Water	kg	5.4402E+00	1.0747E+01	7.7940E-02	4.2401E-01	8.3765E-01	Table 3
	Cadmium, Air	kg	3.9176E+00	1.5554E-01	1.2549E-01	4.9162E-01	1.9519E-02	Table 3
	Chromium VI, Air	kg	1.1693E-01	2.3204E+01	5.2320E-02	6.1177E-03	1.2140E+00	Table 3
	Chromium VI, Water	kg	8.9140E+00	9.1537E+01	1.2206E-01	1.0881E+00	1.1173E+01	Table 3
	D-Limonene, Air	kg	0.0000E+00	3.0186E+02	4.9800E-07	0.0000E+00	1.5033E-04	Table 3
	D-Limonene, Water	kg	0.0000E+00	9.0559E+02	5.3100E-06	0.0000E+00	4.8087E-03	Table 3
	Mercury, Air	kg	3.6395E-02	9.8201E-02	2.3311E+00	8.4840E-02	2.2892E-01	Table 3
	Methane, Air	kg	3.9056E+03	4.8774E+03	2.2900E-05	8.9439E-02	1.1169E-01	Table 3
	Particulates, < 2.5 um, Air	kg	2.8717E+02	5.7049E+02	8.3100E-04	2.3864E-01	4.7407E-01	Table 3
	Sulfur dioxide, Air	kg	5.1935E+03	7.5727E+03	3.1603E-05	1.6413E-01	2.3932E-01	Table 3
	Vanadium, ion, Water	kg	1.0676E+02	1.4978E+01	5.2400E-04	5.5941E-02	7.8485E-03	Table 3
	Xylene, Air	kg	0.0000E+00	2.9780E+01	3.5260E-07	0.0000E+00	1.0500E-05	Table 3
	Xylene, Water	kg	0.0000E+00	8.9340E+01	8.6900E-08	0.0000E+00	7.7637E-06	Table 3
	Zinc, ion, Air	kg	1.5103E+02	3.8076E+02	4.2100E-02	6.3584E+00	1.6030E+01	Table 3
Energy	Electricity (CT)	kWh	1.0751E+06	6.8052E+05	2.3986E-07	2.5788E-01	1.6323E-01	Table 2
	Electricity (VA)	kWh	0.0000E+00	5.0635E+05	4.3567E-07	0.0000E+00	2.2060E-01	Table 2
	Residual Fuel Oil (No. 6)	gallon	1.5632E+09	1.8390E+09	3.1385E-05	4.9059E+04	5.7717E+04	Table 2
Noise	Noise	J	4.3404E+02	1.1530E+03	multiple SFs	1.2745E+02	8.4410E+01	Table 6

Table 14. Aggregation of endpoint impacts

Impact Category	Unit	# of impact units	
		Composite	Steel
Resource Depletion*	MJ depleted	0.0000E+00	0.0000E+00
Human Health	DALYs	7.0744E+04	8.3179E+04
Environmental Health	PDF*m2*yr	4.2867E+09	5.0364E+09

*The beta version of this guidance document does not currently include scoring factors for Resource Depletion.

Step 4: Estimate Sustainability-related Life Cycle Costs

4a. Estimate Sustainability-related Internal Costs

In **STEP 4a**, the procurement costs identified in **STEP 2a** and the impacts identified in **STEP 3** are used to assess and identify any sustainability-related LCCs that would or could be incurred by the DoD and may not be accounted for using existing cost element structures (see Appendix L for an overview of existing cost element structures). All sustainability-related procurement costs should have been collected in **STEP 2a**, but there may be additional costs associated with sustainability-related activities that fall within the system boundary and have not yet been considered. This section provides guidance on how to fill any cost gaps associated with sustainability-related activities and aggregate all sustainability-related costs.

Key Steps

- If required, index all procurement costs collected in **STEP 2a** (see example in Table 2), which were indexed to 2013 dollars, to the year in which the analysis is completed to ensure that all costs estimated in **STEP 4** are indexed to the same year. For each procured item, use the appropriate

Producer Price Index (PPI) for the sector in which that item was purchased to inflate costs recorded in **STEP 2a**, which are in 2013 dollars, to the appropriate value represented in the year of the study.

- Review the drivers of high impacts from **STEP 3** to understand where additional sustainability costs not yet considered might exist. Such activities include, but are not limited to, energy and water use during sustainment activities, medical monitoring, internal waste management processes, additional labor, regulatory administration, and indirect support such as delivery of resources to the system. Many of these costs may be aggregated into overhead costs at the installation level and should be allocated to the system for a more refined estimate of the system's LCC. The assessment in **STEP 3** reveals impacts that would not be previously accounted for before **STEP 3** and lead to incremental hidden costs.
- Combine these new sustainability related costs with those developed in **STEP 2** to establish a Life Cycle Cost Profile. Further guidance for building a Life Cycle Cost Profile is available in Appendix J. The following steps should be used to complete the Life Cycle Cost Profile:
    - Classify all sustainability-related costs (procurement and sustainability-related activities) identified above and in **STEP 2a** into direct, indirect, and contingent costs (see Table 15 for an example). Additional guidance for classifying the DoD's internal sustainability-related costs is available in Appendix K.
    - For better integration into each alternative's LCC estimate, group internal sustainability-related costs into existing DoD cost elements when applicable. Appendix L provides standardized cost element structures for each stage of acquisition. Established cost categories may not be granular enough to adequately support the LCC introduced in this guidance. In such cases, analysts will be required to translate internal sustainability-related costs into the standard cost element structures customarily used in life cycle cost estimation.
    - Collect sustainability-related cost data relevant to the LCC estimates and that have not already been captured (see **STEP 2a** and Table 14). Additional guidance for collecting sustainability-related cost data is available in Appendix M.
    - Estimate internal sustainability-related costs. Appendix N provides guidance and suggested methods for estimating various sustainability-related costs.
- Aggregate all sustainability-related costs (procurement and activity-oriented) and integrate those costs into system-specific LCC estimates.

Discussion

In **STEP 2a**, all relevant items and services purchased by the DoD or its contractors should have been identified in the procurement cost inventory (see Table 2). Unlike procurement costs, most costs associated with sustainability-related activities that fall within the system boundary more than likely have not been considered. This section provides guidance on how to fill any cost gaps associated with sustainability-related activities.

The impact results of **STEP 2** can and should be used to enhance LCC efforts by identifying impacts that result in typically hidden or contingent sustainability-related costs. Sustainability-related costs result from impacts that occur downstream of the initial acquisition (operation, sustainment, and disposal activities). To properly account for these costs, the estimated impacts of the activities identified in the Life Cycle Activity Profile (see **STEP 1b**) should be monetized for comparison with costs traditionally captured by life cycle costing to better assess the cost of sustainability-related risk embedded in the acquisition. Sustainability-related costs are supplemental to other typical life cycle costing efforts. For example, in a tradeoff analysis examining alternative materials, sustainability-related costs—both

internal and external to the DoD—should be included in the analysis along with other costs such as manpower, maintenance, and performance differences.

In this step, estimate internal sustainability-related costs. Internal costs are defined as all costs incurred by the DoD over a system's life cycle. Such costs can be classified as direct, indirect, or contingent. Direct costs are those costs that are traditionally considered in a life cycle costing exercise. Indirect costs are overhead costs that are typically tracked at a facility level and not assigned back to a particular system. Contingent costs are direct or indirect costs that might occur in the future. Examples of hidden and contingent costs can be found in Appendix N and additional information on existing LCC guidance can be found in Appendix L.

Superstructure Alternatives Example

Table 15 provides an example Life Cycle Cost Profile for the superstructure alternatives illustrated in other sections. This exercise identifies the contingent costs associated with changes to hexavalent chromium regulations (e.g., new requirements for personal protective equipment changing facilities), as well as future costs associated with noise output.

Table 15. Life Cycle Cost Profile example

Cost Type	Life Cycle Phase	System Element	System Activity	Input/Emission	Cost Type	Composite Total Cost (NPV)	Steel Total Cost (NPV)
Internal (Direct)	Production	Coating	Application	Air Filter	Procured item/service	$3,928	$137,476
				Electricity (CT)	Procured item/service	$8,507	$13,610
				Paint	Procured item/service	$8,533	$289,335
				PPE	Procured item/service	$2,484	$22,273
				Primer	Procured item/service	$3,230	$109,507
		Insulation	Installation	PPE	Procured item/service	$637	$5,714
				Mineral Wool	Procured item/service	$42,552	$4,500
		Support & Exterior facing	Metal Working	Aluminum (virgin)	Procured item/service	$0	$525,450
				Electricity (CT)	Procured item/service	$0	$15,411
				PPE	Procured item/service	$926	$8,303
				Steel (low alloy)	Procured item/service	$54,984	$1,619,500
				Water (US, quality & source unspecified)	Procured item/service	$41	$533
			Thermoforming	Air Filter	Procured item/service	$185,483	$0
				Electricity (CT)	Procured item/service	$0	$20,034
				Glass fiber	Procured item/service	$972,300	$0
				Polyester resin, unsaturated	Procured item/service	$1,260,000	$0
				Polyurethane, rigid foam	Procured item/service	$675,625	$0
				Thermoforming Facility (including equipment)	Procured item/service	$1,680,000	$0
				Water (US, quality & source unspecified)	Procured item/service	$124	$0

Table 15 (continued). Life Cycle Cost Profile example

Cost Type	Life Cycle Phase	System Element	System Activity	Input/Emission	Cost Type	Composite Total Cost (NPV)	Steel Total Cost (NPV)
Internal (Direct)	Operation	Ship Fuel	Combustion	Residual Fuel Oil (No. 6)	Procured item/service	$5,908,768,657	$6,951,492,537
	Sustainment	Coating	Application	Air Filter	Procured item/service	$0	$4,087,471
				Electricity (VA)	Procured item/service	$803	$27,221
				Paint	Procured item/service	$0	$3,339,537
				PPE	Procured item/service	$0	$408,679
				Primer	Procured item/service	$0	$1,263,944
			Removal	Electricity (VA)	Procured item/service	$55,198	$0
				PPE Suites	Procured item/service	$0	$408,679
				Stripper	Procured item/service	$0	$1,277,191
				Water (US, quality & source unspecified)	Procured item/service	$0	$13,807,110
		Support & Exterior facing	Cleaning	Labor	Sustainability-related activity	$348,360	$0
				Water (US, quality & source unspecified)	Procured item/service	$18,593,138	$0
Internal (Indirect)	Production	Coating	Application	Labor	Sustainability-related activity	$0	$32,320
			Waste Disposal	Air Filter Hazardous Waste	Procured item/service	$537	$18,201
				PPE Hazardous Waste	Procured item/service	$46	$1,554
		Insulation	Installation	Labor	Sustainability-related activity	$4,862,500	$54,381
		Support & Exterior facing	Metal Working	Labor	Sustainability-related activity	$42,609	$47,343,000
			Thermoforming	Labor	Sustainability-related activity	$58,176,000	$0
			Waste Disposal	Hazardous Wastewater	Procured item/service	$207,128	$667,507
				Hazardous Wastewater Permit	Sustainability-related activity	$65,340	$210,570
	Sustainment	Coating	Application	Labor	Sustainability-related activity	$0	$161,600
			Removal	Labor	Sustainability-related activity	$0	$243,125
			Waste Disposal	Air Filter Hazardous Waste	Procured item/service	$0	$91,007
				Hazardous Wastewater	Procured item/service	$0	$11,926,032
				Hazardous Wastewater Permit	Sustainability-related activity	$0	$3,762,155
				PPE Hazardous Waste	Procured item/service	$0	$7,769
Contingent	Production	Coating	Application	PPE Changing Area	Procured item/service	$0	$1,008,000
				Noise	Sustainability-related activity	$0	$535,619

Table 15 (continued). Life Cycle Cost Profile example

Cost Type	Life Cycle Phase	System Element	System Activity	Input/Emission	Cost Type	Composite Total Cost (NPV)	Steel Total Cost (NPV)
Contingent	Production	Support & Exterior facing	Waste Disposal	Hazardous Wastewater Permit	Sustainability-related activity	$16,335	$52,643
	Sustainment	Coating	Application	PPE Changing Area	Procured item/service	$0	$588,000
				Noise	Sustainability-related activity	$0	$5,343,500
			Removal	Noise	Sustainability-related activity	$0	$2,678,095
			Waste Disposal	Hazardous Wastewater Permit	Sustainability-related activity	$0	$940,539
		Support & Exterior facing	Cleaning	Noise	Sustainability-related activity	$12,920,940	$0

4b. Estimate sustainability-related external costs:

STEP 4b provides guidance on how to translate the endpoint impact results from **STEP 3b** into external cost estimates (costs paid for by society or entities outside of the DoD).

Key Steps

- Identify the appropriate external cost factor for each endpoint impact (resource depletion, human and environmental health) recorded in the inventory. External cost factors are available in Appendix I.
- Calculate the resulting external costs by multiplying the aggregated endpoint inventory quantity (see Table 14) by the appropriate external cost factor.

Discussion

The calculation of external costs does not require additional data collection outside of what has already been gathered. External costs are assessed for each endpoint impact quantified in **STEP 3b** and are calculated using endpoint cost factors (multiply the appropriate scoring factor by the inventory quantity).

Superstructure Alternatives Example

Table 16 summarizes how the endpoint impact results from **STEP 3b** are used along with external cost factors from Appendix I to calculate external costs. Note that the endpoint impacts in Table 16 are equivalent to those in Table 14. In this example, the results are driven by the ship's fuel consumption.

Table 16. Calculation of external costs from endpoint impact results

Endpoint Impact Category	Unit	Aggregated Impact Units Composite	Aggregated Impact Units Steel	External Cost Factor (usd2013/unit	Composite Total Cost (NPV)	Steel Total Cost (NPV)	Source in Appendix I
Resource Depletion*	MJ depleted	0.0000E+00	0.0000E+00	Not available in beta version	$0	$0	Table 7
Human Health	DALYs	7.0744E+04	8.3179E+04	1.2962E+05	$9,169,640,329	$10,781,430,410	Table 7
Environmental Health	PDF.m^2.yr	4.2867E+09	5.0364E+09	2.4522E-01	$1,051,192,119	$1,235,034,872	Table 7

*The beta version of this guidance document does not currently include costing factors for Resource Depletion.

Step 5: Synthesize Results and Iterate

With **STEPs 1-4** completed, synthesize and display the results to compare alternatives. The results of the Sustainability Analysis can be presented to compare alternatives at three different levels: (1) midpoint impact; (2) endpoint impact; (3) total life cycle cost. These presentation levels are summarized below and explained in Appendix O.

- **Midpoint impact:** Midpoint impacts provide the analyst with a clear understanding of the relative potency, in terms of physical units, of each system's aggregated outputs. Midpoint results can be very useful in the design phase, as more specific physical units are needed for engineering models and design tradeoffs. Midpoints can also be useful for estimating and reporting purposes (greenhouse gases, energy, water).
- **Endpoint impact:** Endpoint impacts quantify the overall damage, in physical units, that could occur as a result of the system's aggregated impacts. Although additional assumptions are needed to calculate endpoint impacts, endpoints can be valuable when communicating the expected damage that a system could cause over its life cycle.
- **Total life cycle cost:** Presenting impacts in terms of LCC better communicates the overall importance of a particular impact. Furthermore, LCC can directly inform investment decisions and sustainment requirements, as well as highlight any cost-based risks that may be passed on the sustainment community. Lastly, translating impacts into costs allows for a seamless integration into cost-benefit analyses and total cost of ownership assessments.

A Sustainability Analysis is an iterative process. The results in later steps often reveal data gaps that can be re-addressed in earlier steps. Within time and resource constraints, update the Sustainability Analysis when new data become available. Such updates may include altering the system boundary for improved comparability between alternatives, updating life cycle activity and cost profiles, and refining impact and cost results.

Appendix A: Web-based Software

A web-based software application is currently under development. When available, the Sustainability Analysis tool will significantly simplify both the characterization of inputs into comparable impact units for each impact category and the assessment for analysts by completing all calculations for the user, which will include indexing those resulting impacts into relative scores that can be compared across impact categories. In addition to automating Sustainability Analysis impact calculations, the Sustainability Analysis tool will provide various reporting options for users, and a versatile dashboard that will include a table of normalized results, a bar graph of the normalized results, and a radar diagram that compares sustainability footprints of evaluated alternatives across all impact categories. When complete, the Sustainability Analysis tool will significantly reduce the amount of time needed to complete the Sustainability Analysis and allow users to store and recall data from previous analyses.

Appendix B: How the Sustainability Analysis fits into Existing Acquisition Processes

Overview

The intent is for this guidance to be incorporated into the U.S. DoD Integrated Defense Acquisition, Technology, and Logistics Life Cycle Management System to inform tradeoff, design, and supportability decisions for both new system acquisitions[6] and legacy systems[7]. While these methods are applicable to numerous stages in DoD acquisition, it may be most useful in informing five key decisions prior to Milestone B:

- Analysis of Alternatives (AoA) tradeoff analysis—or other alternative assessments—and proposed materiel solution
- Concept Refinement and Technology Development phases
- Major prototype decisions made during the Technology Development phase
- Preliminary Design Review (PDR)
- Supportability Analyses (SA) and the Life Cycle Sustainment Plan (LCSP)

To have the greatest influence on system design, a Sustainability Analysis should be completed during early phases of acquisition, as early as the AoA phase, but can be used as late as disposal activities under the O&S phase. A Sustainability Analysis is most useful in the Systems Engineering process during trade studies in preliminary design and to support the Affordability Analysis and Supportability Analysis. It is also recommended that Sustainability Analyses be updated when more refined data becomes available after Milestone B (sustainment and disposal activities). Sustainability remains a factor throughout acquisition and should be evaluated even if the system enters acquisition at a later phase, as directed by Materiel Development Decision (MDD) and authorized by the Milestone Decision Authority (MDA).

The level of rigor possible in a Sustainability Analysis depends on a number of factors:

- Acquisition Category (ACAT)
- Acquisition milestone, phase, or decision point
- Maturity of the alternatives and available data
- The acquisition strategy (e.g., evolutionary or single step to full capability)
- Direction from the Program Manager (PM) and the MDA, if applicable

For example, Sustainability Analyses for ACAT I acquisitions may be expansive and technically rigorous, while ACAT III acquisitions may have smaller and narrowly focused Sustainability Analyses. Similarly, a Sustainability Analysis might be predominantly qualitative in the Pre-Systems Acquisition period due to a general lack of data and definition of the materiel solutions (see Appendix E for use of qualitative data). Regardless of the ACAT designation, when acquisitions involve legacy platforms, past data from those systems should be used to support the Sustainability Analysis.

The system boundary defined by the Sustainability Analysis and the life cycle stages considered during the acquisition process are aligned. These boundaries include raw material acquisition; production; deployment; operation and sustainment (O&S); and disposal.

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[6] A new system is considered any system that enters the Integrated Defense Acquisition, Technology, and Logistics Life Cycle Management System prior to Milestone B.

[7] Legacy systems are considered to be systems that have already passed Milestone B, but may be undergoing modifications or revised operation and maintenance procedures.

Trade-Off Studies

Analysts use trade-off studies to determine the effects of various concepts and designs on performance, cost, reliability, maintainability, energy use, etc. The available maneuvering room among these variables is called the trade space where design options are analyzed to achieve optimal system performance for the best value. A Sustainability Analysis can provide more robust information on resource use, impacts, and associated life cycle costs, allowing for more informed tradeoff decisions.

Regarding tradeoffs associated with energy consumption, DoDI 5000.02, Enclosure 7, states that "the fully burdened cost of delivered energy shall be used in trade-off analyses conducted for all DoD tactical systems with end items that create a demand for energy." The fully burdened cost of delivered energy (FBCE) is also an important element of the Energy Key Performance Parameter, as detailed in the CJCSI 3170 manual. The data collected in a Sustainability Analysis directly supports the intentions of DoD's initiative to estimate the fully burdened cost of energy of acquired systems by helping to identify and quantify all direct and indirect consumption of energy throughout a system's life cycle. For more information on the computational framework for incorporating FBCE into acquisition tradespace analyses, refer to Section 3.1.6 of the *Defense Acquisition Guidebook*.

System Design

System design is a critical phase of acquisition because decisions made during this phase lock-in most of the life cycle impacts and costs that will be realized during the operations and sustainment of the system. Alternatives with the lowest acquisition cost (initial cost) may result in higher LCC because these systems may not be designed to optimize resource requirements (energy, water, land, etc.) and minimize the resulting impacts to human health, resources, and the environment during operation and sustainment activities. As a result, the embedded impacts and associated costs can be "pushed downstream" to be incurred by operation and sustainment communities.

Sustainability Analyses, as described in this document, use methods that support sustainable design. While systems must be designed to meet performance requirements, they can also be designed to be more sustainable than predecessor systems. Sustainable design principles include the following:

- Using non-toxic, non-hazardous chemicals and materials where possible
- Using renewable materials
- Minimizing wastes and designing systems that recover and recycle chemicals and materials
- Using renewable sources of energy and reducing the fully burdened cost of delivered energy (FBCE), in accordance with Enclosure 7 of DoD Instruction 5000.02.

Table B1 offers references for conducting alternatives assessments, which are used to identify less impactful inputs and inform more sustainable system designs.

Table B1. Resources to identify sustainable alternatives

Institution	Reference	Document Description	Info Type*
Lowell Center for Sustainable Production/ UMASS Lowell	Rossi, M., Tickner, J., & Geiser, K. (2006). Alternatives Assessment Framework of the Lowell Center for Sustainable Production, Version 1.0. Retrieved from http:// www.chemicalspolicy.org/downloads/FinalAltsAssess06.pdf	Developed as a first step in defining the methodology for identifying and evaluating safer alternatives.	F

Table B1 (continued). Resources to identify alternatives

Institution	Reference	Document Description	Info Type*
Business-NGO Working Group (BizNGO)	Rossi, M., Peele, C., & Thorpe, B. (2011). BizNGO Chemical Alternatives Assessment Protocol: How to Select Safer Alternatives to Chemicals of Concern to Human Health or the Environment, Version 1.0. Retrieved from http://www.bizngo.org/pdf/BizNGO_CAAProtocol_30nov2011.pdf	Developed to provide a decision framework for substituting problematic chemicals to human health or the environment with safer alternatives.	F / P_o
Business-NGO Working Group (BizNGO)	Rossi, M., Peele, C., & Thorpe, B. (2012). The Guide to Safer Chemicals: Implementing the BizNGO Principles for Safer Chemicals, Version 1.0. Retrieved from http://www.bizngo.org/pdf/GuideToSaferChemicals-v1_2.pdf	Provides tools and principles to inform businesses on how to replace toxic chemicals with safer alternatives.	P_i / T
US EPA DfE Program	Lavoie, E. T., Heine, L. G., Holder, H., Rossi, M. S., Lee II, R. E., Connor, E. A., et al. (2010). Chemical Alternatives Assessment: Enabling Substitution to Safer Chemicals. Environmental Science & Technology(44), 9244-9249.	Explains the EPA's approach to alternatives assessment under the Design for the Environment (DfE) program. Includes the steps in the process and examples of application of this assessment method.	M_e
Bren School of Environmental Science and Management/ UC Santa Barbara	Kuczenski, B., & Geyer, R. (2011). Safer Product Alternatives Analysis: Methods, Models, and Tools. Retrieved from http://www.dtsc.ca.gov/PollutionPrevention/GreenChemistryInitiative/upload/Safer-Product-Alternatives-Analysis.pdf	Prepared with the objective of identifying and evaluating existing tools, standards, methods and models for assessing and comparing alternatives, with a particular focus on chemicals of concern.	M_e / M_o / T
Lowell Center for Sustainable Production/ UMASS Lowell	Edwards, S., Tickner, J., Torrie, Y., Coffin, M., & Kernan, L. (2011). A Compendium of Methods and Tools for Chemical Hazard Assessment. Retrieved from http://www.sustainableproduction.org/downloads/Methods-ToolsforChemHazardAss5-2011.pdf	Provides an overview of the methods and tools being used by governments, the for-profit private sector, and non-profit organizations to more effectively screen and prioritize chemical hazards and identify safer alternatives.	M_e / T
Toxic Use Reduction Institute/ UMASS Lowell	Edwards, S., Rossi, M., & Civie, P. (2005). Alternatives Assessment for Toxics Use Reduction: A survey of Methods and Tools. Retrieved from http://www.turi.org/About/Library/TURI_Publications/Toxics-Use-Reduction-Policy-Analysis	Presents a collection of techniques, developed by different agencies around the world, for comparing hazard characteristics of different chemicals.	M_e / M_o / T
US DOL OSHA	Occupational Safety & Health Administration, U.S. Department of Labor. (2013). Transitioning to Safer Chemicals: A Toolkit for Employers and Workers. Retrieved from https://www.osha.gov/dsg/safer_chemicals/index.html	Offers a toolkit that helps businesses improve worker well-being through the elimination of hazardous chemicals while also creating other benefits such as cost savings, efficiency gains, etc.)	T
US EPA DfE Program	Office of Pollution Prevention & Toxics, U.S. Environmental Protection Agency. (2011). Design for the Environment Program Alternatives Assessment Criteria for Hazard Evaluation, Version 2.0. Retrieved from http://www.epa.gov/dfe/alternatives_assessment_criteria_for_hazard_eval.pdf	Supports the DfE Alternatives Assessment method by providing a transparent set of criteria for evaluating and differentiating among chemicals based on their human health and environmental hazards. (for a current list of assessments go to: http://www.epa.gov/dfe/alternative_assessments.html)	EC

Appendix C: Documenting the Sustainability Analysis Process

The data inputs, methods, results, and assumptions of the Sustainability Analysis and LCC completed using the above guidance should be documented in an adequate form to ensure transparency. Documentation should include, but is not limited to, the following facets of both the Sustainability Analysis and LCC:

- Reasons for carrying out the analysis
- System boundary, including justification for omissions of life cycle stages
- Scope of the study, including function and performance characteristics of alternative systems and functional unit
- Types of inputs and outputs of the system and assumptions or data limitations
- Decisions about data, including data sources, data quality, and assumptions or limitations
- Choice of impact categories and cost elements, including a description of any new or omitted impact categories or cost elements
- Name and affiliation of analysts and the date of assessment

Appendix D: Life Cycle Activity Profile Guidance

The Life Cycle Activity Profile, to be completed for each alternative being considered, streamlines data collection efforts by focusing the assessment on activities at each life cycle stage that are likely to have the greatest impacts to resource availability (mission), human health, and the environment.

Completion of a Life Cycle Activity Profile requires the analyst to complete the following steps across all life cycle stages:

1. Identify the appropriate activity descriptors for the system
2. Summarize activities that commonly occur within the system's activity descriptor classifications
3. Estimate which activities likely have dominant contributions to impacts

1. Identify the appropriate activity descriptors for the system

Defining key activity descriptors for each alternative enables identification of the activities and life cycle stages that consume the most resources and generate noise.

Alternatives can be classified into one of four activity descriptor groups (Table D1 provides examples of each group):

- **Active and stationary systems** do not move on their own accord and actively consume resources during operation to properly achieve the function.
- **Active and mobile systems** can move on their own accord and actively consume resources during operation to properly achieve the function.
- **Passive and stationary systems** do not move on their own accord and do not consume resources during operation. Being stationary, these systems do not use support systems for mobility to properly achieve the function.
- **Passive and mobile systems** do not move on their own accord and are mobilized using support systems. Being passive, these systems do not directly consume resources during operation to achieve the function.

Table D1. Examples of systems organized by energy activity descriptors

	Stationary	Mobile
Active	HVAC System, Water Purification System	Aircraft, Ground Vehicle, Ship
Passive	Satellite Dish, Barricade Infrastructure	Trailer, Satellite, Bomb

2. Summarize activities that commonly occur within the system's activity descriptor classifications

This section provides guidance, by inventory element, on common types of activities that are typically associated with the descriptor classifications outlined above. Determining which activities to include in the analysis will require expert judgment. The following discussion may be useful in narrowing the scope of the analysis.

Active and Stationary Systems

Active and stationary systems affect the following inventory elements accordingly:

- **Energy:** Active and stationary systems typically consume some form of energy during operation (including support systems), causing the energy-use profile to be dominated by the direct energy

needed to operate and sustain the system and the indirect energy needed to supply that system with necessary resources.

- **Chemicals and Materials (C&M):** Active and stationary systems typically consume the largest inventory (number) of C&M and largest amount (quantity) of those C&M during manufacturing. Although the chemical-and-material-use profile for active and stationary systems is often dominated by manufacturing, operations or sustainment could dominate when the resulting use for a given system is compounded due to a long system lifespan or a high frequency of activities in either stage (e.g., cleaning, maintenance, operations). This could cause such use to outweigh the contribution from manufacturing. Significant use of solvents and lubricants can also lead to higher impacts in operations and sustainment, but this scenario is not as common in active and stationary systems as it is for active and mobile systems.
- **Water:** Active and stationary systems typically consume water for operation, cleaning or maintenance purposes. The water-use profile for active and stationary systems is typically, although not always, dominated by operations and sustainment; both in terms of the direct water needed to operate and sustain the system and the indirect water needed to supply that system with necessary resources. However, it is important to note that the water-use profile for some active systems that do not require the use of water during operation for cleaning or maintenance is often dominated by manufacturing.
- **Land:** Like all systems, regardless of their activity descriptors, the incremental land use caused by active and stationary systems is typically greatest during manufacturing. Any increase in the manufacturing footprint (e.g., new manufacturing facility or expanded manufacturing line) needed to produce a system that causes an incremental increase in the use of previously undeveloped land should be directly tied to that system. In terms of operations and sustainment, any incremental facilities or other developed land needed to store or support the system also should be tied to that system. It is important to note that, unlike for mobile systems, the incremental land requirements in operations and sustainment for stationary systems is typically minor compared to the manufacturing phase.
- **Noise:** Active and stationary systems typically produce some level of noise that is concentrated in a particular location, either indoors or outdoors.

Active and Mobile Systems

An active and mobile system affects the following inventory elements accordingly:

- **Energy:** Active and mobile systems typically consume some form of energy during operation, which includes self-employed mobility. The energy-use profile for active and mobile systems is typically dominated by the direct energy needed to operate and sustain the system and the indirect energy needed to supply that system with necessary resources.
- **Chemicals and Materials:** Active and mobile systems typically consume the largest inventory (number) of C&M and largest amount (quantity) of those C&M during manufacturing, operation and sustainment. Although the chemical-and-material-use profile for active and mobile systems is often dominated by manufacturing, operations and sustainment could dominate when the resulting use for a given system is compounded due to a long system lifespan or a high frequency of activities in either stage (e.g., cleaning, maintenance, operations) and cause such use to outweigh the contributions the manufacturing. Significant use of solvents, lubricants, paints, plastics and metals can also lead to higher impacts in operations and sustainment, and is most common in active and mobile systems.
- **Water:** Active and mobile systems typically consume water for operation, cleaning or maintenance purposes. The water-use profile for active and mobile systems is typically, although not always,

dominated by operations and sustainment; both in terms of the direct water needed to operate and sustain the system and the indirect water needed to supply that system with necessary resources. However, it is important to note that the water-use profile for some active systems that do not require the use of water during operation for cleaning or maintenance is often dominated by manufacturing.

- **Land:** Like all systems, regardless of their activity descriptors, the incremental land use caused by active and mobile systems is typically greatest during manufacturing. Any increase in the manufacturing footprint (e.g., new manufacturing facility or expanded manufacturing line) needed to produce a system that causes an incremental increase in the use of previously undeveloped land should be directly tied to that system. In terms of operations and sustainment, any incremental facilities or other developed land needed to store or support the system also should be tied to that system. It is important to note that mobile systems typically have a larger land impact, in terms of proportion of impact throughout the system life cycle, than stationary systems. The mobile nature of these systems typically requires the use of more land because operation and sustainment activities can occur in multiple locations (e.g., runways, depots, ports). It is also important to note that the end-of-life land requirements needed for mobile systems can also be large due to greater waste streams.
- **Noise:** Active and mobile systems typically produce some level of noise that is dispersed across multiple locations, often outdoors.

Passive and Stationary Systems

A passive and stationary system affects the following inventory elements accordingly:

- **Energy:** The energy-use profile for passive and stationary systems is typically dominated by manufacturing because these systems do not consume energy during operation and sustainment requirements are generally minimal.
- **Chemicals and Materials:** Passive and stationary systems typically consume the largest inventory (number) of C&M and largest amount (quantity) of those C&M during manufacturing. Minimal operation requirements typically lead to minimal sustainment activity (chemical and material repair and replacement). When chemicals or materials are consumed during operation and sustainment, it is typically for cleaning and maintenance due to exposure to harsh environmental conditions. It is important to note that passive and stationary systems that have a long lifespan and are frequently cleaned and maintained could consume a proportionally large amount of C&M in operation and sustainment relative to other life cycle stages.
- **Water:** The water-use profile for passive and stationary systems is typically dominated by manufacturing because these systems typically do not consume much water for operation and sustainment activities. When water is consumed during operation and sustainment, it is typically for cleaning and maintenance due to exposure to harsh environmental conditions. It is important to note that passive and stationary systems that have a long lifespan and are frequently cleaned and maintained could consume a proportionally large amount of water in operation and sustainment relative to other life cycle stages.
- **Land:** Like all systems, regardless of their activity descriptors, the incremental land use caused by passive and stationary systems is typically greatest during manufacturing. Any increase in the manufacturing footprint (e.g., new manufacturing facility or expanded manufacturing line) needed to produce a system that causes an incremental increase in the use of previously undeveloped land should be directly tied to that system. In terms of operations and sustainment, any incremental facilities or other developed land needed to store or support the system also should be tied to that

system. It is important to note that, unlike for mobile systems, the incremental land requirements in operations and sustainment for stationary systems is typically minor compared to the manufacturing phase.

- **Noise:** Passive and stationary systems typically do not produce noise.

Passive and Mobile Systems

A passive and mobile system affects the following inventory elements accordingly:

- **Energy:** The energy-use profile for passive and mobile systems is typically dominated by manufacturing because these systems do not consume energy during operation. It is important to note that passive and mobile systems that are frequently transported by support systems could have a high energy impact during operations and sustainment if the amount of indirect energy use for that transport is significant.
- **Chemicals and Materials:** Passive and mobile systems typically consume the largest inventory (number) of C&M and largest amount (quantity) of those C&M during manufacturing. Low operation requirements typically lead to less sustainment activity (chemical and material repair and replacement). When chemicals or materials are consumed during operation and sustainment, it is typically for cleaning and maintenance due to exposure to harsh environmental conditions. It is important to note that passive and stationary systems that have a long lifespan and are frequently cleaned and maintained could consume a proportionally large amount of C&M in operation and sustainment relative to other life cycle stages.
- **Water:** The water-use profile for passive and mobile systems is typically dominated by manufacturing because these systems typically do not consume much water for operation and sustainment activities. When water is consumed during operation and sustainment, it is typically for cleaning and maintenance due to exposure to harsh environmental conditions. It is important to note that passive and mobile systems that have a long lifespan and are frequently cleaned and maintained could consume a proportionally large amount of water in operation and sustainment relative to other life cycle stages.
- **Land:** Like all systems, regardless of their activity descriptors, the incremental land use caused by passive and mobile systems is typically greatest during manufacturing. Any increase in the manufacturing footprint (e.g., new manufacturing facility or expanded manufacturing line) needed to produce a system that causes an incremental increase in the use of previously undeveloped land should be directly tied to that system. In terms of operations and sustainment, any incremental facilities or other developed land needed to store or support the system also should be tied to that system. It is important to note that mobile systems typically have a larger land impact, in terms of proportion of impact throughout the system life cycle, than stationary systems. The mobile nature of these systems typically requires the use of more land because operation and sustainment activities can occur in multiple locations (e.g., runways, depots, ports). It is also important to note that the end-of-life land requirements needed for mobile systems can also be large due to greater waste streams.
- **Noise:** Passive and mobile systems typically do not produce noise; however, these systems often require support systems for transport resulting in noise dispersed across multiple locations, often outdoors.

3. Identify activities that likely have dominant contributions to impacts

Table D2 provides a template for completing the Life Cycle Activity Profile. The activities identified above should be recorded in the cell that corresponds to the appropriate inventory element and life cycle

stage. After entering all activities into the table, identify high-impact activities. In this example, cells in the table have been color coded to indicate activities that are most material for the analysis (most likely to result in greater impact and associated costs).

Once completed, the Life Cycle Activity Profile guides data collection by identifying when resources are consumed and noise is emitted and which activities drive those results; thus focusing data collection efforts on activities that are most material in terms of total impact and associated costs.

Table D2. Example Life Cycle Activity Profile for Generic Aircraft

Inventory Element	Life Cycle Stages			
	Production & Deployment (Investment)	Operation (Including Support Systems)	Sustainment	Disposal
Energy	• Material fabrication and assembly • Flight testing	• Fuel use (direct) • Transportation of fuel to FOB or depot (indirect) • Transportation of water to FOB or depot (indirect)	• Overhead electricity consumed at depot (indirect) • Overhead fuel use consumed at depot (indirect)	• Reconditioning of engines for reuse • Recycling of aluminum frame, scraps & electronics
Water	• Coating application	• N/A	• Coating stripping (direct) • Engine and airframe cleaning (direct)	• Recycling of aluminum frame, scraps & electronics
Chemicals & Materials	• Coating application • Use of solvents • Use of oils and lubricants	• Use of oils and lubricants	• Resurfacing (grinding) • Coating stripping • Coating application • Use of solvents • Use of oils and lubricants	• Reconditioning of engines for reuse • Recycling of aluminum frame, scraps & electronics
Land Use	• Incremental footprint for existing manufacturing facility	• Two additional runways for takeoff/landing	• New hangar needed for fleet sustainment	• Additional landfill acreage needed for solid waste disposal
Noise	• Operation of machinery	• Aircraft idle, takeoff, cruise and landing	• Operation of machinery	• Operation of machinery

Legend			
Minimal to No Impact	Low Impact	Medium Impact	High Impact

Appendix E: Data Collection Guidance

Before collecting data for the Sustainability Analysis, it is helpful to record what data exist and are available for the analysis and identify the source, ownership, and format of the data.

Data for the Sustainability Analysis can come from multiple sources. Sources of the data may include, but are not limited to (1) purchase records from similar existing platforms and legacy systems, (2) sustainment data for operation and maintenance of similar existing platforms and legacy systems, (3) an estimated bill of materials informed by initial designs or technology development activities, (4) use of inputs from initial tests during technology development, and (5) estimates (engineering, parametric, etc.) of input use or consumption during all appropriate life cycle stages.

Whenever possible, use verifiable data to meet the requirements established in Appendix F. In some cases, however, some data elements (e.g., quantity and cost data) needed to conduct the analysis will not exist or maybe difficult to obtain. As a result, analysts will have to provide estimates for each data element needed to appropriately model all inventory elements (system inputs and outputs). The following sections provide guidance on how to (1) collect and use system-specific data, (2) use data or modeled relationships from legacy systems as proxy estimates for system-specific data elements, and (3) develop proxy estimates for system-specific data elements from qualitative assessments.

System-specific data

Quantitative life cycle data for inventory elements should be continually collected throughout all phases of acquisition and updated as needed. Data updates are especially important during the sustainment of the system, as resource consumption and resulting impacts vary the most in this phase of the system's life cycle. Collecting additional data elements for resource consumption during sustainment can be used for trend analyses that better inform future resource allocation decisions, both for the system of interest as well as future systems. When system-specific data for inventory elements are modeled using engineering or parametric models, updates to parameters used to define relationships in those models are also critical when new information becomes available.

As data are collected throughout the life of the system, the data should be stored in a central repository that is accessible for use in future Sustainability Analyses. In general, it is recommended that previous analyses be updated with newly acquired data to improve results for the specified system and all future system acquisitions. Updating these assessments will also provide Program Offices with the ability to compare the system's realized impacts with the expected impacts estimated by the Sustainability Analysis method. Such comparisons are important for understanding why systems performed differently than expected and provide insight for reducing the use of resources and resulting emissions.

Legacy data

When system-specific data are not available or too costly and time consuming to collect, consider using proxy data from legacy systems, components, or parts that have similar functions and performance expectations. Legacy data are often derived from models (e.g., engineering and parametric) that may need to be adjusted (e.g., appropriately scaling parameters that define modeled relationships) before they are used as proxy data inputs into the Sustainability Analysis. When adjustments in modeled data are required, document any assumptions and ensure that they are consistent across relevant data elements and evaluated alternatives.

Qualitative data

If legacy data or models are unavailable, analysts can derive estimates for data elements from a qualitative assessment that compares the relative magnitude of a particular data element with the

magnitude of identical data elements across alternative systems. When estimating specified data elements for a particular inventory element, analysts should first assess each alternative according to a qualitative scale. A qualitative scale is not based on actual data; it should represent engineering judgment for the order of performance (best to worst), as well as an estimated magnitude of difference in performance among the alternatives for the specified element. Such qualitative scales should be bounded between 0% and 100%, with the alternative resulting in the highest value (worst performing) receiving a score of 100%. Once the worst alternative has been identified, approximate—in appropriate units—the value for that alternative's specified data element. Once the estimated value is determined for the worst performer, multiply each remaining alternative's qualitative score by that value to derive the estimated values for those alternatives.

Sometimes system-specific or legacy data may exist for only a fraction of the alternatives considered in the Sustainability Analysis. In such instances, analysts can infer estimates for missing data elements by assuming that they represent a percentage of the respective data elements for alternatives for which system-specific or legacy data are available. The relationships between alternatives should be developed using best-available engineering expertise.

Provide estimates for data elements that lack system-specific or legacy data, even if those estimates are crude. Because the Sustainability Analysis is a comparative analysis, the relative magnitude of difference between alternatives is more important than that actual value when data are unavailable.

Appendix F: Data Requirements for the Life Cycle Inventory

The sections below provide a detailed explanation of the data requirements for each inventory element (energy, C&M, water, and land inputs, and noise output) when building a Life Cycle Inventory (LCI) for each alternative.

Data Requirements for Energy Inputs

When collecting data on system energy use, analysts should consider all life cycle energy (cradle-to-grave) that is consumed by the system within the system boundary established in **STEP 1**. Analysts should focus data collection efforts on energy consumption resulting from the high-impact activities identified in the Life Cycle Activity Profile (see **STEP 1**). The collected data should consider all direct and indirect energy (see definitions in Appendix Q) necessary for the functional unit (see **STEP 1**). The following data are required to estimate the system's life cycle impacts from energy consumption:

- **Energy type:** Identify all types of energy (diesel fuel, JP-8, electricity, etc.) that a system will consume during the production, operation, sustainment, and disposal of the system. Appendix I provides analysts with a list of all energy types that should be considered when collecting data for the LCI.
- **Activity:** Identify all relevant activities (diesel fuel combustion in a land vehicle, electricity consumption from a specified location, etc.) that occur for each specified type of energy consumed by the system. Appendix I provides a list of all energy types and associated activities that should be considered when collecting data for the LCI. (NOTE: the activity categories provided in Appendix I are intentionally broad to simplify data collection and modeling requirements.)
- **Quantity of energy consumption:** The quantity of energy consumption is used to estimate downstream impacts associated with the system. Determine the total estimated quantity of energy consumed by the system during manufacturing, operation, sustainment, and disposal activities (downstream impacts) and aggregate the data by each energy type and activity. Quantity data for each energy type should be recorded in the units specified in Appendix I. Guidance is provided in Appendix E on collecting quantity data, as well as how to estimate quantity when data are unavailable.
- **Cost of energy procurement:** The procurement cost of all energy consumed by the system is used to estimate upstream impacts associated with the system's supply chain. Collect the total estimated life cycle procurement cost of each energy type recorded above and aggregate those costs according to the appropriate industry sector. Appendix I classifies each energy type into a specified industry sector. If the procurement cost of one or more energy types is unknown, use standard energy prices provided by the Defense Logistics Agency (DLA) and the quantity recorded above to estimate the procurement cost for those types of energy.[8]

The list of scoring factors provided in Appendix I—organized by energy type and activity—is robust but not exhaustive. This is particularly true for unconventional sources of energy or newly developed activities that require energy. In such cases, analysts have two options: identify an energy type and activity that can serve as a proxy estimate or develop a new scoring factor. When developing new scoring factors, analysts must develop emission factors resulting from the specified energy type and activity, either through research or testing, and multiply each emission factor by the appropriate impact characterization factor provided by the LCIA methodologies documented in Appendix I.

[8] DLA Energy Standard Prices can be downloaded at: http://www.energy.dla.mil/DLA_finance_energy/Pages/dlafp03.aspx

Analysts are required to estimate and compare each alternative's life cycle energy consumption during trade-off studies. DoDI 5000.02, Enclosure 7, states that "the fully burdened cost of delivered energy shall be used in trade-off analyses conducted for all DoD tactical systems with end items that create a demand for energy." The fully burdened cost of delivered energy (FBCE) is also an important element of the Energy Key Performance Parameter, as detailed in the CJCSI 3170 manual. The data collected as described in this section directly supports the intentions of DoD's initiative to estimate the fully burdened cost of energy of acquired systems by identifying and quantifying all direct and indirect consumption of energy throughout a system's life cycle. For more information on the computational framework for incorporating FBCE into acquisition tradespace analyses, refer to Section 3.1.6 of the *Defense Acquisition Guidebook*.

Data Requirements for Chemical & Material Inputs

Collect data on the procured C&M (raw materials, components, and parts) inputs to the system and any chemical releases (emissions) resulting from industrial processes (metal working, plastics molding, painting and stripping, solvent use, etc.) that occur during the production, sustainment, and disposal of the system (downstream). Focus data collection efforts primarily on chemical and material inputs and resulting emissions from high-impact activities that are identified in the Life Cycle Activity Profile (see **STEP 1**). All data collected should be consistent with the established system boundary (see **STEP 1**). The following data are needed to estimate the system's life cycle impacts from chemical and material consumption and resulting chemical emissions:

- **Quantity chemical and material inputs:** The quantity of chemical and material inputs are used to estimate downstream impacts associated with resource depletion and inform the estimation of chemical emissions from industrial processes (see bullet below). Collect and aggregate the total estimated quantity of each chemical or material consumed by the system during manufacturing, operation, sustainment, and disposal activities (downstream impacts). Quantity data for all chemical and materials should be recorded in units of mass, as specified in Appendix I. Guidance is provided in Appendix E on collecting quantity data, as well as how to estimate quantity when data are unavailable.
- **Quantity of chemical emissions:** The quantity of chemical emissions is used to estimate downstream impacts associated with the system. Unlike with energy combustion, where scoring factors incorporate standardized emission profiles for specified activities, the unique properties of chemical and material transformations that occur during industrial processes make it very difficult to standardize chemical emissions from those processes. The scoring factors provided in Appendix I do not account for chemical emissions; therefore, analysts must provide estimates of downstream emissions from high-impact industrial processes that are identified in the Life Cycle Activity Profile (see Appendix D). To avoid double counting, chemical releases from industrial processes do not include emissions from energy combustion, which is already accounted for in the energy estimates.

  Consistent with the conservation of mass, use mass balance techniques for estimating chemical emissions to the air, water, and land that result from the use and transformation of chemical compounds during industrial processes. When more precise data are not available, Material Safety Data Sheets (MSDSs) may be used to estimate quantities of chemicals embedded in procured materials and chemical compounds that may be released during industrial processes. Although not exhaustive, Appendix I provides analysts with a list of chemical emissions that should be considered when collecting data for the LCI. Quantity data for all chemical compounds should be recorded in units of mass, as specified in Appendix I. Guidance is provided in Appendix E on collecting quantity data, as well as how to estimate quantity when data are unavailable.

- **Procurement cost of chemical and material inputs:** The procurement cost of all chemical and material inputs used by the system is used to estimate upstream impacts associated with the system's supply chain. Collect the total estimated life cycle procurement cost of each chemical compound recorded above and aggregate those costs according to the appropriate industry sector. Appendix I classifies each chemical compound into a specified industry sector. Consult with experts to develop estimates for any unknown costs.

The list of scoring factors for chemical emissions in Appendix I is not exhaustive and represents only those emissions for which the risk of impact can be characterized using established scientific research. There are hundreds—if not thousands—of C&M that may be prevalent within the established system boundary and result in harmful emissions. Use expert judgment to determine which C&M should be included in the Sustainability Analysis A chemical or material should be included in the Sustainability Analysis if it is potentially toxic or harmful, has high emission control or waste management costs, is at risk of supply disruption; or is critical to the system. NOTE: if an emission is not listed in Appendix I, this does not imply that the chemical compound poses no risk. Instead, it is possible that the chemical compound of interest lacks scientific evidence of impact risk. In such cases, consult with subject matter experts to assess the risk of impact that the chemical emission poses. Further, analysts may consider modeling the composing constituents of the chemical compound emitted when that specific compound is not available in Appendix I.

Data Requirements for Water Inputs

When collecting data on system water use, analysts should consider all life cycle water (cradle-to-grave) that is consumed by the system within the established system boundary (see **STEP 1**). Analysts should focus data collection efforts on water consumption resulting from high-impact activities that are identified in the Life Cycle Activity Profile (see **STEP 1**). Data collected by analysts should consider all direct and indirect water (see definitions in Appendix Q) necessary for the functional unit (see **STEP 1**). The following data are required to estimate the system's life cycle impacts from energy consumption:

- **Water source:** Identify all sources of water (river, lake, ground water, water utility, etc.) supplying the water that a system will consume during the production, operation, sustainment, and disposal stages of the life cycle (downstream impacts). Local water utilities will provide water for most activities that occur during those life cycle stages. Appendix I provides a list of all sources of water that should be considered when collecting data for the LCI.
- **Water location:** Identify the country from which the water from each source identified above is consumed. Appendix I provides a list of scoring factors that provide average water-related impacts for each country.
- **Water quality:** Consider the quality of the water provided by each source identified above. Table F1 summarizes the various levels of water quality available throughout the world. The scoring factors in Appendix I pairs water regions, identified above, with the average quality of the water consumed from that region.

Table F1. Summary of various levels of water quality available worldwide

Quality Category	Microbial Content	Toxicity Content
Excellent	Low	Low
Good	Low	Medium
Average	Medium	Medium
Average (high toxicity)	Low	High

Table F1 (continued). Summary of various levels of water quality available worldwide

Quality Category	Microbial Content	Toxicity Content
Average (high microbial)	High	Low
Poor	High	Medium
Very Poor	High	High
Unusable	N/A	N/A
Rain Water	N/A	N/A

- **Quantity of water consumption:** The quantity of water consumed is used to estimate downstream impacts associated with the system. Collect information on the total estimated quantity of water, aggregated by common source, region, and quality classification, that is consumed by the system during manufacturing, operation, sustainment, and disposal activities (downstream impacts). Quantity data for each water classification should be recorded in units of volume, as specified in Appendix I. Guidance is provided in Appendix E on collecting quantity data, as well as how to estimate quantity when data are unavailable.
- **Cost of water procurement:** The procurement cost (utility price of water) of all water consumed by the system is used to estimate upstream impacts associated with the system's supply chain. Collect information on the total estimated life cycle procurement cost of water consumed during the production, use, sustainment, and disposal of the system.
- **Cost of direct water withdrawal:** Not all water used during the system's downstream activities is purchased from water utilities. The costs associated with water withdrawn directly from rivers, lakes or reservoirs, treated, and consumed during the production, use, sustainment, and disposal of the system should also be considered. Although these costs are not used to estimate system impacts, these costs will inform data collection efforts for life cycle costing (see **STEP 4**).

The scoring factors for water-related midpoint impacts in Appendix I are available when the water source, location, or quality is unspecified. Thus, data provided for any combination of these parameters can be used to generate midpoint impact results. NOTE: the use of scoring factors with unspecified parameters will produce less accurate results.

Data Requirements for Land Inputs

Analysts should consider all incremental land use (see definition in Appendix Q) that is required to support the system during the production, sustainment, and disposal of the system (downstream impacts). Calculating upstream impacts from incremental land use is not applicable because all impacts for this element are realized during and after the transformation and occupation of the specified plot of land. For the Sustainability Analysis, a system's incremental land use should only refer to basing space (see definition in Appendix Q), which includes, but is not limited to, land acreage, piers and shoreline, runways, hangers, etc. Operational space (see definition in Appendix Q) is not typically considered in a Sustainability Analysis, but can be incorporated by analysts as needed. Analysts should focus data collection efforts on incremental land use resulting from high-impact activities that are identified in the Life Cycle Activity Profile (see **STEP 1**). The following data are required to estimate the system's life cycle impacts from energy consumption:

- **Land use designation:** Identify the land use designation for each incremental area of land occupied to support the system during the production, operation, sustainment, and disposal of the system (downstream impacts). A land-use designation represents the general activity that will occur on the

specified area of land while occupied (see Table F2). Land-use types are organized by four general land use groups: artificial, agriculture, forest, and wetlands.

Table F2. Land use types for consideration in Sustainability Analysis

Land Use Group	Land Use Type	Description
Artificial Areas	Artificial Areas (non-agriculture vegetated areas)	Green urban areas and sport and leisure facilities
	Construction Site	Land under construction
	Dump Site	Land used to dispose of solid waste
	Industrial Area	Industrial parks and general industrial uses
	Urban Center	Continuous urban fabric
	Traffic area	Road and rail networks and associated land, port areas, and airports
	Mineral Extraction Site	Land used to extract minerals
Agricultural Areas	Agroforestry	Land management involving the growing of trees in association with food crops or pastures
	Annual crops	Production of plants that last for one season, and must be replanted after each harvest
	Arable	Land suitable for farming and includes irrigated and non-irrigated agricultural activities
	Fallow Ground	Uncultivated land that has been plowed and unseeded for a season or more
	Paddy Rice	Rice fields
	Permanent crops	Production of plants that last for many seasons, rather than being replanted after each harvest
	Pastures and Meadows	Land covered with grass and other low lying plants suitable for grazing animals and making hay
Forest and Semi-natural Areas	Forest (used)	Land covered with trees and underbrush and is actively used and maintained
	Forest (intensive)	Land covered with trees and underbrush that is actively managed to produce forest products, mainly timber
	Forest (not used)	Land covered with trees and underbrush and is not actively used and maintained
	Grassland/Prairie	Land covered by a diversity of perennial herbaceous plants growing between grasses
	Secondary Vegetation	A forest or woodland that has regrown after a major disturbance
	Shrub land	Vegetation dominated by shrubs, often also including grasses, herbs, and geophytes
	Tropical Rain Forest	Dense forest of evergreen trees growing in regions of heavy year-round rainfall in tropical latitudes
Wetlands	Wetlands	Inland and coastal wetlands such as marshes, peat bogs, salines, and intertidal flats

- **Occupation time**: Estimate the amount of time all incremental land for each land type will be occupied. Occupation time should be recorded in years.

- **Area of incremental land use:** Record the area of each incremental plot of land that will be occupied to support the system during the production, sustainment, and disposal of the system, and aggregate those results by land type. Area of increment land use should be recorded in units of area, as specified in Appendix I. Guidance is provided in Appendix E for collecting data, as well as how to estimate values when data are unavailable. It is important to note that area estimates may need to be allocated to the system of interest when (1) more than one units of the system are needed for the functional unit (see **STEP 1a**) or (2) multiple systems and/or activities, in addition to the system of interest, will occupy the incremental area of land. For example, if a new hangar must be built (10 acres of incremental land use) to house and maintain a new aircraft and the functional unit requires 10 aircraft to meet the desired capability, then the total amount of land allocated to a single aircraft would be 1 acre. Using this same example, if other aircraft not captured in the analysis will also be housed and maintained at this facility, then the total acreage assigned to one aircraft should be 10 acres divided by the total number of aircraft at the facility.
- **Cost of incremental land acquisition:** The costs associated with any incremental land acquired to support the system should also be considered. Although these costs are not used to estimate system impacts, these costs will inform data collection efforts for life cycle costing (see **STEP 4**). As with land area, the cost of land must be allocated according to the same rules described in the bullet above.

Data Requirements for Noise Outputs

When collecting data for noise output, consider the increase in sound pressure resulting from the use of the system and how the resulting noise affects people in proximity of the source of emission. The estimates of the quantity of noise output can be based on measurements at the source or estimates using proxy data from legacy systems, predictive models, or expert elicitation. Existing DoD occupational and environmental health-related exposure monitoring data may be used to estimate the level of noise output. The following data are required to estimate the system's life cycle impacts from energy consumption:

- **Sound Power:** Record the power of the sound emitted by the source. Sound power is not typically collected, but can be derived from sound pressure level, which is commonly measured with a sound level meter. The equation below can be used to convert sound pressure level, measured in decibels (dB), to sound power, measured in Watts (W). Sound power should be recorded in units of area, as specified in Appendix I. Guidance is provided in Appendix E for collecting data, as well as how to estimate values when data are unavailable.

$$Sound\ Power\ (W) = 1.0E^{-12} \times 10^{Sound\ Pressure\ Level\ (dB)/10}$$

- **Duration of Exposure:** Record the total duration of time for which the system emits noise over the functional unit (see **STEP 1**). For example, if the functional unit is to complete 20 cycles every day for 20 years, and each cycle lasted for 1 minute, then the total duration of exposure over the system's life cycle would be 233,600 minutes[9], or roughly 162 days. If calculating midpoint impacts manually (see Appendix G), all units of time should be converted to seconds, which will allow the user to multiply the total sound-related energy in joules (J)—which are watts per second—by the appropriate noise-related midpoint scoring factor. When using the web-based software tool (see Appendix A) unit conversions are not required by the user.
- **Time of Exposure:** Record the time of day for which the noise is emitted. To simplify calculations and data collection, general profiles relating to the time of exposure have been provided for analysts in Appendix I. These profiles include: day, evening, night, and unspecified. If the system produces

[9] $20\ cycles \times 1\ minute\ per\ cycle \times 365\ days\ per\ year \times 20\ years$

noise during multiple times of day, treat the exposure for each time of day as separate emissions to ensure greater accuracy in the impact results.

- **Frequency of Sound:** Record the frequency, in hertz (Hz), of the sound emitted by the source. To simplify calculations and data collection, the central frequency for the 8 octave bands that can be detected by the human ear. These octave bands and central frequency are summarized in Table F3.

Table F3. Summary of various levels of water quality available worldwide

Octave Band	Central Frequency (Hz)	Frequency Range (Hz)
1	63	44-88
2	125	88-177
3	250	177-354
4	500	354-707
5	1,000	707-1,414
6	2,000	1,414-2,828
7	4,000	2,828-5,656
8	8,000	5,656-11,312

- **Place of Exposure:** Record the place in which the exposed population resides. To simplify calculations and data collection, general profiles relating to the place of exposure have been provided for analysts in Appendix I. These profiles include: urban, suburban, rural, industrial, indoor, and unspecified.

Appendix G: Midpoint Impact Categories and Calculations

Overview of Midpoint Impacts

Midpoints are the relative impacts at a common midpoint along the cause-effect chain. As shown in Figure 2 (see overview), the use of resources (system inputs) can negatively impact availability of non-renewable resources, air quality, water and land resources, and toxicity to humans or ecosystems. Similarly, chemical and noise emissions can result in air, water, soil and noise pollution. A midpoint analysis minimizes the use of forecasting and effect modeling to assess impacts, which reduces the complexity of the modeling, simplifies communication, and provides a higher level of confidence in the impact assessment results. Estimating impacts at midpoint can inform environment, health, and safety requirements (personal protective equipment, permitting, emissions reporting, etc.) that are likely to have associated LCCs that may not have been captured in **STEP 2a**. However, midpoint impact characterization makes comparing the importance or magnitude of impact across midpoint impact categories difficult because those impacts are measured in different—and incomparable—units. Further, valuation of midpoint impacts is difficult because the costs of such impacts are abstract (e.g., what is the cost of emitting a specified quantity of pollution into the air or water?). These limitations result in the need to also characterize the impact at the endpoint of the cause-effect chain (see **STEP 3b**). A summary of all midpoint impact categories considered in a Sustainability Analysis is provided in Table G1.

Table G1. Midpoint impact categories used in Sustainability Analysis

Impact Grouping	Midpoint Impact Categories	Unit of Measure	Metric Indicates
Non-Renewable Resources	Fossil Fuel Use Impact	MJ deprived	• Resource availability • Competing demand • Availability of substitutes
	Mineral and Metal Use Impact	kg deprived	
Air Quality	Global Warming Potential	kg CO_2eq	• All emissions to air that are classified as greenhouse gases
	Respiratory Effects (Inorganic)	kg $PM_{2.5}$eq	• All inorganic air emissions that can result in respiratory illness
	Respiratory Effects (Organic)	kg NMVOCeq	• All organic air emissions that can result in respiratory illness
Water Resources	Water Use Impact	m^3 deprived	• Resource availability • Competing demand • Availability of substitutes
Land Resources	Land Degradation Potential	ha.yr arable eq	• Biological quality of the incremental land being transformed and occupied
Toxicity	Cancer (External)	CTU_h	• Potential for cancer as a result of releases to air, land, or water
	Non-Cancer (External)	CTU_h	• Potential for non-cancer illness as a result of releases to air, land, or water
	Ecosystem Toxicity	CTU_e	• Potential for biodiversity loss
Noise Output	Human Noise Exposure	person.Pa/W	• Number of people exposed to a specified sound pressure over a specified period of time

Detailed Explanation of Midpoint Impact Calculations

There are two approaches for assessing midpoint impacts based on the gathered LCI data. The first approach uses the automated Sustainability Analysis tool as described in Appendix A. The second approach assesses impacts manually by using the midpoint scoring factors provided in Appendix I.

In the simplest terms, the calculation of midpoint impacts from the data inventory determined in **STEP 3a** is a matter of multiplying the estimated quantity of each inventory item by the scoring factors presented in Appendix I, while paying careful attention to the units used for the inventory and ensuring they line-up with the units of the scoring factors. Additional guidance on how to use the scoring factors and manually calculate midpoint impacts is provided below in this appendix.

Fossil Fuel Use Impact

The use of fossil fuels affects the DoD mission by potentially reducing access to future energy resources. The term fossil fuel refers to a group of resources that contain hydrocarbons, ranging from volatile materials like methane to more stable liquid petroleum products to non-volatile materials like coal. The goal of this impact category is to ensure that (1) analysts consider the amount of fossil fuels used by each evaluated alternative and (2) renewable sources of energy are used by the system when possible.

Impacts associated with fossil fuel use are expressed in mega joules (MJ) of deprived fossil fuel resources, which is an indicator of the fuel's availability, the presence of competing demand for the fuel, and the availability of alternatives that provide the same functionality (alternate fuels or electricity sources).

The impacts of fossil fuel use are embedded in the supply chain of procured resources (energy, chemicals, materials, water, and land), components, and parts (upstream impacts) and also realized in the direct energy (see definition in Appendix Q) used to operate the system and the indirect energy (see definition in Appendix Q) used to sustain and protect the system (downstream impacts). Appendix I provides scoring factors that directly translate data collected in the inventory to MJ of deprived fossil fuel resources. An explanation for estimating total life cycle impacts for each alternative in this impact category is provided below:

- **Upstream impacts:** To calculate the upstream midpoint impacts of fossil fuel use for alternative x $\left(FFU_{x_{upstream}}\right)$, sum the results of multiplying (1) the alternative's total cost (C_{xi}), in dollars, of all purchased resources, components, or parts in each applicable industry sector (i), as recorded in the LCI, by (2) the upstream scoring factor (USF_i) for fossil fuel use that is designated to that industry sector. Equation 1a summarizes this calculation. The results of this calculation represent the total amount of fossil fuel energy (MJ) deprived as a result of all fossil fuel energy consumption embedded in all system purchases.

  (1a) $$FFU_{x_{upstream}} = \sum_{i=1}^{n} C_{xi} \times USF_i$$

- **Downstream impacts:** To calculate the downstream midpoint impacts of fossil fuel use for alternative x $\left(FFU_{x_{downstream}}\right)$, sum the results of multiplying (1) the total quantity (Q_{ta}) of each energy type (t) and specified activity (a) used by the alternative, as recorded in the LCI, by (2) the downstream scoring factors (DSF_{ta}) assigned to each energy type (t) and specified activity (a). Equation 1b summarizes this calculation. The results of this calculation represent the total amount of fossil fuel energy (MJ) deprived as a result of all fossil fuel energy consumed to produce, operate, sustain, and protect the system.

  (1b) $$FFU_{x_{downstream}} = \sum_{t=1}^{m} \sum_{a=1}^{n} Q_{ta} \times DSF_{ta}$$

- **Total life cycle impacts:** To calculate the total life cycle midpoint impacts of fossil fuel use for alternative x $\left(FFU_{x_{total}}\right)$, sum the results from Equations 1a and 1b (see Equation 1c). The results of

this calculation represent the total amount of fossil fuel energy (MJ) deprived as a result of all fossil fuel energy consumed over the system's life cycle.

(1c) $$FFU_{x_{total}} = FFU_{x_{upstream}} + FFU_{x_{downstream}}$$

Within this metric, alternatives with a lower $FFU_{x_{total}}$ have lower risk of depleting fossil fuel resources, and thus, should be preferred over other alternatives with higher scores.

Mineral and Metal Use Impact

Minerals and metals used in defense systems affect the DoD's mission by potentially reducing future access to those mineral and metal resources. The goal of this impact category is to ensure that analysts consider the amount of minerals and metals used by each evaluated alternative, as identified in accordance with the data requirements in Appendix F, and understand any supply- or cost-related risks associated with the use of those inputs. Impacts associated with the use of a particular mineral and metal resource are expressed in kilograms (kg) of deprived resource, which is an indicator of that resource's availability, the presence of competing demand for the resource, and the availability of replacement alternatives.

The impacts of mineral and metal use are (1) embedded in the supply chain of procured resources (energy, chemicals, materials, water, and land), components, and parts (upstream impacts) and (2) realized in the consumption of minerals and metals used to produce, and sustain the system (downstream impacts). For the purpose of scoring alternatives in this impact category, Appendix I provides scoring factors that directly translate data collected in the data inventory to kilograms (kg) of deprived resource. An explanation for estimating total life cycle impacts for each alternative in this impact category is provided below:

- **Upstream impacts:** To calculate the upstream midpoint impacts of mineral and metal use for alternative x $\left(MMU_{x_{upstream}}\right)$, sum the results of multiplying (1) the alternative's total cost (C_{xi}), in dollars, of all purchased resources, components, or parts in each applicable industry sector (i), as recorded in the LCI, by (2) the upstream mineral or metal use scoring factor (USF_i) for mineral or metal use that is designated to that industry sector. Equation 2a summarizes this calculation. The results of this calculation represent the total amount of minerals and metals (kg) deprived as a result of all mineral and metal consumption embedded in all system purchases.

  (2a) $$MMU_{x_{upstream}} = \sum_{i=1}^{n} C_{xi} \times USF_i$$

- **Downstream impacts:** To calculate the downstream midpoint impacts of mineral and metal use for alternative x $\left(MMU_{x_{downstream}}\right)$, sum the results of multiplying (1) the total quantity (Q_t) of each mineral or metal type (t) used by the alternative, as recorded in the LCI, by (2) the downstream scoring factors (DSF_t) assigned to each mineral or metal type (t). Equation 2b summarizes this calculation. The results of this calculation represent the total amount of minerals and metals (kg) deprived as a result of all mineral and metal resources consumed to produce, operate, and sustain the system.

  (2b) $$MMU_{x_{downstream}} = \sum_{t=1}^{m} Q_t \times DSF_t$$

- **Total life cycle impacts:** To calculate the total life cycle midpoint impacts of mineral and metal use for alternative x $\left(MMU_{x_{total}}\right)$, sum the results from Equations 2a and 2b (see Equation 2c). The results of this calculation represent the total amount of minerals and metals (kg) deprived as a result of all mineral and metal resources consumed over the system's life cycle.

  (2c) $$MMU_{x_{total}} = MMU_{x_{upstream}} + MMU_{x_{downstream}}$$

Within this metric, alternatives with a lower $MMU_{x_{total}}$ have lower risk of depleting mineral and metal resources and thus should be preferred over other alternatives with higher scores.

Global Warming Potential

The combustion of fuels for energy, either directly at the source or indirectly through the use of electricity, leads to air pollutants (greenhouse gases) that cause global warming. Non-combustion emissions such as sulfur hexafluoride (SF_6) can also cause global warming. The goal of this impact category is to ensure that analysts consider these resulting greenhouse gas emissions and their impact on global warming for each evaluated alternative and limit those emissions when possible. The impact associated with each greenhouse gas emission is expressed in units of carbon dioxide equivalents (CO_2eq), which is an indicator of that emission's global warming potential relative to the global warming potential of carbon dioxide.

Greenhouse gas emissions are (1) embedded in the supply chain of procured resources (energy, chemicals, materials, water, and land), components, and parts (upstream impact), (2) realized as a result of the direct energy (see definition in Appendix Q) used to operate the system and the indirect energy (see definition in Appendix Q) used to sustain and protect the system (downstream impacts), and (3) realized when non-combustion greenhouse gases are released by industrial processes occurring during the production, operation, sustainment and disposal of the system. For the purpose of scoring alternatives in this impact category, Appendix I provides scoring factors that directly translate data collected in the data inventory to units of global warming potential (CO_2eq). An explanation for estimating total life cycle impacts for each alternative in this impact category is provided below:

- **Upstream impacts:** To calculate the upstream global warming potential of all greenhouse gases emitted by alternative x $\left(GWP_{x_{upstream}}\right)$, sum the results of multiplying (1) the alternative's total cost (C_{xi}), in dollars, of all purchased resources, components, or parts in each applicable industry sector (i), as recorded in the LCI, by (2) the upstream scoring factor (USF_i) for global warming potential that is designated to that industry sector. Equation 3a summarizes this calculation. The results of this calculation represent the combined potency of all greenhouse gases emitted as a result of all energy consumption embedded in all system purchases.

  (3a) $$GWP_{x_{upstream}} = \sum_{i=1}^{n} C_{xi} \times USF_i$$

- **Downstream impacts (energy):** To calculate the downstream global warming potential resulting from all greenhouse gas emissions from energy consumed by alternative x $\left(GWP_{x_{dawnstream_e}}\right)$, sum the results of multiplying (1) the total quantity (Q_{ta}) of each energy type (t) and specified activity (a) used by the alternative, as recorded in the LCI, by (2) the downstream scoring factors (DSF_{ta}) assigned to each energy type (t) and specified activity (a). Equation 3b summarizes this calculation. The results of this calculation represent the total combined potency of all greenhouse gases emitted as a result of all energy consumed to produce, operate, sustain, and protect the system.

  (3b) $$GWP_{x_{dawnstream_e}} = \sum_{t=1}^{m} \sum_{a=1}^{n} Q_{ta} \times DSF_{ta}$$

- **Downstream impacts (industrial processes)**: As explained in Appendix F, standardized emission profiles for greenhouse gas releases that result from chemical reactions during industrial processes are not available. To calculate the downstream global warming potential resulting from all greenhouse gases emitted from industrial processes during the production and sustainment of alternative x $\left(GWP_{x_{downstream_i}}\right)$, sum the results of multiplying (1) the total quantity (Q_t) of each greenhouse gas (t) emitted by the alternative, as recorded in the LCI, by (2) the downstream scoring factors (DSF_t) assigned to each greenhouse gas (t). Equation 3c summarizes this calculation. The results of this calculation represent the total combined potency of all greenhouse gases emitted as a result of industrial processes that occur during the production, sustainment, and operation of the system.

(3c) $GWP_{x_{downstream_i}} = \sum_{t=1}^{m} Q_t \times DSF_t$

- **Total life cycle impacts:** To calculate the total life cycle global warming potential of all greenhouse gases emitted by alternative x $\left(GWP_{x_{total}}\right)$, sum the results from Equations 3a, 3b, and 3c (see Equation 3d). The results of this calculation represent the combined potency of all greenhouse gases emitted as a result of all energy consumed over the system's life cycle.

  (3d) $GWP_{x_{total}} = GWP_{x_{upstream}} + GWP_{x_{downstream}} + GWP_{x_{downstream_i}}$

Within this metric, alternatives with a lower $GWP_{x_{total}}$ have lower risk of global warming potential and thus should be preferred over other alternatives with higher scores.

Respiratory Effects (Inorganic)

Industrial processes and the combustion of fuels for energy—either directly at the source or indirectly through the use of electricity—emits inorganic criteria air pollutants that can lead to negative human respiratory impacts, such as asthma and allergic reactions. The goal of this impact category is to ensure that analysts consider these resulting emissions and their impact on human health for each evaluated alternative, and limit those emissions when possible. The impact associated with each criteria air pollutant emitted is expressed in units of fine particulate matter equivalents ($PM_{2.5}$eq), which is an indicator of that emission's potential for causing respiratory effects relative to the potential of fine particulate matter to cause those effects.

Emissions of inorganic compounds are (1) embedded in the supply chain of procured resources (energy, chemicals, materials, water, and land), components, and parts (upstream impacts), (2) realized as a result of the direct energy (see definition in Appendix Q) used to operate the system and the indirect energy (see definition in Appendix Q) used to sustain and protect the system (downstream impacts), and (3) realized as a result of industrial processes such as solvent use (downstream impacts). For the purpose of scoring alternatives in this impact category, Appendix I provides scoring factors that directly translate data collected in the data inventory to units of fine particulate matter equivalents ($PM_{2.5}$eq). An explanation for estimating total life cycle impacts for each alternative in this impact category is provided below:

- **Upstream impacts:** To calculate the upstream potential of respiratory effects resulting from all inorganic air pollutants emitted by alternative x $\left(IRE_{x_{upstream}}\right)$, sum the results of multiplying (1) the alternative's total cost (C_{xi}), in dollars, of all purchased resources, components, or parts in each applicable industry sector (i), as recorded in the LCI, by (2) the upstream scoring factor (USF_i) for inorganic respiratory effects that is designated to that industry sector. Equation 4a summarizes this calculation. The results of this calculation represent the combined potency of all inorganic air pollutants emitted as a result of all energy consumption and industrial processes embedded in all system purchases.

  (4a) $IRE_{x_{upstream}} = \sum_{i=1}^{n} C_{xi} \times USF_i$

- **Downstream impacts (energy)**: To calculate the downstream potential of respiratory effects resulting from all inorganic air pollutants emitted from energy consumed by alternative x $\left(IRE_{x_{downstream_e}}\right)$, sum the results of multiplying (1) the total quantity (Q_{ta}) of each energy type $(t)$and specified activity (a) used by the alternative, as recorded in the LCI, by (2) the downstream scoring factors (DSF_{ta}) assigned to each energy type (t) and specified activity (a). Equation 4b summarizes this calculation. The results of this calculation represent the total combined potency of all inorganic air pollutants emitted as a result of all energy consumed to produce, operate, sustain, and protect the system.

  (4b) $IRE_{x_{downstream_e}} = \sum_{t=1}^{m} \sum_{a=1}^{n} Q_{ta} \times DSF_{ta}$

- **Downstream impacts (industrial processes)**: As explained in Appendix F, standardized emission profiles for chemical releases, including all inorganic compounds, that result from chemical reactions during industrial processes are not available. To calculate the downstream potential of respiratory effects resulting from all inorganic air pollutants emitted from industrial processes during the production and sustainment of alternative x $\left(IRE_{x_{downstream_i}}\right)$, sum the results of multiplying (1) the total quantity (Q_t) of each inorganic compound type (t) emitted by the alternative, as recorded in the LCI, by (2) the downstream scoring factors (DSF_t) assigned to each inorganic compound type (t). Equation 4c summarizes this calculation. The results of this calculation represent the total combined potency of all inorganic air pollutants emitted as a result of industrial processes that occur during the production and sustainment of the system.

  (4c) $$IRE_{x_{downstream_i}} = \sum_{t=1}^{m} Q_t \times DSF_t$$

- **Total life cycle impacts:** To calculate the total life cycle potential of respiratory effects resulting from all inorganic air pollutants emitted by alternative x $\left(IRE_{x_{total}}\right)$, sum the results from Equations 4a, 4b, and 4c (see Equation 4d). The results of this calculation represent the combined potency of all inorganic air pollutants emitted as a result of all energy consumption and chemical transformations over the system's life cycle.

  (4d) $$IRE_{x_{total}} = IRE_{x_{upstream}} + IRE_{x_{downstream_e}} + IRE_{x_{downstream_i}}$$

Within this metric, alternatives with a lower $IRE_{x_{total}}$ have lower risk of respiratory effects from inorganic air emissions and thus should be preferred over other alternatives with higher scores.

Respiratory Effects (Organic)

Industrial processes and the combustion of fuels for energy—either directly at the source or indirectly through the use of electricity—emits hydrocarbon compounds that can lead to negative human respiratory impacts, such as asthma and allergic reactions. The goal of this impact category is to ensure that analysts consider these emissions and their impact on human health for each evaluated alternative, and limit those emissions when possible. The impact associated with each VOC emitted is expressed in units of unspecified non-methane volatile organic compound equivalents (NMVOCeq), which is an indicator of that emission's potential for causing respiratory effects relative to the potential of an unspecified non-methane volatile organic compound to cause those effects.

Emissions of organic compounds are (1) embedded in the supply chain of procured resources (energy, chemicals, materials, water, and land), components, and parts (upstream impacts), (2) realized as a result of the direct energy (see definition in Appendix Q) used to operate the system and the indirect energy (see definition in Appendix Q) used to sustain and protect the system (downstream impacts), and (3) realized as a result of industrial processes such as solvent use or painting (downstream impacts). For the purpose of scoring alternatives in this impact category, Appendix I provides scoring factors that directly translate data collected in the data inventory to units of NMVOCeq. An explanation for estimating total life cycle impacts for each alternative in this impact category is provided below:

- **Upstream impacts:** To calculate the upstream potential of respiratory effects resulting from all organic air pollutants emitted by alternative x $\left(ORE_{x_{upstream}}\right)$, sum the results of multiplying (1) the alternative's total cost (C_{xi}), in dollars, of all purchased resources, components, or parts in each applicable industry sector (i), as recorded in the LCI, by (2) the upstream scoring factor (USF_i) for organic respiratory effects that is designated to that industry sector. Equation 5a summarizes this calculation. The results of this calculation represent the combined potency of all organic air

pollutants emitted as a result of all energy consumption and industrial processes embedded in all system purchases.

(5a) $$ORE_{x_{upstream}} = \sum_{i=1}^{n} C_{xi} \times USF_i$$

- **Downstream impacts (energy):** To calculate the downstream potential of respiratory effects resulting from all organic air pollutants emitted from energy consumed by alternative x $\left(ORE_{x_{dawnstream_e}}\right)$, sum the results of multiplying (1) the total quantity (Q_{ta}) of each energy type (t) and specified activity (a) used by the alternative, as recorded in the LCI, by (2) the downstream scoring factors (DSF_{ta}) assigned to each energy type (t) and specified activity (a). Equation 5b summarizes this calculation. The results of this calculation represent the total combined potency of all organic air pollutants emitted as a result of all energy consumed to produce, operate, sustain, and protect the system.

  (5b) $$ORE_{x_{downstream_e}} = \sum_{t=1}^{m} \sum_{a=1}^{n} Q_{ta} \times DSF_{ta}$$

- **Downstream impacts (industrial processes):** As explained in Appendix F, standardized emission profiles for chemical releases, including all organic compounds, that result from chemical reactions during industrial processes are not available. To calculate the downstream potential of respiratory effects resulting from all organic air pollutants emitted from industrial processes during the production and sustainment of alternative x $\left(ORE_{x_{downstream_i}}\right)$, sum the results of multiplying (1) the total quantity (Q_t) of each organic compound type (t) emitted by the alternative, as recorded in the LCI, by (2) the downstream scoring factors (DSF_t) assigned to each organic compound type (t). Equation 5c summarizes this calculation. The results of this calculation represent the total combined potency of all organic air pollutants emitted as a result of industrial processes that occur during the production and sustainment of the system.

  (5c) $$ORE_{x_{downstream_i}} = \sum_{t=1}^{m} Q_t \times DSF_t$$

- **Total life cycle impacts:** To calculate the total life cycle potential of respiratory effects resulting from all organic air pollutants emitted by alternative x $\left(ORE_{x_{total}}\right)$, sum the results from Equations 5a, 5b, and 5c (see Equation 5d). The results of this calculation represent the combined potency of all organic air pollutants emitted as a result of all energy consumed and chemical transformations over the system's life cycle.

  (5d) $$ORE_{x_{total}} = ORE_{x_{upstream}} + ORE_{x_{downstream_e}} + ORE_{x_{downstream_i}}$$

Within this metric, alternatives with a lower $ORE_{x_{total}}$ have lower risk of respiratory effects from organic air emissions and thus should be preferred over other alternatives with higher scores.

Water Use Impact

The use of water affects the DoD's mission because water availability is scarce and diminishing in certain areas, or lack of water infrastructure makes the supply and transport of water difficult in areas where local water resources are unavailable. The goal of this impact category is to ensure that analysts consider (1) how much water is used by the system across all activities throughout its life cycle and (2) the location-specific availability of the required quality of water needed by the system. Impacts associated with the use of a water resource are expressed in meters cubed (m^3) of deprived water, which is an indicator of the water source's availability, the presence of competing demand for the water from that source, and the availability of other sources of water at the required quality.

The impacts of water use are (1) embedded in the supply chain of procured resources (energy, chemicals, materials, water, and land), components, and parts (upstream impacts) and (2) realized in the

direct water (see definition in Appendix Q) used to operate the system and the indirect water (see definition in Appendix Q) used to sustain and protect the system (downstream impacts). For the purpose of scoring alternatives in this impact category, Appendix I provides scoring factors that directly translate data collected in the data inventory to meters cubed (m^3) of deprived water resources. An explanation for estimating total life cycle impacts for each alternative in this impact category is provided below:

- **Upstream impacts:** To calculate the upstream midpoint impacts of water use for alternative x $\left(WU_{x_{upstream}}\right)$, sum the results of multiplying (1) the alternative's total cost (C_{xi}), in dollars, of all purchased resources, components, or parts in each applicable industry sector (i), as recorded in the LCI, by (2) the upstream scoring factor (USF_i) for water use that is designated to that industry sector. Equation 6a summarizes this calculation. The results of this calculation represent the total amount of water resources (m^3) deprived as a result of all water consumption embedded in all system purchases.

  (6a) $$WU_{x_{upstream}} = \sum_{i=1}^{n} C_{xi} \times USF_i$$

- **Downstream impacts**: To calculate the downstream midpoint impacts of water use for alternative x $\left(WU_{x_{downstream}}\right)$, sum the results of multiplying (1) the total quantity $\left(Q_{slq}\right)$ of water used from each specified source (s) (river, lake, ground water, unspecified), location of use (l), and quality (q), as recorded in the LCI, by (2) the downstream scoring factors (DSF_{slq}) assigned to the specified water quality (q), location of use (l), and source (s). Equation 6b summarizes this calculation. The results of this calculation represent the total amount of water resources (m^3) deprived as a result of all water consumed to produce, operate, sustain, and protect the system.

  (6b) $$WU_{x_{downstream}} = \sum_{s=1}^{m} \sum_{l=1}^{n} \sum_{q=1}^{o} Q_{slq} \times DSF_{slq}$$

- **Total life cycle impacts**: To calculate the total life cycle midpoint impacts of water use for alternative x $\left(WU_{x_{total}}\right)$, sum the results from Equations 6a and 6b (see Equation 6c). The results of this calculation represent the total amount of water resources (m^3) deprived as a result of all water consumed over the system's life cycle.

  (6c) $$WU_{x_{total}} = WU_{x_{upstream}} + WU_{x_{downstream}}$$

Within this metric, alternatives with a lower $WU_{x_{total}}$ have lower risk of depleting water resources and thus should be preferred over other alternatives with higher scores.

Land Use Degradation Potential

Land occupation by the DoD usually results in the degradation of existing ecosystems, which can result in the loss of biodiversity supported by the land in its pre-occupied state. The goal of this impact category is to ensure that analysts consider the potential for land degradation resulting from the incremental land occupation of the alternative being evaluated and give preference to alternatives that minimize ecosystem degradation. Impacts associated with incremental land use are measured as the area of arable land equivalents per year (ha.yr arable eq) that would be lost when occupying the land to produce, support, protect, and dispose of the system. The indexed unit of ha.yr arable eq is an indicator of a plot of land's level of biodiversity relative to the typical amount of biodiversity of arable land.

The impacts of land use are (1) embedded in the supply chain of procured resources (energy, chemicals, materials, water, and land), components, and parts (upstream impacts) and (2) realized in the incremental land occupied to operate, sustain, and protect the system (downstream impacts). For the purpose of scoring alternatives in this impact category, Appendix I provides scoring factors that directly translate data collected in the data inventory to ha.yr arable eq lost due to incremental land occupation by the system.

An explanation for estimating total life cycle impacts for each alternative in this impact category is provided below:

- **Upstream impacts:** To calculate the upstream land degradation potential from the incremental land occupation of alternative x $\left(LDP_{x_{upstream}}\right)$, sum the results of multiplying (1) the alternative's total cost (C_{xi}), in dollars, of all purchased resources, components, or parts in each applicable industry sector (i), as recorded in the LCI, by (2) the upstream land occupation scoring factor (USF_i) for water use that is designated to that industry sector. Equation 7a summarizes this calculation. The results of this calculation represent the land degradation potential (total hectare years of arable land equivalents lost) as a result of all land occupation embedded in all system purchases.

  (7a) $$LDP_{x_{upstream}} = \sum_{i=1}^{n} C_{xi} \times USF_i$$

- **Downstream impacts:** To calculate the downstream land degradation potential from the incremental land occupation of alternative x $\left(LDP_{x_{downstream}}\right)$, first sum the results of multiplying (1) the total area (A_d) of each land use designation (d) that will be incrementally occupied by the system by (2) the total amount of time (T_d) that land use designation will be occupied by the system and by (3) the downstream scoring factors (DSF_d) assigned to the specified land use designation. Equation 7b summarizes this calculation. The results of this calculation represent the land degradation potential (total hectare years of arable land equivalents lost) due to incremental land occupation to produce, operate, sustain, and protect the system.

  (7b) $$LDP_{x_{downstream}} = \sum_{d=1}^{n} A_d \times T_d \times DSF_d$$

- **Total life cycle impacts:** To calculate the total life cycle land degradation potential from the incremental land occupation of alternative x $\left(LDP_{x_{total}}\right)$, sum the results from Equations 7a and 7b (see Equation 7c). The results of this calculation represent the total land degradation potential (total hectare years of arable land equivalents lost) as a result of all land occupied over the system's life cycle.

  (7c) $$LDP_{x_{total}} = LDP_{x_{upstream}} + LDP_{x_{downstream}}$$

Within this metric, alternatives with a lower $LDP_{x_{total}}$ have lower risk of degrading land and thus should be preferred over other alternatives with higher scores.

Cancer (External)

Hazardous chemical emissions to air, soil, and water present human toxicity concerns. The goal of this impact category is to ensure that analysts identify the emissions of hazardous chemicals that could significantly increase the probability of causing cancer illnesses given elevated levels of exposure, and consider system designs that eliminate the use of these chemicals. The impact associated with each toxic chemical emitted is expressed in comparable toxicity units (CTU_h) for humans, which is an indicator of the fraction of cancer cases, external to the DoD, that are expected to result per kilogram (kg) of toxic emission.

Emissions of toxic compounds are (1) embedded in the supply chain of procured resources (energy, chemicals, materials, water, and land), components, and parts (upstream impacts), (2) realized as a result of the direct energy (see definition in Appendix Q) used to operate the system and the indirect energy (see definition in Appendix Q) used to sustain and protect the system (downstream impacts), and (3) realized as a result of industrial processes such as plastics molding, painting, and metal working (downstream impacts). For the purpose of scoring alternatives in this impact category, Appendix I provides scoring factors that directly translate data collected in the data inventory to CTU_h for humans. An explanation for estimating total life cycle impacts for each alternative in this impact category is provided below:

- **Upstream impacts:** To calculate the upstream potential of external cancer illnesses resulting from all chemical pollutants released by alternative x $\left(EC_{x_{upstream}}\right)$, sum the results of multiplying (1) the alternative's total cost (C_{xi}), in dollars, of all purchased resources, components, or parts in each applicable industry sector (i), as recorded in the LCI, by (2) the upstream scoring factor (USF_i) for cancer potential that is designated to that industry sector. The scoring factors used in this calculation characterize impacts to human health by accounting for (1) the transport of these emissions through environmental media to the exposed population via exposure routes (inhalation and ingestion) and (2) the change in disease probability due to the intake of a particular chemical or material of a population over a system's lifetime. Equation 8a summarizes this calculation. The results of this calculation represent the combined potency of all chemical pollutants released as a result of all energy consumption and industrial processes embedded in all system purchases to cause external cancer illnesses.

  (8a) $$EC_{x_{upstream}} = \sum_{i=1}^{n} C_{xi} \times USF_i$$

- **Downstream impacts (energy):** To calculate the downstream potential of external cancer illnesses resulting from all chemical pollutants released as a result of energy consumed by alternative x $\left(EC_{x_{downstream_e}}\right)$, sum the results of multiplying (1) the total quantity (Q_{ta}) of each energy type (t) and specified activity (a) used by the alternative, as recorded in the LCI, by (2) the downstream scoring factors (DSF_{ta}) assigned to each energy type (t) and specified activity (a). The scoring factors used in this calculation characterize impacts to human health by accounting for (1) the transport of these emissions through environmental media to the exposed population via exposure routes (inhalation and ingestion) and (2) the change in disease probability due to the intake of a particular chemical or material of a population over a system's lifetime. Equation 8b summarizes this calculation. The results of this calculation represent the total combined potency of all chemical pollutants released as a result of all energy consumed to produce, operate, sustain, and protect the system to cause external cancer illnesses.

  (8b) $$EC_{x_{downstream_e}} = \sum_{t=1}^{m} \sum_{a=1}^{n} Q_{ta} \times DSF_{ta}$$

- **Downstream impacts (industrial processes):** As explained in Appendix F, standardized emission profiles for chemical releases, including all toxic compounds, that result from chemical reactions during industrial processes are not available. To calculate the downstream potential of external cancer illnesses resulting from all chemical pollutants released from industrial processes during the production and sustainment of alternative x $\left(EC_{x_{downstream_i}}\right)$, sum the results of multiplying (1) the total quantity (Q_t) of each toxic chemical compound type (t) emitted by the alternative, as recorded in the LCI, by (2) the downstream scoring factors (DSF_t) assigned to each toxic compound type (t). The scoring factors used in this calculation characterize impacts to human health by accounting for (1) the transport of these emissions through environmental media to the exposed population via exposure routes (inhalation and ingestion) and (2) the change in disease probability due to the intake of a particular chemical or material of a population over a system's lifetime. Equation 8c summarizes this calculation. The results of this calculation represent the total combined potency of all chemical pollutants released as a result of industrial processes that occur during the production and sustainment of the system to cause external cancer illnesses.

  (8c) $$EC_{x_{downstream_i}} = \sum_{t=1}^{m} Q_t \times DSF_t$$

- **Total life cycle impacts:** To calculate the total life cycle potential of external cancer illnesses resulting from all chemical pollutants released by alternative x $\left(EC_{x_{total}}\right)$, sum the results from Equations 8a, 8b, and 8c (see Equation 8d). The results of this calculation represent the combined potency of all

chemical pollutants released as a result of all energy consumed and chemical transformations over the system's life cycle to cause external cancer illnesses.

(8d) $$EC_{x_{total}} = EC_{x_{upstream}} + EC_{x_{downstream_e}} + EC_{x_{downstream_i}}$$

Within this metric, alternatives with a lower $EC_{x_{total}}$ have lower risk of causing cancer illnesses and thus should be preferred over other alternatives with higher scores.

Non-Cancer (External)

Hazardous chemical emissions to air, soil, and water present human toxicity concerns. The goal of this impact category is to ensure that analysts identify the emissions of hazardous chemicals that could significantly increase the probability of causing non-cancer illnesses given elevated levels of exposure, and consider system designs that eliminate the use of these chemicals. The impact associated with each toxic chemical emitted is expressed in CTU_h for humans, which is an indicator of the fraction of non-cancer cases that are expected to result per kilogram (kg) of toxic emission.

Emissions of toxic compounds are (1) embedded in the supply chain of procured resources (energy, chemicals, materials, water, and land), components, and parts (upstream impacts), (2) realized as a result of the direct energy (see definition in Appendix Q) used to operate the system and the indirect energy (see definition in Appendix Q) used to sustain and protect the system (downstream impacts), and (3) realized as a result of industrial processes such as solvent use, plastics molding, and metal working (downstream impacts). For the purpose of scoring alternatives in this impact category, Appendix I provides scoring factors that directly translate data collected in the data inventory to CTU_h for humans. An explanation for estimating total life cycle impacts for each alternative in this impact category is provided below:

- **Upstream impacts:** To calculate the upstream potential of external non-cancer illnesses resulting from all chemical pollutants released by alternative x $\left(ENC_{x_{upstream}}\right)$, sum the results of multiplying (1) the alternative's total cost (C_{xi}), in dollars, of all purchased resources, components, or parts in each applicable industry sector (i), as recorded in the LCI, by (2) the change in disease probability due to the intake of a particular chemical or material of a population over a system's lifetime. The scoring factors used in this calculation characterize impacts to human health by accounting for (1) the transport of these emissions through environmental media to the exposed population via exposure routes (inhalation and ingestion) and (2) the change in disease probability due to the intake of a particular chemical or material of a population over a system's lifetime. Equation 9a summarizes this calculation. The results of this calculation represent the combined potency of all chemical pollutants released as a result of all energy consumption and industrial processes embedded in all system purchases to cause external non-cancer illnesses.

  (9a) $$ENC_{x_{upstream}} = \sum_{i=1}^{n} C_{xi} \times USF_i$$

- **Downstream impacts (energy)**: To calculate the downstream potential of external non-cancer illnesses resulting from all chemical pollutants released as a result of energy consumed by alternative x $\left(ENC_{x_{downstream_e}}\right)$, sum the results of multiplying (1) the total quantity (Q_{ta}) of each energy type (t) and specified activity (a) used by the alternative, as recorded in the LCI, by (2) the downstream scoring factors (DSF_{ta}) assigned to each energy type (t) and specified activity (a). The scoring factors used in this calculation characterize impacts to human health by accounting for (1) the transport of these emissions through environmental media to the exposed population via exposure routes (inhalation and ingestion) and (2) the change in disease probability due to the intake of a particular chemical or material of a population over a system's lifetime. Equation 9b summarizes this calculation. The results of this calculation represent the total combined potency of

all energy consumed to produce, operate, sustain, and protect the system to cause external non-cancer illnesses of all chemical pollutants released as a result.

(9b) $$ENC_{x_{downstream_e}} = \sum_{t=1}^{m} \sum_{a=1}^{n} Q_{ta} \times DSF_{ta}$$

- **Downstream impacts (industrial processes):** As explained in Appendix F, standardized emission profiles for chemical releases, including all toxic compounds, that result from chemical reactions during industrial processes are not available. To calculate the downstream potential of external non-cancer illnesses resulting from all chemical pollutants released from industrial processes during the production and sustainment of alternative x $\left(ENC_{x_{downstream_i}}\right)$, sum the results of multiplying (1) the total quantity (Q_t) of each toxic chemical compound type (t) emitted by the alternative, as recorded in the LCI, by (2) the downstream scoring factors (DSF_t) assigned to each toxic compound type (t). The scoring factors used in this calculation characterize impacts to human health by accounting for (1) the transport of these emissions through environmental media to the exposed population via exposure routes (inhalation and ingestion) and (2) the change in disease probability due to the intake of a particular chemical or material of a population over a system's lifetime. Equation 9c summarizes this calculation. The results of this calculation represent the total combined potency of all chemical pollutants released as a result of industrial processes that occur during the production and sustainment of the system to cause external cancer illnesses.

  (9c) $$ENC_{x_{downstream_i}} = \sum_{t=1}^{m} Q_t \times DSF_t$$

- **Total life cycle impacts:** To calculate the total life cycle potential of external non-cancer illnesses resulting from all chemical pollutants released by alternative x $\left(ENC_{x_{total}}\right)$, sum the results from Equations 9a, 9b, and 9c (see Equation 9d). The results of this calculation represent the combined potency of all chemical pollutants released as a result of all energy consumed and chemical transformations over the system's life cycle to cause external non-cancer illnesses.

  (9d) $$ENC_{x_{total}} = ENC_{x_{upstream}} + ENC_{x_{downstream_e}} + ENC_{x_{downstream_i}}$$

Within this metric, alternatives with a lower $ENC_{x_{total}}$ have lower risk of causing non-cancer illnesses and thus should be preferred over other alternatives with higher scores.

Ecological Toxicity

Hazardous chemical emissions to ecosystems present toxicity concerns for wildlife residing in those ecosystems. The goal of this impact category is to ensure that analysts identify the use of hazardous chemicals that could significantly increase the probability of ecological toxicity given elevated levels of exposure, and consider system designs that eliminate the use of these chemicals. The impact associated with each toxic chemical emitted is expressed in CTU_e for ecosystems, which is an indicator of percentage of species that would be lost per kilogram (kg) of toxic emission into a specified environmental medium (air, water and soil).

Emissions of toxic compounds are (1) embedded in the supply chain of procured resources (energy, chemicals, materials, water, and land), components, and parts (upstream impacts), (2) realized as a result of the direct energy (see definition in Appendix Q) used to operate the system and the indirect energy (see definition in Appendix Q) used to sustain and protect the system (downstream impacts), and (3) realized as a result of industrial processes such as solvent use, plastics molding, and metal working (downstream impacts). For the purpose of scoring alternatives in this impact category, Appendix I provides scoring factors that directly translate data collected in the data inventory to CTU_e for ecosystems. An explanation for estimating total life cycle impacts for each alternative in this impact category is provided below:

- **Upstream impacts:** To calculate the upstream potential of ecological toxicity resulting from all chemical pollutants released by alternative x $\left(ET_{x_{upstream}}\right)$, sum the results of multiplying (1) the alternative's total cost (C_{xi}), in dollars, of all purchased resources, components, or parts in each applicable industry sector (i), as recorded in the LCI, by (2) the upstream scoring factor (USF_i) for ecological toxicity that is designated to that industry sector. These scoring factors are used to represent the collective steps along the cause-effect chain starting with the emission of C&M into an environmental compartment (air, soil, and water), followed by the fate and transport through the environment, exposure to wildlife, and the resulting effects on the exposed populations. Equation 10a summarizes this calculation. The results of this calculation represent the combined potency of all chemical pollutants released as a result of all energy consumption and industrial processes embedded in all system purchases to cause loss of species.

  (10a) $$ET_{x_{upstream}} = \sum_{i=1}^{n} C_{xi} \times USF_i$$

- **Downstream impacts (energy):** To calculate the downstream potential of ecological toxicity resulting from all chemical pollutants released as a result of energy consumed by alternative x $\left(ENC_{x_{downstream_e}}\right)$, sum the results of multiplying (1) the total quantity (Q_{ta}) of each energy type (t) and specified activity (a) used by the alternative, as recorded in the LCI, by (2) the downstream scoring factors (DSF_{ta}) assigned to each energy type (t) and specified activity (a). These scoring factors are used to represent the collective steps along the cause-effect chain starting with the emission of C&M into an environmental compartment (air, soil, and water), followed by the fate and transport through the environment, exposure to wildlife, and the resulting effects on the exposed populations. Equation 10b summarizes this calculation. The results of this calculation represent the total combined potency of all chemical pollutants released as a result of all energy consumed to produce, operate, sustain, and protect the system to cause loss of species.

  (10b) $$ET_{x_{downstream_e}} = \sum_{t=1}^{m} \sum_{a=1}^{n} Q_{ta} \times DSF_{ta}$$

- **Downstream impacts (industrial processes):** As explained in Appendix F, standardized emission profiles for chemical releases, including all toxic compounds, that result from chemical reactions during industrial processes are not available. To calculate the downstream potential of ecological toxicity resulting from all chemical pollutants released from industrial processes during the production and sustainment of alternative x $\left(ET_{x_{downstream_i}}\right)$, sum the results of multiplying (1) the total quantity (Q_t) of each toxic chemical compound type (t) emitted by the alternative, as recorded in the LCI, by (2) the downstream scoring factors (DSF_t) assigned to each toxic compound type (t). These scoring factors are used to represent the collective steps along the cause-effect chain starting with the emission of C&M into an environmental compartment (air, soil, and water), followed by the fate and transport through the environment, exposure to wildlife, and the resulting effects on the exposed populations. Equation 10c summarizes this calculation. The results of this calculation represent the total combined potency of all chemical pollutants released as a result of industrial processes that occur during the production and sustainment of the system to cause loss of species.

  (10c) $$ET_{x_{downstream_i}} = \sum_{t=1}^{m} Q_t \times DSF_t$$

- **Total life cycle impacts:** To calculate the total life cycle potential of ecological toxicity resulting from all chemical pollutants released by alternative x $\left(ET_{x_{total}}\right)$, analysts should sum the results from Equations 10a, 10b, and 10c (see Equation 10d). The results of this calculation represent the combined potency of all chemical pollutants released as a result of all energy consumed and chemical transformations over the system's life cycle to cause loss of species.

(10d) $$ET_{x_{total}} = ET_{x_{upstream}} + ET_{x_{downstream_e}} + ET_{x_{downstream_i}}$$

Within this metric, alternatives with a lower $ET_{x_{total}}$ have lower risk of causing ecological toxicity and thus should be preferred over other alternatives with higher scores.

Human Noise Exposure

Systems that emit high levels of noise for sustained periods of time can adversely impact human health. The goal of this impact category is to ensure that analysts identify all sources of excessive noise output—both in terms of level and duration—that could significantly increase the probability of hearing loss and other negative impacts to human health. Unlike other midpoint impacts that result from the consumption of resources, noise output is a byproduct of activities that occur during the system's life cycle. The midpoint impact of noise output is the number of people exposed to a specified sound pressure, in Pascal (Pa), over a specified period of time (person*Pa/s).

Harmful noise exposure associated with a particular system is an impact that can be realized during the production, operation, sustainment, and disposal of that system (downstream impacts). For the purpose of scoring alternatives in this impact category, the potential impacts from noise are determined by considering the sound power for which that group is exposed (W_{ftp}); taking into consideration frequency of the sound (f), the time of exposure (t), and the place of exposure (p). Sound power (W_{ftp})can be estimated from sound pressure level (dB) when sound pressure is measured using a sound pressure meter (see Appendix F). As summarized in Equation 11, the system's aggregated sound power output (W_{ftp}) should be multiplied by the duration of the sound over the system's life cycle (D_{ftp}) and the downstream scoring factor (DSF_{ftp}) assigned to the specified combination of frequency, time of exposure, and place of exposure. The results of this calculation represent the total estimated number of people exposed to a specified sound pressure, in Pascal (Pa), over a specified period of time (person*Pa/s).

(11) $$N_x = \sum_{f=1}^{x} \sum_{t=1}^{y} \sum_{p=1}^{z} W_{ftp} \times D_{ftp} \times DSF_{ftp}$$

Within this metric, alternatives with a lower N_x have lower risk of causing hearing loss and other impacts to human health and thus should be preferred over other alternatives with higher scores.

Other Midpoint Impact Considerations

Some midpoint impacts that are important for determining the overall sustainability of a system can only be assessed qualitatively. This section provides analysts with two midpoint impacts that should be evaluated qualitatively (summarized below). Analysts may also choose to include additional impacts for qualitative consideration when applicable.

Energy Source Reliability

Reliable sources of energy are critical for meeting the DoD's mission. The goal of this impact category is to ensure that analysts assess the overall reliability of the sources of energy that will be used throughout the life cycle of the systems evaluated and give preference to alternatives that use energy from more reliable sources. Analysts should flag any energy sources that pose some reliability-related risk, both in the production and distribution of energy. The number of energy sources marked as posing a reliability-related risk should be compared among all alternatives.

An energy source is considered reliable if that source presents a relatively low source, economic, and resource risk. Each type of risk is summarized below:

- **Source risk:** Occurs when the source of energy is extracted outside of a U.S.-controlled territory or within a politically unfriendly or unstable sovereignty.

- **Economic risk:** Occurs when the source of energy is potentially cost prohibitive or possesses a risk of substantial cost increase.
- **Resource risk:** Occurs when the source of energy is subject to supply interruptions caused by lack of resource availability or instability in distribution infrastructure.

To assess the total reliability risk across those three criteria, analysts should make note of or flag any sources of energy that pose any of the above mentioned risks. Evaluate the magnitude of risk for each flagged source of energy.

Chemical Availability

Many defense systems use chemicals that present risk in terms of availability for future supply needs. The goal of this impact category is to ensure that evaluators consider variables affecting availability across the system's life cycle and give preference to alternatives that use reliable chemicals. The variables affecting availability include supply chain, criticality to the system, and human health or environmental toxicity; they are summarized below:

- **Supply chain risk**: The risk to the system due to global economic drivers, global competitiveness in manufacturing, and geopolitical relationships or geographic location. Supply chain risk may be due to economic or non-economic disruptions. The reliance on a single supplier of a chemical poses risk to the system's usability because the single supplier can supper production, transportation, or production issues or the single supplier may elect to remove itself from the marketplace due to costs unrelated to DoD production requirements.
- **Criticality risk**: The risk to the system due to scarce or limited natural abundance of chemicals determined to be critical to the system and the availability and suitability of substitutes for chemicals.
- **Health effects and exposure**: The risk to the system due to newly-identified routes of human or environmental exposure, newly-identified populations of concern who may be exposed, and newly-recognized or better understanding of human or environmental health effects associated with a chemical's hazards.

To assess total availability, take note of those chemicals used by the system that may be affected by the risks listed above. Predicting when these variables may apply to the chemicals and materials relevant to the system is challenging. Drivers influencing these variables mature over varying time spans and may or may not overlap with the system's life cycle. Risk management should be implemented by program evaluation officers or program managers to accept, transfer, or mitigate these risks. A solution that may address these risks is the implementation of legislative and administrative such as regulatory and policy directives that aim to prevent impacts from these risks.

Appendix H: Endpoint Impact Categories and Calculations

Overview of Endpoint Impacts

Endpoint impact categories estimate damage caused to resource availability, human health, and the environment as a result of midpoint impacts. Endpoint impacts have real costs that can be quantified and tied to system-level activities. Endpoint impacts can also affect DoD's mission. For example, depleting fossil fuel resources today affects future missions because current consumption of nonrenewable resources reduces the availability of those resources in the future.

Using endpoint scoring factors requires additional modeling assumptions (e.g., fate and transport of emissions and probabilities of exposure), which increases uncertainty in the results. However, since LCC can be more easily assigned to endpoint impacts, these impacts are easily understood by decision makers. Endpoint impact characterization can also be a powerful LCC tool for estimating often hidden mission (resource availability), human health, and the environmental costs. A summary of all endpoint impact categories considered in a Sustainability Analysis is provided in Table H1.

Table H1. Endpoint impact categories used in Sustainability Analysis

Endpoint Impact Category	Unit of Measure	Metric Indicates
Resource Availability	MJ depleted	• Damage to the future availability of resources (e.g., water, minerals, energy) caused by current consumption
Human Health	Disability Adjusted Life Years (DALYs)	• Probability of human disease and disease severity (mortality and morbidity) resulting from human exposure to pollution
Environmental Heath	Potentially Disappeared Fraction (PDF) of species per square meter per year	• Biodiversity loss resulting from environmental exposure to pollution

Detailed Explanation of Endpoint Impact Calculations

Similar to midpoint impact characterization (see Appendix G), there are two approaches for assessing endpoint impacts based on the midpoint impact results. The first approach uses the automated Sustainability Analysis tool as described in Appendix A. The second approach assesses impacts manually by using the endpoint scoring factors provided in Appendix I.

In the simplest terms, the calculation of endpoint impacts from the aggregated midpoint impact results determined in **STEP 3b** is a matter of multiplying the estimated quantity of each inventory item by the scoring factors presented in Appendix I, while paying careful attention to the units used for the inventory and ensuring they line-up with the units of the scoring factors. Additional guidance on how to use the scoring factors and manually calculate endpoint impacts is provided in this appendix.

Impacts to Resource Availability (Mission)

As explained in the Sustainability Analysis overview, multiple midpoint impacts can result in negative impacts to the overall sustainability of the mission, which is measured in terms of the availability of resources needed to complete the mission. For example, current consumption of high-demand, low-availability resources (petroleum products, rare earth metals, water in water-scarce areas, etc.) can significantly deplete available resource stocks, thereby limiting access to and increasing the cost of these resources for future operations.

Endpoint impacts to resource availability are measured in MJ depleted, which is a commonly used endpoint metric for summarizing overall resource availability, competing demand, and availability of resource substitutes across all types of resource use. Similar to midpoint impact characterization process

documented in Appendix G, Appendix I provides endpoint scoring factors (ESF_c) for translating each of alternative x's inputs (energy, C&M, water, land) and outputs (chemical emissions and noise) (c) into overall damage to resource availability (DRA_x). To calculate alternative x's contribution to damage to resource availability (DRA_x), in terms of MJ depleted, multiply the quantity of each identified input and output identified in Appendix G (Q_{cx}) by the appropriate endpoint scoring factors for those inputs and outputs. Equation 1 summarizes this calculation below.

$$(1)\ \ DRA_x = \sum_{c=1}^{n} Q_{cx} \times ESF_c$$

Within this metric, alternatives with a lower DRA_x contribute less to damage to resources, and thus, should be preferred over other alternatives with higher scores.

Impacts to Human Health

As explained in the Sustainability Analysis overview, multiple midpoint impacts can degrade human health, both internally for DoD personnel and externally for surrounding communities. Endpoint impacts to human health are measured in Disability Adjusted Life Years (DALY) (see definition in Appendix G), which is a commonly used endpoint metric that accounts for the statistical probability of mortality and morbidity for an individual.

Similar to midpoint impact characterization process documented in Appendix G, Appendix I provides endpoint scoring factors (ESF_c) for translating each of alternative x's inputs (energy, C&M, water, land) and outputs (chemical emissions and noise) (c) into overall damage to human health (DHH_x). To calculate alternative x's contribution to damage to human health (DHH_x), in terms of DALYs, multiply the quantity of each identified input and output identified in Appendix G (Q_{cx}) by the appropriate endpoint scoring factors for those inputs and outputs. Equation 2 summarizes this calculation below.

$$(2)\ \ DHH_x = \sum_{c=1}^{n} Q_{cx} \times ESF_c$$

Within this metric, alternatives with a lower DHH_x contribute less to human health degradation and thus should be preferred over other alternatives with higher scores.

Impacts to Environmental Health

As explained in the Sustainability Analysis overview, multiple midpoint impacts can degrade environmental health. Environmental health is measured in Potentially Disappeared Fraction (PDF) (see definition in Appendix Q) of the diversity of species per area (m^2) per unit of time (year). This commonly used endpoint metric quantifies the potential loss of species, in terms of percentage of total population, over a specified quantity of area and time.

Similar to midpoint impact characterization process documented in Appendix G, Appendix I provides endpoint scoring factors (ESF_c) for translating each of alternative x's inputs (energy, C&M, water, land) and outputs (chemical emissions and noise) (c) into overall damage to environmental health (DEH_x). To calculate alternative x's contribution to damage to environmental health (DEH_x), in terms of PDF/m^2/yr, multiply the quantity of each identified input and output identified in Appendix G (Q_{cx}) by the appropriate endpoint scoring factors for those inputs and outputs. Equation 3 summarizes this calculation below.

$$(3)\ \ DEH_x = \sum_{c=1}^{n} Q_{cx} \times ESF_c$$

Within this metric, alternatives with a lower DEH_x contribute less to species loss, and thus, should be preferred over other alternatives with higher scores.

Appendix I: Upstream and Downstream Scoring Factors and Cost Factors

Table I1. Interim midpoint and Endpoint scoring factors and external cost factors

All scoring factor data can be found at: http://www.denix.osd.mil/esohacq/

Table I2. Economic Input-Output LCA data used for upstream scoring factors

Database	References
Open IO	• Cox, R.W., 2011. Open IO: Developing a transparent, fully accessible economic input-output life cycle assessment database. The Sustainability Consortium. http://www.sustainabilityconsortium.org/wp-content/themes/sustainability/assets/pdf/OpenIO_ModelDocumentation_June2011.pdf • Database downloaded at: http://www.sustainabilityconsortium.org/open-io/resources/

Table I3. Emission factors used for downstream scoring factors

Emission Type	References
Greenhouse Gases	• Argonne National Laboratory. "Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model." GREET1_2012. U.S. Department of Energy, 2012. 8 February 2013. http://greet.es.anl.gov/. • Eastern Research Group. "Emission Factors for Priority Biofuels in Minnesota." Minnesota Pollution Control Agency, 2007. 8 February 2013. http://www.pca.state.mn.us/index.php/view-document.html?gid=3402. • Intergovernmental Panel on Climate Change. "2006 Guidelines for National Greenhouse Gas Inventories." 2006. 8 February 2013. http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html. • McCormick, R.L., et al. "Effects of Biodiesel Blends on Vehicle Emissions." NREL/MP-540-40554. National Renewable Energy Laboratory, 2006. • National Renewable Energy Laboratory. "An Overview of Biodiesel and Petroleum Diesel Lifecycles." NREL/TP-580-24772. National Renewable Energy Laboratory, 1998. 8 February 2013. http://www.local23.org/biodiesel/Overview_of_Biodiesel_and_Petroleum_Diesel_life_Cycles.htm. • Office of Atmospheric Programs. "Final Rule for Mandatory Reporting of Greenhouse Gases: Petroleum Products and Natural Gas Liquids: Definitions, Emission Factors, Methods and Assumptions." U.S. Environmental Protection Agency, 2009. 8 February 2013. http://www.epa.gov/ghgreporting/documents/pdf/2009/SubpartMMProductDefinitions.pdf. • Robbins, C. et al. "Biodistillate Transportation Fuels 2. - Emissions Impacts." 2 November 2009. Sustainability AnalysisE International. 8 February 2013. http://papers.sae.org/2009-01-2724/. • U.S. Energy Information Administration. "Data on U.S.Electricity Net Generation and Emissions, by State." Forms: EIA-767, EIA-906, EIA-923. 2010. 8 February 2013. http://www.eia.gov/electricity/data.cfm AND http://www.eia.gov/survey/#electricity. • U.S. Energy Information Administration. "Instructions for Form EIA-1605, Voluntary Reporting of Greenhouse Gases." 2009. 8 February 2013. http://www.eia.gov/survey/form/eia_1605/. • U.S. Energy Information Administration. "2013 Annual Energy Outlook." June 2012. DOE/EIA-0383(2012) http://www.eia.gov/forecasts/archive/aeo12/pdf/0383(2012).pdf.

Table I3 (continued). Emission factors used for downstream scoring factors

Emission Type	References
Criteria Air Pollutants	• European Environment Agency. "EMEP/EEA air pollutant emission inventory guidebook 2009." ISSN 1725-2237. 2009. 8 February 2013. http://www.eea.europa.eu/publications/emep-eea-emission-inventory-guidebook-2009/. • McCormick, R.L., et al. "Effects of Biodiesel Blends on Vehicle Emissions." NREL/MP-540-40554. National Renewable Energy Laboratory, 2006. • Jacobson, Mark. "Effects of Ethanol (E85) Versus Gasoline Vehicles on Cancer and Mortality in the U.S." Environmental Science and Technology (2007). • National Renewable Energy Laboratory. "An Overview of Biodiesel and Petroleum Diesel Lifecycles." NREL/TP-580-24772. National Renewable Energy Laboratory, 1998. 8 February 2013. http://www.local23.org/biodiesel/Overview_of_Biodiesel_and_Petroleum_Diesel_life_Cycles.htm. • Robbins, C. et al. "Biodistillate Transportation Fuels 2. - Emissions Impacts." 2 November 2009. Sustainability AnalysisE International. 8 February 2013. http://papers.sae.org/2009-01-2724/. • U.S. Energy Information Administration. "Data on U.S.Electricity Net Generation and Emissions, by State." Forms: EIA-767, EIA-906, EIA-923. 2010. 8 February 2013. http://www.eia.gov/electricity/data.cfm AND http://www.eia.gov/survey/#electricity. • U.S. Energy Information Administration. "2013 Annual Energy Outlook." June 2012. DOE/EIA-0383(2012) http://www.eia.gov/forecasts/archive/aeo12/pdf/0383(2012).pdf. • U.S. Environmental Protection Agency. "AP-42, Compilation of Air Pollutant Emission Factors." Volume I, Stationary Point and Area Sources. 1996. 8 February 2013. http://www.epa.gov/ttn/chief/ap42/index.html.
Hazardous Air Pollutants	• Forthcoming

Table I4. Impact characterization methodologies used for downstream scoring factors

Impact Type	Impact Category	References
Midpoint	**Fossil Fuel Use Impact**	• Forthcoming
	Mineral & Metal Use Impact	• Forthcoming
	Global Warming Potential	• De Schryver A.M., Brakke K.W., Goedkoop M.J. and Huijbregts M.A., 2009. Characterization factors for global warming in life cycle assessment based on damages to humans and ecosystems. Environmental Science and Technology 43(6) p.1689-1695.
	Respiratory Effects (Inorganic)	• Humbert S., Marshall J.D., Shaked S., Spadaro J., Nishioka Y., Preiss P.H., McKone T.E., Horvath A. and Jolliet O., 2011. Intake fractions for particulate matter: Recommendations for life cycle assessment. Environmental Science and Technology, 45 (11) 4808-4816.
	Respiratory Effects (Organic)	• Forthcoming

Table I4 (continued). Impact characterization methodologies used for downstream scoring factors

Impact Type	Impact Category	References
Midpoint	**Respiratory Effects (Organic)**	• Forthcoming
	Water Use Impact	• Boulay A.-M., Bouchard C., Bulle C., Deschênes L., and Margni M., 2011. Categorizing water for LCA inventory. International Journal of Life Cycle Assessment, 16(7), 639-651. Springer Berlin / Heidelberg. • Boulay A.-M., Bulle C., Bayart J.-B., Deschênes L., and Margni M., 2011. Regional Characterization of Freshwater Use in LCA: Modeling Direct Impacts on Human Health. Environmental Science & Technology, 45(20), 8948-8957. American Chemical Society. • Maendly R. and Humbert S., 2012. Empirical characterization model and factors assessing aquatic biodiversity damages of hydropower water use. Submitted in: International Journal of Life Cycle Assessment.
	Land Degradation Potential	• Saad R., Koellner T., and Margni M., 2012. Land use impacts on freshwater and erosion regulation and water purification: A spatial approach for a global scale level. Submitted in: International Journal of Life Cycle Assessment. • Saad R., Margni M., Koellner T., Wittstock B. and Deschênes L., 2011. Assessment of land use impacts on soil ecological functions: development of spatially differentiated characterization factors within a Canadian context. International Journal of Life Cycle Assessment, 16(3), 198-211.
	Cancer (External)	• Hauschild M., Huijbregts M., Jolliet O., Margni M., MacLeod M., van de Meent D., Rosenbaum R.K., McKone T., 2008. Building a model based on scientific consensus for Life Cycle Impact: Assessment of Chemicals: the Search for Harmony and Parsimony. Environmental Science and Technology 42(19), 7032-7036. • Henderson A., Hauschild M., Van de Meent D., Huijbregts M.A.J., Larsen H.F., Margni M., McKone T.E., Payet J., Rosenbaum R.K., Jolliet O., 2011. USEtox fate and ecotoxicity factors for comparative assessment of toxic emissions in Life Cycle Assessment: Sensitivity to key chemical properties. International Journal of Life Cycle Assessment 16(8), 701-709. • Humbert S., Manneh R., Shaked S., Horvath A., Deschênes L., Jolliet O. and Margni M., 2009. Assessing regional intake fractions and human damage factors in North America. Science of the Total Environment 407, 4812-4820. • Rosenbaum R.K., Bachmann T.K., Gold L.S., Huijbregts M.A.J., Jolliet O., Juraske R., Koehler A., Larsen H.F., MacLeod M., Margni M., McKone T.E., Payet J., Schuhmacher M., Van de Meent D., Hauschild M.Z., 2008. USEtox-The UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in Life Cycle Impact Assessment. International Journal of Life Cycle Assessment 13(7) 532-546. • Rosenbaum R.K., McKone T. and Jolliet O., 2009. CKow - A Dynamic Model for Chemical Transfer to Meat and Milk. Environmental Science and Technology 43(21), 8191-8198. • Rosenbaum R.K., Huijbregts M., Henderson A., Margni M., McKone T.E., van de Meent D., Hauschild M.Z., Shaked S., Li D.S, Gold L.S, Jolliet O., 2011. USEtox human exposure and toxicity factors for comparative assessment of toxic emissions in Life Cycle Analysis: Sensitivity to key chemical properties. International Journal of Life Cycle Assessment 16(8), 710-727. • Rosenbaum R.K., Margni M., Jolliet O., 2007. A flexible matrix algebra framework for the multimedia multipathway modeling of emission to impacts. Environment International 33(5), 624-634.
	Non-Cancer (External)	
	Ecosystem Toxicity	

Table I4 (continued). Impact characterization methodologies used for downstream scoring factors

Impact Type	Impact Category	References
Midpoint	**Human Noise Exposure**	• Cucurachi, S., Heijungs, R., Ohlau, K., 2012. Towards a general framework for including noise impacts in LCA. International Journal of Life Cycle Assessment 17, 471-487. • Cucurachi, S., Heijungs, R., 2014. Characterisation factors for life cycle assessment. Science of the Total Environment 468-469, 280-291.
Endpoint	**Human Health**	• Impact World+ Publication Forthcoming • Cucurachi, S., Heijungs, R., 2014. Characterisation factors for life cycle assessment. Science of the Total Environment 468-469, 280-291.
	Resource Availability	
	Environmental Health	

Table I5. Valuation methodologies used by Sustainability Analysis

Valuation Unit	References
$/MJ depleted	• Weidema, B.P., 2009. Using the budget constraint to monetarise impact assessment results. Ecological Economics 68, 1591-1598.
$/DALY	
$/PDF.m^2.yr	

Appendix J: Building a Life Cycle Cost Profile for Life Cycle Costing

Before collecting cost data for LCC estimates, complete a Life Cycle Cost Profile for each alternative being considered. This effort is supplemental to and should be integrated into existing LCC profiles developed using traditional life cycle costing methods. This is a critical step in the life cycle costing process because the cost profile will identify all major resource requirements and activities that occur within the system's boundary that are likely to be drivers of LCC. This high-level screening process allows analysts to identify the most important data elements so that limited data-collection resources will capture the highest proportion of sustainability-related costs over the system's life cycle. Once completed, this additional step should significantly reduce the amount of time and resources spent on data collection.

When completing a Life Cycle Cost Profile, leverage the results of the Life Cycle Activity Profile (see Appendix D) and impact assessment in **STEP 3** to better identify potentially hidden or contingent sustainability-related costs. A Life Cycle Cost Profile can support life cycle costing by:

- Identifying activities that are expected to be the largest drivers of sustainability-related costs over the system's life cycle
- Supplementing existing standardized cost element structures (see Appendix L) by identifying relevant sustainability-related cost categories for which LCC may be hidden and not included in traditional life cycle costing methods
- Identifying which entities will assume the sustainability-related costs (e.g., the acquisition program, installations, other agencies, society, or the environment) (see Appendix K)
- Identifying cost clusters (see definition in Appendix Q) for which the system's LCC could be significantly reduced if the drivers of those clusters are eliminated (e.g., removing cadmium and hexavalent chromium from the system's exterior surface to eliminate the production of toxic waste and use of PPE during aircraft painting and stripping)

By leveraging the results of the Life Cycle Activity Profile developed under the guidance in Appendix D, the Life Cycle Cost Profile can better identify (1) all activities, processes, and investments (collectively referred to as activities) that result in costs and (2) the specific activities that will result in the largest drivers of LCC. Often, although not always, activities that consume the most amount of resources and present the greatest risk of impact to the mission, human health, and the environment result in the highest LCC. In terms of identifying cost drivers, key characteristics of cost accounting that could influence an activity's overall cost implications include, but may not be limited to, the following:

- **The price and quantity of system inputs:** Systems that consume greater amounts of resource inputs over their life cycle often have higher total LCC than systems that consume fewer resources; however, note that activities with less consumption of higher-cost inputs could result in higher LCC than activities with greater consumption of lower-cost inputs.
- **The cost of risk and risk mitigation activities:** From a cost perspective, there is always a tradeoff between assuming the risk of costs associated with future impacts versus the cost of risk mitigation investments. In general, although not always, up-front investments in risk mitigation (PPE, control systems, material substitutions, etc.) can prevent much larger costs caused by resulting impacts experienced later in the life cycle. For additional guidance on assessing risk tradeoffs, refer to the most recent versions of MIL-STD-882 and the *DoD Risk Management Guide for DoD Acquisition*.

Analysts should complete a Life Cycle Cost Profile for internal and external sustainability-related costs to quickly identify large drivers of sustainability-related costs and to inform and reduce data collection efforts. These costs classifications are discussed in Appendix K.

Appendix K: Classifying Sustainability-related Costs

From the perspective of total cost accounting, sustainability-related costs fall into two broad classifications, internal and external. Consider the classification of each sustainability-related cost before grouping those costs into standard DoD cost element structures (see Appendix L). A summary of the taxonomy for sustainability-related costs is provided in the sections below.

Internal (DoD) Costs

Internal costs are those that will be paid by the DoD at some point during the system's life cycle. From the DoD's perspective, there are three main types of internal costs that relate to sustainability and should be collected or estimated by the analysts during life cycle costing efforts. These cost types are explained below.

- **Direct costs:** Recurring and non-recurring costs that can be directly allocated to the acquired system, including activities or processes that occur during the life cycle of the system. Although DoD 5000.4-M requires analysts to capture the direct costs tied to an acquisition program, direct sustainability-related costs are often not included because the drivers of these costs are hidden. Most sustainability-related direct costs are directly associated with the consumption of resources. For example, compliance investments and activities may be needed when using harmful chemicals or materials. Likewise, back-end costs such as labor and equipment may be needed to properly dispose of waste containing those substances during sustainment and disposal phases of acquisition. Additional examples of hidden sustainability-related costs and guidance for collecting data on these costs are provided in Appendix M.
- **Indirect costs:** Recurring and non-recurring costs that cannot be easily allocated to the acquired system. Indirect sustainability-related costs are typically aggregated in overhead costs at the installation level during the operation and sustainment of the system; therefore, indirect costs associated with activities or processes must be assigned to the system according to an allocation factor, such as units of manpower, area, mass, or energy consumption. Similar to direct costs, indirect costs can be hidden. For example, costs associated with risk mitigation or prevention (equipment controls, personal protective equipment, staging areas, etc.) are typically not assigned to the system. Additional examples of hidden sustainability-related costs and guidance for collecting data on these costs are provided in Appendix M.
- **Contingent costs:** Internal costs associated with future events that may or may not occur, depending on management decisions and other factors that are possibly outside the purview of the acquisition manager (regulatory changes, supply disruptions, accidents, etc.). Contingent costs represent the value of DoD's assumed risk that is embedded in the DoD's consumption of resources, created when risk mitigation or prevention investments are not made, or created if there is a possibility that existing risk mitigation or prevention investments can fail. For example, the use of hazardous chemicals could be restricted due to future regulatory actions, resulting in additional costs to qualify and implement a replacement substance, and could also cause injury or illness to DoD personnel, with resulting medical costs, if equipment controls and personal protective equipment fail. Thus, reducing or excluding the use of such chemicals also reduces or eliminates those associated risks. Another example is the risk related to noise; acceptance of a certain noise level may result in eventual hearing loss and hearing loss compensation for employees. The Services and the Occupational Safety and Health Administration (OSHA) have data that can be used to predict these damages. Additional examples of contingent sustainability-related costs and guidance for collecting data on these costs are provided in Appendix M.

Contingent costs are more difficult to quantify than direct or indirect internal costs because they require analysts to identify the cost associated with an event that has not yet occurred and assess the probability of that event actually occurring. Although considered a type of internal cost, contingent costs should not be aggregated with other internal costs because the probability of these costs being realized is unknown. Instead, contingent costs should be presented separately to quantify the risk embedded in a system acquisition.

Acquisition programs often do not account for hidden (direct or indirect) and contingent internal costs because they occur after the system has been acquired. Such costs should be considered in the analyses phases of a system acquisition to prevent unexpected costs at the installation and operational levels.

External (non-DoD) Costs

External costs are those borne by non-DoD government agencies, society at large (the taxpayer), or the environment. Also called "externalities", external costs are the tangible and intangible costs associated with endpoint impacts (Appendix H) resulting from the consumption of resources or exposure to harmful outputs when impact mitigation or prevention efforts are not considered or fail (medical costs, loss of biodiversity, decreased resource availability, property damage, etc.). For example, impacts to human health outside of the DoD (expressed in disability adjusted life years) result in both tangible medical costs and intangible valuation of healthy life lost due to illness. Estimating these costs presents a significant challenge to the analyst, inasmuch as the actual costs of these impacts are not routinely collected. However, many of these costs can be estimated using empirical models to calculate tangible costs that are captured in market transactions and nonmarket valuation methods that estimate the value of intangible costs.

While these costs can be significant in magnitude, they are not traditionally captured within a LCC estimate, nor are they addressed in depth in cost-benefit analyses. Similar to contingent costs, external costs should not be aggregated with other costs because they are not borne by the DoD. Instead, external costs should be presented separately to quantify the total impacts to resource availability, human health and environmental health that are embedded in a system acquisition. This information helps analysts make fully informed decisions. General guidance for collecting data on external costs is provided in Appendix M.

Although external sustainability-related costs are not realized by the DoD, these costs should be calculated to account for the risk borne by others as a result of the DoD's acquisition decisions. Such calculations promote sustainability stewardship and support the intentions of OMB Circular A-94.

Appendix L: Review of Existing Guidance and Cost Element Structures

In addition to providing a methodology for assessing a system's resource consumption and the associated impacts, this document also guides analysts on how to use existing life cycle costing guidance and cost-element structures to collect and classify sustainability-related cost data. The sections below provide a high-level overview of existing life cycle costing guidance and standardized cost element structures for each phase of acquisition to help analysts better incorporate hidden sustainability-related costs into current LCC estimates.

Life cycle costing guidance

Department of Defense Manual 5000.4-M sets forth authoritative guidance on developing LCC estimates for DoD systems. The manual focuses on procedures that follow when preparing estimates to support milestone decision reviews. However, the cost structure described in that manual also applies to other analyses, such as those used to support AoAs, BCAs, SAs, and LCSPs. The *Defense Acquisition Guidebook* describes the boundary of an LCC analysis as consisting of all elements directly associated with the system (acquisition program) plus other indirect costs that are "logically attributed to the program."[10] In summary, this boundary should include the total cost to the taxpayer that can be traced to a system alternative being assessed when executing any life cycle costing analysis, regardless of agency, appropriation, or timing.

As discussed in Section 4.6.2 of the *DoD Product Support BCA Guidebook*, cost estimations compile and forecast the costs to perform the tasks associated with each Integrated Product Support (IPS) Element, for each alternative, during a specified time period of analysis (the life cycle). Cost considerations must be included in every decision relating to resource allocation. The appropriate cost-estimating method depends on the program being evaluated and the availability of data.

At a minimum, the *DoD Product Support BCA Guidebook* states that work within the following guidelines (most of which are also addressed in DoD 5000.4-M and other cost analysis guides):

- Include all incremental, direct, and indirect costs to the taxpayer, which includes costs external to DoD and borne by society.
- Support the comparative analysis process by fully documenting the status quo (existing system) and providing its cost estimate.
- Include all relevant anticipated direct and indirect costs associated with each feasible alternative over the life of the program. Show all resources—including natural resources such as water and land—required to achieve the stated objective. Estimate all future costs from the start of the earliest alternative (other than the status quo) through implementation, operation, and disposal for a program or project. In the disposal phase, include the cost of disposal, and/or residual value for the old unit.
- Ensure that cost estimates are consistent with the assumptions, ground rules, and objectives of the product support strategy.
- Estimate all relevant future costs from inception through implementation, operation, and disposal for the program or project, bearing in mind that all cost elements do not necessarily deserve the same weighted importance. If a cost associated with a certain element is very small and not significant to the program, spend an appropriate amount of time estimating this element.

[10] Section 3.1.1 of the *Defense Acquisition Guidebook*, accessed at: https://acc.dau.mil/CommunityBrowser.aspx?id=488331&lang=en-US

- Devote the appropriate time to the more significant cost driving elements, which discusses the concept of using a Life Cycle Cost Profile to identify cost drivers and cost clusters. The cost of an alternative includes the cost of operating the status quo programs until the chosen alternative is fully implemented.
- Do not include sunk costs as part of the evaluation, analysis, or recommendation.
- Disclose confidence levels per the Weapon System Acquisition Reform Act (WSARA) of 2009.

Standardized cost element structures by acquisition phase

As DoD 5000.4-M indicates, LCC should be captured under the following four high-level categories: Research and Development (R&D), Investment, Operations and Support (O&S), and Disposal. These categories are summarized below.

Research and Development (R&D)

This category consists of development costs incurred from the beginning of the materiel solutions analysis phase through the end of the engineering and manufacturing development phase and potentially into low rate initial production. The major elements of R&D costs include the following:

- **Development engineering:** Includes the study, design development, evaluation, testing and redesign of system components.
- **Prototype manufacturing** includes fabrication, processing, assembly, installation of parts and equipment; raw and semi-fabricated materiel and purchased parts used in manufacturing prototype.
- **System test and evaluation** includes planning, conduct, support, data reduction, specially fabricated hardware necessary for testing.
- **Systems engineering and program management** integrates cost, schedule, performance, and risk, using an approach that is disciplined and using consistent activities and processes.

Each military department has developed a cost element structure for R&D that varies slightly from the above list. Reference the appropriate guidance from the department making the acquisition.

Investment

This category includes production and deployment costs incurred from the beginning of low-rate initial production through completion of deployment. Include military construction costs in this category. Major elements are listed below:

- **Non-recurring production**: Initial production facilities that include dies, templates, patterns, form block manufacture, jigs, fixtures, master forms, inspection equipment, handling equipment, load bars, work platforms, and test equipment.
- **Recurring production**: Includes fabrication, checkout, and processing of parts, subassemblies, and major assemblies or subsystems needed for the final system. Recurring engineering, sustaining tooling, quality control, and other recurring production-related costs are also included.
- **Engineering changes**: Includes alterations made to a system while it is still in the manufacturing process.
- **System test and evaluation**: Procurement-funded costs of the system-related production test activities that are identifiable with the evaluation of the system. Included are the costs of hardware to obtain or validate data.
- **Training devices and simulators**: System-specific, procurement-funded costs of training devices, accessories, aids, equipment, facilities, and parts used to facilitate instruction through which

personnel will acquire sufficient concepts, skills, and aptitudes to operate and maintain the system efficiency.

- **Program management**: Overall planning, direction, and control of the definition, development, and production of the system/program, including functions of logistics engineering and IPS management, e.g., maintenance support, facilities, personnel, training, testing, and activation of a system.

As with the cost elements associated with the R&D phase, each military department has developed slightly different cost element structures for the Investment phase. Reference the appropriate guidance from the department making the acquisition.

Operations and Support (O&S)

This category includes costs incurred from the initial system deployment through the end of system operations. It includes all costs of operating, maintaining, and supporting a fielded system. Specifically, this category consists of direct or indirect costs incurred by the government and contractors for personnel, equipment, supplies, software, and services associated with operating, modifying, maintaining, supplying, training, and supporting a system in the DoD inventory. Analysts can find additional, detailed guidance for estimating O&S costs in the latest edition of the DoD *OSD Cost Assessment and Program Evaluation (CAPE) O&S Cost Estimating Guide*. The guide calls for an O&S cost element structure divided into six major categories, as follows:

- **Unit-level manpower:** Includes the cost of operators, maintainers, and other support manpower assigned to operating units; may include military, civilian, or contractor manpower.
- **Unit operations:** Includes the cost of unit operating material (e.g., fuel and training material), unit support services, and unit travel; excludes all maintenance and repair material.
- **Maintenance:** Includes the cost of all maintenance other than maintenance manpower assigned to operating units; may include contractor maintenance. For example, the costs of energy, water, chemicals, and materials used during maintenance activities should be included. These costs should also include environmental permits, sampling, personnel medical monitoring, emission control equipment, waste handling and disposal, and workplace monitoring. Some of these costs may be borne by supporting organizations or facilities and can be included in Indirect Support. In some cases where activity-based cost detail is not available, it may be necessary to apportion a cost from overhead.
- **Sustaining support:** Includes the cost of support activities other than maintenance that can be attributed to a system and are provided by organizations other than operating units.
- **Continuing system improvements:** Includes the cost of hardware and software modifications to keep the system operating and operationally current. A modification program aimed at improving a system's emissions profile, which is a sustainability-related activity, could be included in this element.
- **Indirect support:** Includes the cost of support activities that provide general services that cannot be directly attributed to a system. Indirect support is generally provided by centrally managed activities that support a wide range of activities (e.g., recurring costs associated with air filtration and wastewater treatment at a depot where a system maintained or overhauled).

Disposal

This category consists of costs associated with the demilitarization and disposal of a military system at the end of its useful life. Demilitarization and disposal costs of a system can be significant. DoD 5000.4-M does not provide specific guidance on the estimation of these costs. Therefore, system-specific

factors and other information should be used when developing these estimates. These costs should include any natural resource requirements and environmental-compliance–related costs. As an example, deactivation of some weapons platforms requires the use of land for long-term storage of the deactivated systems.

Appendix M: Collecting Sustainability-related Cost Data

Once sustainability-related costs have been organized and classified, analysts can begin collecting the data that will populate the cost element structures described in Appendix L. This appendix provides guidance for identifying likely sources of data for internal and external sustainability-related costs.

Internal (DoD) Costs

Traditionally, sustainability-related internal costs (direct, indirect, and contingent) are not systematically collected or are hidden in aggregated cost data. Ensure that sustainability-related costs are identified and incorporated in LCC estimates. In general, sustainability-related internal costs originate from three sources: (1) the direct costs associated with the quantity and price of resource inputs, (2) the cost of any investments that mitigate or prevent sustainability-related risk (e.g., equipment controls, PPE), and (3) potential costs that may arise (contingent) due to embedded risk not prevented. Table M1 provides DoD-specific examples of potentially hidden and contingent internal costs. Some suggestions for identifying sustainability-related costs, depending on the phase of acquisition, are provided in the sections below.

R&D and Investment

To date, the military departments and the Office of the Secretary of Defense have not systematically collected costs specifically related to sustainability; thus, there is no central repository for such costs. When collecting sustainability-related cost data for a Sustainability Analysis, analysts should identify systems with activities during the R&D and investment phases that are analogous to the system that is being evaluated. For example, if the system under evaluation is a new engine, the sustainability-related costs occurring during the R&D and investment phase could be approximated by assuming that these costs are similar in nature to the costs allocated to a legacy engine of similar size and performance.

There are two main sources for collecting sustainability-related costs: (1) the Cost and Software Data Reporting (CSDR) system and (2) the contractor's internal data system. The CSDR system is the most likely source for finding sustainability-related costs for legacy systems. Under the CSDR system, contractors are required to report their actual costs in Contractor Cost Data Reports (CCDRs). The CCDRs show actual costs using a standard work breakdown schedule that addresses development engineering, prototype manufacturing, and other cost elements. Contractors also submit CCDRs during the production portion of the investment phase; these CCDRs contain detailed information about incurred costs for recurring and non-recurring production. To access CCDRs, analysts must work through government program office since these reports contain extensive proprietary information. If the CCDRs do not address sustainability-specific costs, data may also be found in the contractors' internal data systems. The analyst—working with the government program office—should meet with the contractors to determine if these data are available.

Operations and Support (O&S)

To estimate sustainability-related costs likely to occur during the operations and sustainment phase, work with the government program offices to obtain data that has been collected under the auspices of the DoD Visibility and Management of Operating Support Costs (VAMOSC) program. As with information gathered for the R&D and investment phases, consider the initial collection of data made available by program offices as an important first step. Follow-up discussions with contractors and—to the extent possible—with government organizations, especially military units, are essential. In many cases, sustainability-related activities, such as pollution prevention and hazardous waste cleanup, are managed by installation officials. Discussions with these individuals can provide essential insights into required funding levels, schedules, and risks associated with these projects.

Disposal

The disposal phase includes costs related to the demilitarization and disposal of a system at the end of its useful service life. According to the *DoD Operating and Support Cost-Estimating Guide*, these costs include the "disassembly, materials processing, decontamination, collection, storage, and disposal of hazardous materials or waste, safety precautions, and transportation of the system to the disposal site." The departments have not systematically collected disposal phase costs, and a central repository for such data does not exist. As with costs for the other phases of acquisition, analysts can estimate sustainability-related costs by identifying an analogous system where disposal costs have been collected by government or contractor entities.

Table M1. Potentially hidden and contingent sustainability-related costs

	Potentially Hidden	Contingent
Non-Recurring	Support costs for the system	Increased price of system inputs
	Environmental-related R&D	Medical costs for active DoD personnel
	NEPA studies	Environmental clean-up (e.g., remediation, reclamation, restoration)
	Equipment Controls	Additional training
	Personal protective equipment (PPE)	Changes in regulation and additional compliance
	Industrial staging areas	Legal expenses
	Training	Damage payments
Recurring	Storage	Penalties and fines
	Conservation	Future audits
	Pollution prevention	R&D to mitigate hazard
	Permitting	Future land restrictions
	Compliance administration	
	Waste (solid and hazmat) management	
	Medical surveillance	
	Training	

External (non-DoD) Costs

In general, external costs are not systematically collected or reported in LCC estimates. External costs estimates rely on modeling that require two general types of data: (1) the expected impacts, in appropriate units of measure, to other agencies, society, or the environment that are expected to occur during the system's life cycle and (2) the total estimated cost per unit of impact. The endpoint impact results of **STEP 3a** satisfy the first requirement by providing quantifiable impacts in measurable units. In terms of costs per unit, the external cost factors in Appendix I provide analysts with default costs per unit of endpoint impact (MJ depleted, DALYs, and PDF/m^2/yr). These endpoint cost factors were developed using best available non-market valuation methods. Table M2 provides an explanation of each external cost factor and key assumptions used to develop them. Although not necessarily representative of all potential external costs that may be *associated with the endpoint impacts identified in* **STEP 3a***, these generalized external cost factors, when adjusted to current year dollars, will meet the data requirements for most LCC analyses.* When using the external cost factors provided in Appendix I, no additional data are required to be collected by the analysts.

Table M2. Explanation of external cost factors and assumptions

Endpoint Impact Unit	Explanation of External Cost Factor	Key Assumptions and Notes
MJ depleted	Represents the value of the extra energy that will be required to extract the resource in the future relative to the energy required today.	• Depleted reserves will cause future energy, mineral and metal resources to become more difficult to extract in the future. • These resources must be extracted using unconventional methods that are more energy-intensive, thereby increasing the marginal cost of extraction. • Does not account for regional differences in cost.
DALY	Represents the value of one year of productive work lost from an average U.S. worker.	• The value of human health is tied to worker productivity. • Based on the average per capita income in the United States. • Average per capita income is adjusted for unemployment. • Since a DALY conceptually covers all aspects of human well-being that one would be willing to pay for, all income will on average be spent on total production to maintain full well-being, assuming that there is no long-term change in capital stock. • Does not account for regional differences in cost.
PDF/m^2/yr	Represents the value of biodiversity lost in one year per area of land	• Valuation of total ecosystem health is equivalent to 2% of total human health valuation; which is supported by the fact that current environmental protection expenditures in developed countries are roughly 2% of Gross Domestic Product. • Does not account for regional differences in cost.

Appendix N: Estimating Sustainability-related Costs

In addition to providing a methodology for assessing a system's resource consumption and the associated impacts, the sections below provide a high-level overview of existing life cycle costing guidance, reviewing established methods used to estimate LCC, and facilitating a high-level discussion that describes how to incorporate hidden sustainability-related costs into current LCC estimates.

After a LCC Profile is completed and all necessary data has been collected, analysts can begin to estimate sustainability-related costs associated with the resulting impacts of each assessed alternative. This appendix provides methods for estimating the sustainability-related costs associated with the system's life cycle impacts, which are often not included in LCC estimates. The following subsections guide analysts, for each phase of acquisition, on how to assigning internal and external costs to the impact results recorded in **STEP 3**. (NOTE: the discussion in this appendix does not include procurement costs, which are already included under existing life cycle costing guidance). Additional guidance for environmental-specific, hidden, contingent, and external costs is available in the EPA's *Guidelines for Preparing Economic Analyses*[11] and the GAO's *Cost Estimating and Assessment Guide*[12].

Available life cycle costing methods

In addition to DoD 5000.4-M and the Product Support BCA Guide, other cost-estimating methods can be used such as the Government Accountability Office's (GAO's) Cost Estimating and Assessment Guide; the Army's Cost Benefit Analysis Guide; OMB Circular A-94; and other best-practice publications. The approach used depends significantly on the availability of reliable and validated data. The discussion of these approaches below is in an order defined by the availability of data (least available to most available).

- **Expert Opinion:** When few data are available, typically early in the development of a new system, an "Expert Opinion" approach may be used. In this method, the analyst will develop a structured questionnaire and solicit the opinions of subject matter experts with appropriate credentials in the field. While this technique can be useful in early stages of acquisition, these estimates are normally highly uncertain and have a low confidence rating. In general, this technique is used to understand the general direction and magnitude of the costs or cost avoidances.
- **Analogy:** When data that describe the physical attributes or performance characteristics of a system are available, the "Analogy" approach may be used. This approach is based on direct comparison with actual data, such as historical information of similar existing activities, systems, or components. While this method is better than the "Expert Opinion" method, it uses judgment in translating empirical data on analogous systems to the system under examination.
- **Parametric:** In parametric cost estimating, the cost is based on physical attributes or performance characteristics and their relationships to highly aggregated component costs. For example, in aviation systems, fuel costs may be related to aircraft weight, and speed and ship structural and propulsion costs may be related to ship displacement and speed. The mathematical relationships between physical or performance parameters and costs are called Cost Estimating Relationships

[11] *Guidelines for Preparing Economic Analyses*. U.S. Environmental Protection Agency, National Center for Environmental Economics, Office of Policy. December 17, 2010. Accessed at: http://yosemite.epa.gov/ee/epa/eerm.nsf/vwAN/EE-0568-50.pdf/$file/EE-0568-50.pdf

[12] *GAO Cost Estimating and Assessment Guide: Best Practices for Developing and Managing Capital Program Costs*. U.S. Government Accountability Office, Applied Research and Methods. March 2009. GAO-09-3SP. Accessed at: http://www.gao.gov/new.items/d093sp.pdf

(CERs). When using this method, the physical attribute or performance parameter of the system under investigation should be within the empirical envelope of the data on which the CER is based.

- **Engineering (Bottom-Up)**: When there is extensive information available about the system[13], the "Engineering" or "Bottom-Up" approach may be used. This approach can be broadly defined as an examination of separate segments of work at a low level of detail and a synthesis of the many detailed estimates into a total. Different methods can be used to estimate the costs of a particular segment of the work to bolster confidence in the estimate. For example, when estimating the costs of a new, complex engine design, an Expert Opinion survey may be used in addition to an analysis of an analogous system. The Engineering Approach is not appropriate until well into a system's development (e.g., after the Critical Design Review).

Estimating Internal (DoD) Costs

This section provides analysts with guidance for estimating sustainability-related hidden (direct and indirect) and contingent costs. A detailed discussion on each is provided in the sections below.

Hidden Costs

Whether direct or indirect, hidden internal costs are embedded in many cost elements across multiple life cycle stages. Given the large variability in data availability for hidden costs, different costing methods are recommended for each cost element and life cycle stage.

Table N1 provides a list of the major cost elements in the R&D and Investment phases, their definitions, and suggested estimating methods. The costs described in this table are incurred in developing and ultimately producing components that address the system inputs in the Sustainability Analysis framework (e.g., the costs incurred in the R&D and Investment phases to produce a noise-abated engine). Comments and suggested methods for estimating costs are provided in the rightmost two columns.

Table N2 provides a list of the sustainability-related cost elements where the cost implications of initiatives launched in the R&D and Investment phases might be reasonably expected to occur in the O&S phase. Endpoint impact categories related to those elements are presented in the middle column to provide a clear link between endpoint impacts and cost elements. Comments and suggested methods for estimating costs are provided in the rightmost two columns.

Table N3 provides a list of the cost elements where the cost implications of initiatives launched in the R&D and Investment phases might be reasonably expected to occur in the disposal of the system. In the table, the sustainability-related cost elements for the disposal stage of the life cycle are listed; these cost elements are consistent with the *DoD Operating and Support Cost-Estimating Guide*. Endpoint impact categories related to those elements are included to provide a clear link between endpoint impacts and cost elements. Comments and suggested methods for estimating costs are provided in the two right columns.

[13] This includes, but is not limited to when the system's characteristics are well known, when empirical costs have been collected and validated, and when production processes have settled.

Table N1. Sustainability-related costs in R&D and Investment phases

Phase	Major Cost Element	Brief Description	Suggested Methods	Cost Notes
R&D	Development Engineering	Study, design development, evaluation, testing and redesign of system components	• Expert opinion and analogy early in the systems' life • Use actuals from Technology Development if collected	• Costs driven largely by labor; need to estimate engineering staff years dedicated to sustainability • Could relate to mission, human health and environmental health endpoints
	Prototype Manufacturing	Fabrication, processing, assembly, installation of parts and equipment including raw and semi-fabricated materiel and purchased parts used in manufacturing prototype	• Expert opinion and analogy early in the systems' life • Use actuals from Technology Development, if collected. • Catalogs and other similar sources may be used	• A significant element in the R&D phase -- can be 25-40% of the total R&D cost estimate • Prototypes incorporate results of development and systems engineering • Could relate to mission, human health and environmental health endpoints
	System Engineering	Cost, schedule, performance, and risk analysis integrated using disciplined and consistent activities and processes	• Expert opinion and opinion in early stages • Actuals from TD if available	• Cost driver is engineering effort needed to integrate sustainability components into overall system
	Test and Evaluation	Plan, execute, and support system testing including data reduction and creation of specially fabricated hardware	• Expert opinion and analogy in early stages • Actuals from TD if available	• Objectives and performance measurement related to sustainability must be addressed
Investment	Production	Fabrication of final system including materials and labor, for checkout and processing of parts and assemblies needed for the final system	• Expert opinion and analogy in early stages of system's life cycle • EMD actuals for prototype manufacturing or early production lots	• Manufacturing process and materials specifically related to sustainability • Could relate to mission, human health and environmental health endpoints

Table N2. Sustainability-related costs for O&S phase

Cost Element	Related Endpoint Impact Categories	Suggested Methods	Cost Notes
Other Unit Level Manpower (1.3)	• Human Health	• In early stages of system acquisition, use Expert Opinion and appropriate analogies, where available • In later stages, use actuals from Visibility and Management of Operating and Support Costs (VAMOSC) and discussions with program offices • Consult unit tables of organization and equipment for analogous organizations to identify related positions	• Completely a manpower-related cost
Energy (2.1.1)	• Resource Depletion • Human Health • Environmental Health	• In early stages of system acquisition, use Expert Opinion and appropriate analogies, where available • In later stages, use actuals from Operational Test, actuals from VAMOSC systems to develop estimates based on parametrics (system speed and weight may be candidates for dependent variables)	• Applies to all sources of energy use
Depot Maintenance (3.1)	• Resource Depletion • Human Health • Environmental Health	• In early stages of system acquisition, use Expert Opinion and appropriate analogies, where available • In later stages, work with actuals from VAMOSC. Conduct discussions with program offices and depots – will require site visits and detailed discussions	• Consists of both manpower- and materiel-related costs
Other Maintenance (3.4)	• Resource Depletion • Human Health • Environmental Health	• In early stages of system acquisition, use Expert Opinion and appropriate analogies, where available • In later stages, use actuals from Visibility and Management of Operating and Support Costs (VAMOSC) and discussions with program offices • Consult unit tables or organization and equipment to identify related positions	• Consists of both manpower- and materiel-related costs
Sustaining and Systems Engineering (4.3)	• Resource Depletion • Human Health • Environmental Health	• In early stages of system acquisition, use Expert Opinion and appropriate analogies, where available • In later stages, use actuals from Visibility and Management of Operating and Support Costs (VAMOSC) and discussions with program offices • Consult program office tables of organization to identify related positions	• Consists entirely of manpower costs
Hardware Modifications (5.1)	• Resource Depletion • Human Health • Environmental Health	• In early stages of system acquisition, use Expert Opinion and analogies, where available • In later stages, use actuals from Visibility and Management of Operating and Support Costs (VAMOSC) and discussions with program offices • Consult unit tables or organization and equipment to identify related positions • Work with past budget justification materials	• Consists of both manpower- and materiel-related costs

Table N2 (continued). Sustainability-related costs for O&S phase

Cost Element	Related Endpoint Impact Categories	Suggested Methods	Cost Notes
Installation Support (6.1)	• Resource Depletion • Human Health • Environmental Health	• In early stages of system acquisition, use Expert Opinion and analogies, where available • In later stages, use actuals from Visibility and Management of Operating and Support Costs (VAMOSC) and discussions with program offices • Consult unit tables or organization and equipment to identify related positions • Consult Budget justification materials • Consult factors developed by military departments for base operating costs • Consult factors typically derived from command operating budgets as executed. Air Force, for example, uses Element of Expense Identification Codes; Army uses factors published in the Army Cost Factors Handbook	• Consists of manpower (typically DoD civilians and contractors) and other costs funded in the Operations & Maintenance appropriations

Table N3. Sustainability-related costs for Disposal phase

Cost Element	Related Endpoint Impact Categories	Suggested Methods	Cost Notes
Disassembly, materials processing, and decontamination	• Resource Depletion • Human Health • Environmental Health	• In early stages of system acquisition, use Expert Opinion and appropriate analogies, where available • In later stages of system as the system's characteristics are more clearly defined, work with program offices' logistics engineers and conduct appropriate research to develop estimates	• Contains costs related to both labor and materials
Collection, storage, and disposal of hazardous materials and/or waste	• Resource Depletion • Human Health • Environmental Health	• In early stages of system acquisition, use Expert Opinion and appropriate analogies, where available • In later stages of system as the system's characteristics are more clearly defined, work with program offices' logistics engineers and conduct appropriate research to develop estimates	• Will vary significantly from one commodity to another.
Safety precautions	• Human Health • Environmental Health	• In early stages of system acquisition, use Expert Opinion and appropriate analogies, where available • In later stages of system as the system's characteristics are more clearly defined, work with program offices' logistics engineers and conduct appropriate research to develop estimates	• Includes risk mitigation investments that lower or prevent risk of human or environmental health degradation

Table N3 (continued). Sustainability-related costs for Disposal phase

Cost Element	Related Endpoint Impact Categories	Suggested Methods	Cost Notes
Transportation to and from disposal site	• Resource Depletion • Human Health • Environmental Health	• Factors for transportation costs, based on mode and distances, are published and widely available. For example, the Army has published rates, updated annually, in its *Cost Factors Handbook*.	• Need analysts to be prepared to address cost risks associated with transportation of hazardous materials

Contingent Costs

Contingent costs are the valuation of a system's embedded risk, and thus the concepts of risk must apply to properly assign value to future events. Risk has two components: the magnitude of impact associated with a future event and the probability that the event will occur and the impact will be realized. For most sustainability-related risks, neither component of risk is well-defined, which makes it very difficult to assign cost to such risk.

Contingent costs are often estimated by first identifying all potential consequences of a future event. Keep in mind that multiple consequences can result from a single event. Once the consequences of each event have been identified, assess the magnitude of impact associated with the consequences. Finally, analysts should assign a representative cost to each identified impact.

In most cases, analysts can use analogy costing methods and historical data from similar events to estimate the costs of impacts resulting from future events. For example, the cost of a remediation project resulting from the transformation and occupation of land supporting the system can be estimated analogously by using cost data from past remediation efforts that are similar in type and scope. In this example, analysts may need to scale these costs up or down depending on the expected size of the remediation project. In doing so, develop mathematical relationships among data elements, using analytical tools such as S-curves and regression analysis, to create appropriate scaling factors. In this notional example, analysts may determine that the remediation cost per area of land is fairly constant, and thus use this linear relationship to estimate the potential costs of a future remediation project on a specified area of land.

Contingent costs may also be estimated as the increased cost of business resulting from a future event. For example, if it is likely that a regulation will ban or restrict the use of a toxic chemical or material, the DoD would be required to invest in additional research and development to find a replacement for the banned substance, and then invest in the production and deployment of the replacement. In this example, analysts could use historical costs for R&D, production and deployment, along with analogy methods, to estimate this increased cost of business. Similar methods can be used for estimating the cost of escalating prices for system inputs (e.g., energy, water).

Analysts should also use analytical tools such as sensitivity analyses, Monte Carlo simulation, and scenario-based methods to account for potential ranges of magnitude for identified impacts and the unknown probability of those impacts being realized. Sensitivity analyses address the sensitivity of the cost estimate to change given key underlying assumptions. Specifically, sensitivity analyses recalculate the estimate with different quantitative values for various input parameters and then compare the new estimate to the original estimate. Analysts can find a good discussion for conducting sensitivity analyses in the *GAO Cost*

Estimating and Assessment Guide.[14] Monte Carlo simulations enable the cost analyst to use different input variables (impact magnitude and probability of occurrence) over thousands of simulations to identify a distribution of potential outcomes. Scenario-based methods involve articulating selected alternative scenarios, estimating the costs associated with each outcome, and comparing those results with the original estimate. In recent years, enhancements to this method have been introduced. Analysts can find additional discussions of Monte Carlo simulations, scenario-based methods and other techniques in the *Journal of Cost Analysis and Parametrics*[15]. Ideally, the cost analyst should consider using two or more of these methods to communicate the uncertainty of the cost estimate to decision makers.

Estimating External (non-DoD) Costs

External costs resulting from impacts to human and environmental health are easily calculated using the external cost factors in Appendix I. To calculate external costs, multiply the quantity of each endpoint impact, aggregated by appropriate endpoint units as specified in **STEP 3b**, by the relevant external cost factor. The results of these calculations will provide analysts with an estimated total valuation of resource depletion, lost quality of human life, and lost biodiversity. These results should be adjusted to current year dollars. The Sustainability Analysis tool referenced in Appendix A automatically calculates external costs for each alternative for which a Sustainability Analysis has been completed. These costs are based on assumptions and historical data and are therefore not used in the system's official life cycle cost estimate. However, they can be valuable for relative comparisons among alternatives.

[14] *GAO Cost Estimating and Assessment Guide: Best Practices for Developing and Managing Capital Program Costs*. U.S. Government Accountability Office, Applied Research and Methods. March 2009. GAO-09-3SP. Accessed at: http://www.gao.gov/new.items/d093sp.pdf

[15] Garvey, Paul R., Flynn, B., Braxton, P., and Lee, R., "Enhanced Scenario-Based Method for Cost Risk Analysis: Theory, Application, and Implementation." Journal of Cost Analysis and Parametrics, Volume 5, Number 2, July-December 2012, pp. 98-142.

Appendix O: Comparing Alternatives and Displaying Results

Comparing Midpoint and Endpoint Impacts across Alternatives

The methodology presented in this section provides relative impact values under each impact category for each alternative evaluated. These values are recorded in appropriate units of impact for each of the 11 midpoint impact categories (see Appendix G) or 3 endpoint impact categories (see Appendix H). The following subsections describe an effective decision analysis method for comparing the overall sustainability of alternatives across all relevant midpoint and endpoint impact categories.

Normalizing Impact Scores

Midpoint and endpoint impact category results generated from the use of scoring factors are recorded in different units of measure and are incomparable. To compare alternatives across dissimilar metrics, it is recommended that evaluators normalize the results. The Sustainability Analysis tool referenced in Appendix A automatically calculates midpoint and endpoint results, normalizes the results, and generates various graphical displays of the data. However, if evaluators choose to conduct the assessment manually, guidance is provided below for normalizing the impact results and generating graphical displays of those results.

The results of the midpoint or endpoint impact assessment can be used to assign normalized scores (NS_x) to each alternative within a particular impact category by calculating each alternative's impact in terms of percentage of the worst performer. According to this methodology, the worst performer will be assigned a normalized score of 100% and represents the outermost parameter of the scale against which all other alternatives will be assessed. NS_x for all alternatives not considered worst is calculated as the difference between the worst performing score (A_{worst}) and Alternative x's score (A_x), subtracted from the number one and divided by the worst performer's score (see Equation 1). This value is then converted into a percentage by multiplying by 100.

$$(1) \qquad NS_x = \left[\frac{1-(A_{worst}-A_x)}{A_{worst}}\right] \times 100$$

It is important to note that when comparing alternatives, larger impacts indicate less desirable alternatives and result in larger overall sustainability footprints. This implies that alternatives with relatively smaller impact footprints (smaller normalized scores) are considered more sustainable and are thus preferred.

Presenting Impact Results

Once a normalized score is assigned to each alternative within each midpoint or endpoint impact category, evaluators can present these dimensionless scores in multiple graphical displays. Figures O1 and O2 are example display formats that can be used to present midpoint or endpoint results.

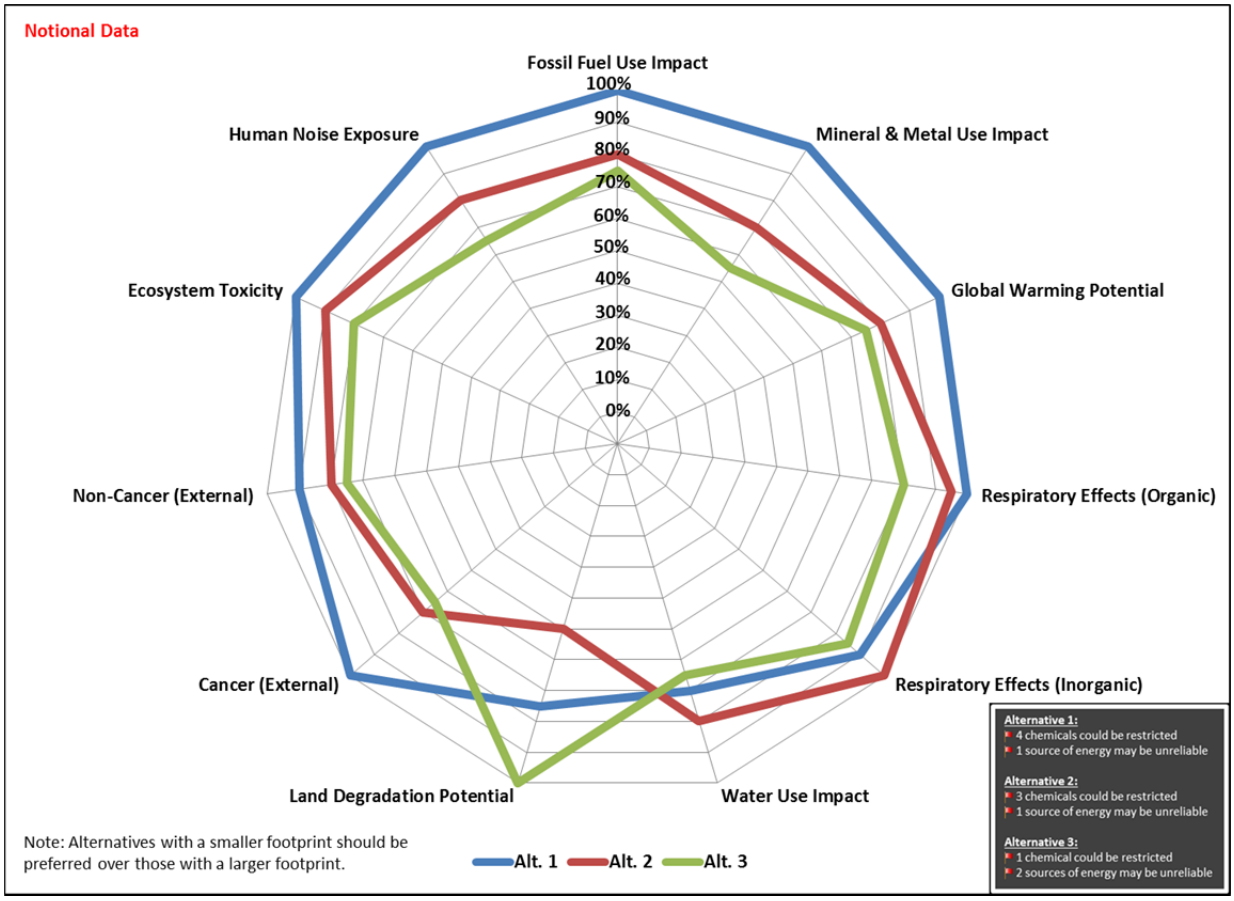

Figure O1. Example radar diagram for presenting midpoint impact results

The radar diagram presented in Figure O1 provides a visual means of comparing alternatives based on their sustainability impacts, normalized on a comparable scale of 0% to 100%. Each "spoke" of the diagram represents one of the 11 midpoint impact categories. Impact category results for each alternative are then plotted on the diagram. Alternatives with the largest impact are represented by lines on the outside perimeter of the radar diagram. All other alternatives are displayed as a percentage of the alternative with largest impact. This allows a quick comparison of alternatives for each impact. Alternatives with the smallest impact are represented by lines closest to the center of the radar diagram (the smallest footprint). In many cases, systems will have small impacts for some impact categories, but large impacts for others, resulting in an asymmetrical plot on the radar diagram. Use the radar diagram to identify impacts with large differences between evaluated alternatives to discern tradeoffs in impact categories for a single system as well as tradeoffs among multiple systems. Sources of energy and chemicals used by the system that are flagged for risk in terms of reliability or availability should also be presented in the display (see box in lower right corner of Figure O1).

Once all alternatives are graphed on a radar diagram, evaluators can reduce the number of acceptable alternatives by eliminating those that have the largest impact footprint. In Figure O1, Alternative 3 has the smallest footprint for most impact categories and is more likely to be the most sustainable alternative. However, most scenarios will not be as obvious and will require tradeoffs across impact categories. Determine and provide justification for the methodology used for making such trades and eliminating alternatives.

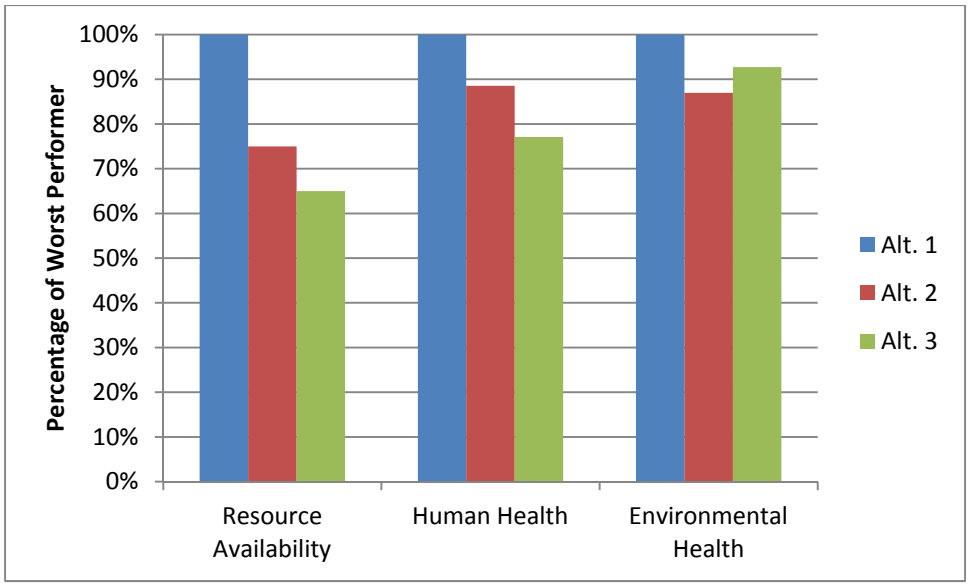

Figure O2. Example radar diagram for presenting midpoint impact results

The bar chart presented in Figure O2 provides another visual means of comparing alternatives based on their sustainability impacts, normalized on a comparable scale of 0% to 100%. In this example, the worst performer, in terms of endpoint impact, results in the largest bar; thus alternatives with a smaller bar would be considered most sustainable within the specified impact category. Similar to the radar diagram, once all alternatives are graphed on a bar chart, evaluators can reduce the number of acceptable alternatives by eliminating those that have the largest impact footprint.

Comparing Life Cycle Costs across Alternatives

Once all sustainability-related costs have been quantified for each alternative, evaluators can integrate those results with the results from traditional LCC estimates to provide an estimate of each alternative's total LCC in terms of net present value (NPV). As shown in Figure O3, evaluators can present total LCC on a stacked bar chart to compare alternatives across internal, external, and contingent costs. As demonstrated by Figure O3, alternatives with the lowest internal costs are not necessarily the best investments. In this notional example, Alternative D offers the lowest internal costs, but also causes high external impact, which results in the second highest NPV across all available alternatives. Conversely, Alternative B has slightly higher internal costs, but results in a much lower overall NPV. Given that all alternatives meet performance requirements, Alternative B would more than likely be chosen as the most cost-effective alternative.

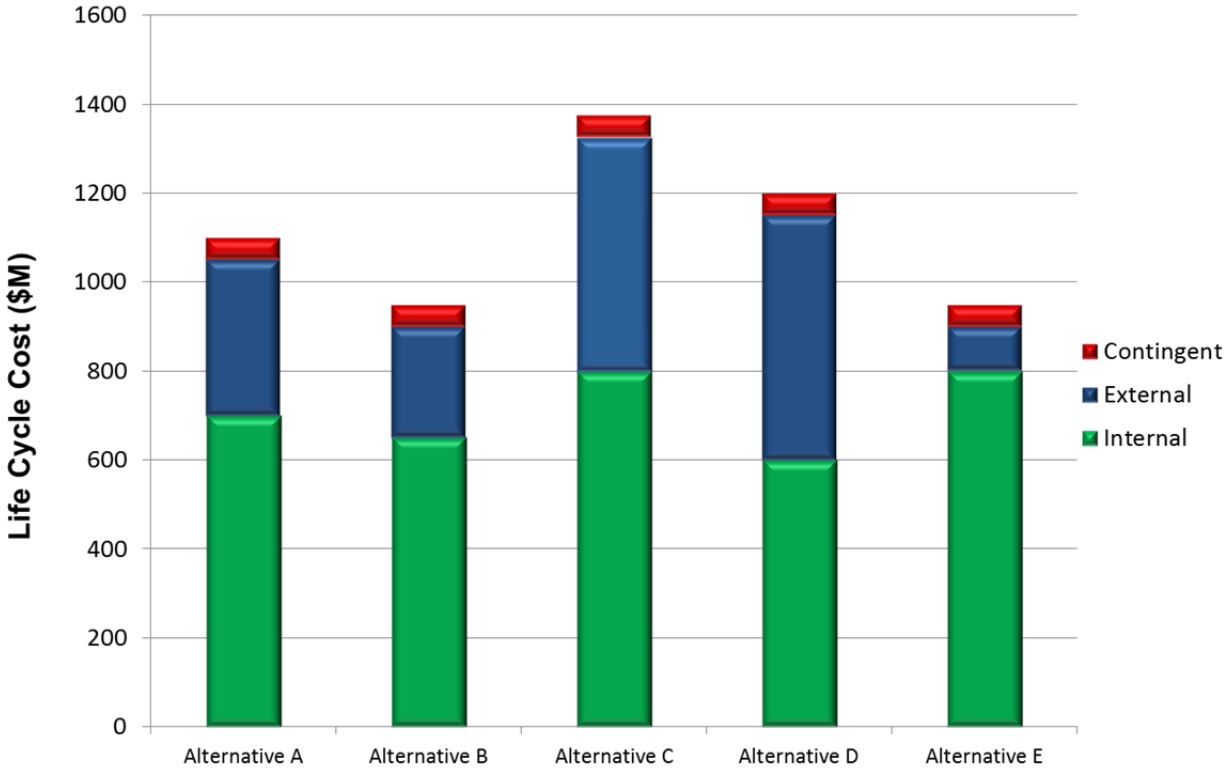

Figure O3. Example stacked bar chart for presenting LCC results

Appendix P: Acronyms and Abbreviations

The acronyms and abbreviations used in this guidance are defined as follows:

ACAT	Acquisition Category
AoA	Analysis of Alternatives
ASSIST	Acquisition Streamlining and Standardization Information System
BCA	Business Case Analysis
CAPE	Office of Cost Assessment & Program Evaluation
CER	Cost Estimating Relationship
C&M	Chemical & Material
CDD	Capability Development Document
CCDR	Contractor Costs Data Report
CDD	Capability Development Document
CDR	Critical Design Review
CFC	Chlorofluorocarbon
CONOPS	Concept of Operations
CO_2	Carbon Dioxide
CTU_e	Comparative Toxic Unit for environmental health
CTU_h	Comparative Toxic Unit for human health
DALY	Disability Adjusted Life Year
dBA	Decibel A-weighting
DLA	Defense Logistics Agency
DoD	U.S. Department of Defense
EIO	Economic Input-Output
E.O.	Executive Order
EMP	Engineering and Manufacturing Development
EPA	U.S. Environmental Protection Agency
FBCE	Fully Burdened Cost of delivered Energy
FRP	Full-Rate Production
GAO	Government Accountability Office
HVAC	Heating, Ventilation, and Air Conditioning
ICD	Initial Capabilities Document
IPS	Integrated Product Support
ISO	International Organization for Standardization
Kg	Kilogram
KPP	Key Performance Parameter
KSA	Key System Attribute
LCA	Life Cycle Assessment

LCC	Life Cycle Cost
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSP	Life Cycle Sustainment Plan
MCC	Marginal Cost of Consumption
MDA	Milestone Decision Authority
MDAP	Major Defense Acquisition Program
MDD	Material Development Decision
MSDS	Material Safety Data Sheet
MT	Mission Task
NO_X	Nitrogen Oxide
NPV	Net Present Value
O&S	Operations and Support
PDF	Potentially Disappeared Fraction
PDR	Preliminary Design Review
PM	Program Manager
$PM_{2.5}$	Particulate Matter (fine particulates less than 2.5 micrograms)
PPE	Personal Protective Equipment
SA	Supportability Analysis
RAM-C	Reliability, Availability, Maintainability—Cost
SE	Systems Engineering
SME	Subject Matter Expert
SSPP	Strategic Sustainability Performance Plan
TDS	Technology Development Strategy
VAMOSC	Visibility and Management of Operating Support Costs

Appendix Q: Glossary

Activity descriptor: Key characteristics of a system that describe that system's function or purpose. An activity descriptor is used to identify activities resulting in high life cycle human health and environmental impacts.

Basing space: Land use that includes, but is not limited to, piers, shoreline, runways, and hangars and should be included in evaluation of alternatives using LCA methods.

Characterization factor: A conversion factor used in the DoD Sustainability Analysis methodology to convert an inventory input to an impact. Characterization factors are derived from widely accepted risk assessments, life cycle impact assessment methodologies, and scientific literature.

Chemical: A substance produced by or used in a chemical process. A chemical is any element, chemical compound or mixture of elements or compounds. Chemicals are the constituents of materials. A chemical "mixture," also known as a chemical "preparation," includes multiple chemicals.

Closed-loop system design: Closed-loop system design reuses resources so that waste generation is reduced or eliminated. Resource requirements such as energy, chemicals and materials, and water are also drastically minimized or eliminated.

Contingent cost: Costs that might occur in the future as a result of decisions made today or future events (e.g., litigation, site remediation, hospitalization, disability, increased cost or unavailability of resources). These costs are classified as a type of internal cost to the DoD.

Cost cluster: A group of costs that, when taken together, comprise a significant portion or majority of the LCC in a given alternative. Most often, an individual cost within the group cannot be eliminated unless the entire group of costs is eliminated. For example, the costs associated with personal protective equipment, hazardous waste, and environmental controls in the workplace cannot be eliminated unless all hazardous chemicals and materials that drive those costs are also eliminated from the workplace environment. In this example, the elimination or substitution of a single chemical may not affect total LCC.

Cost-effective: An alternative is cost-effective if it has a lower net life cycle cost than other alternatives after considering any differences in performance and including all internal and external costs related to impacts.

Deployment: A life cycle stage of the Production & Deployment Phase in the Integrated Defense Acquisition, Technology, and Logistics Life Cycle Management System that falls within the Sustainability Analysis study boundary discussed in this guidance.

Disability Adjusted Life Year (DALY): A measure of overall disease burden, expressed as the number of person-years lost due to ill-health, disability, or early death. The DALY relies on an acceptance that the most appropriate measure of chronic illness impact is time; both time lost due to premature death and time spent disabled by disease.

Disposal: A life cycle stage of the O&S phase in the Integrated Defense Acquisition, Technology, and Logistics Life Cycle Management System that falls within the Sustainability Analysis study boundary discussed in this guidance. Disposal (end-of-life) management activities include decommissioning, demilitarization, disposal, re-using, re-purposing, recycling, incinerating, and land filling.

Direct energy: The amount of energy required to operate a system throughout its life cycle, including energy required by all subsystem components.

Direct Water: The amount of water required to operate a system throughout its life cycle, including water required by all subsystem components.

Economic Input-Output (EIO) LCA: The EIO-LCA method estimates the resource inputs required for, and the environmental emissions resulting from, activities in our economy. This method uses accounting data (e.g., purchase orders, operation and maintenance bills, etc.) and industry-specific economic and environmental information to estimate the materials and energy sources required for, and the environmental emissions resulting from, upstream activities in the economy. Results from using the EIO-LCA quantify the upstream impacts embedded in the procurement of raw materials, components or parts throughout the life cycle stages of the system.

Emission factor: A measure of the average quantity of a specific pollutant or material discharged into a particular environmental medium (e.g., air, soil and water) by a specific process, fuel, equipment, or source. It is important to note that an emission factor provides a quantitative measure of the expected intensity of emissions associated with a specified activity. For example: kilograms of carbon dioxide emitted per gallon of diesel consumed by an internal combustion engine used to power a stationary generator.

Emission profile: An estimated inventory of the quantity of all chemical compounds emitted during a specified activity or process. When applicable, equipment controls that reduce the total quantity of emissions (e.g., air filtration) should be accounted for when developing an emission profile.

External cost: Costs borne by society or organizations outside of DoD as a result of pollutant emissions, waste disposal, human heath degradation or resource consumption during the lifetime of the system.

External cost factor: An indexed unit that assigns a standardized monetary value to a specified endpoint impact category.

Functional unit: The functional unit defines the identified functions (performance characteristics) of a system. The primary purpose of a functional unit is to provide a reference for which the inputs and outputs of a specified system are related. This reference is necessary to ensure comparability of Sustainability Analysis results across alternative systems. For a further explanation please see ISO 14040 and 14044.

Hazardous chemical or material: Any item or substance that, due to its chemical, physical, toxicological, or biological nature, could cause harm to people, equipment, or the environment (see MIL-STD 882E) or for which a facility must maintain a safety data sheet.

Impact category: A standalone category representing a potential impact to the resource availability, human health, or the environment resulting from a system's LCI. Impact categories are defined by the impact resulting from the inputs and processes that occur as a result of the LCA, as quantified by an impact indicator (e.g., global warming, human toxicity) and its associated unit of measure (e.g., kg CO_2eq, CTU_h).

Incremental land use: An area of undeveloped land that would be developed for the purpose of supporting activities directly or indirectly tied to the newly acquired system (e.g., system use, basing, maintenance, system support infrastructure). The term incremental implies that this land would only be developed as a result of acquiring the new system or alternative.

Indirect energy: The amount of energy required to produce, sustain (e.g., maintain, transport, decommission) and protect the system, excluding any energy needed to directly operate the system (direct energy).

Indirect water: The amount of water used to produce, sustain (e.g., maintain, transport, decommission) and protect the system, excluding any water needed to directly operate the system (direct water).

Integrated Product Support (IPS) Elements: The package of support functions required to deploy and maintain the readiness and operational capability of major weapon systems, subsystems, and

components, including all functions related to weapon systems readiness. IPS Elements are functional components of a weapon system's product support infrastructure. These elements support sustainment planning and execution throughout a system's entire life cycle, translating force provider capability and performance requirements into tailored product support.

Internal cost: Costs borne by the DoD during the lifetime of the system. These costs include direct costs (e.g., materials, fuel, labor), indirect costs (e.g., overhead) and hidden costs that may not be typically allocated to a system under traditional cost accounting methodologies (e.g., personal protective equipment, medical monitoring, permitting).

Inventory element: Any system input (energy, chemicals, materials, water, and land) or output (chemical and noise emissions) that occurs within the system boundary.

Legacy system: Legacy systems are considered systems already passed Milestone B, but may be undergoing notable modifications or revised operation and maintenance procedures.

Life cycle assessment (LCA): The compilation and evaluation of the inputs, outputs, and the potential impacts to human health and the environment of a system throughout its life cycle. LCA is a technique used to assess the environmental aspects and potential impacts associated with a product, process, or service, by (1) compiling an inventory of relevant energy and material inputs and environmental releases, (2) evaluating the potential environmental impacts associated with identified inputs and environmental releases, and (3) interpreting the results to inform decision making.

Life Cycle Inventory (LCI): A life cycle inventory involves creating an inventory of flows from and to the environment for weapon systems, platforms or equipment. Inventory flows include inputs of water, energy and raw materials, and releases to air, land and water.

Life Cycle Impact Assessment (LCIA): The LCIA phase of an LCA is the evaluation of potential human health and environmental impacts of the environmental resources and releases identified during the LCI. Impact assessment should address ecological and human health effects, and consider resource depletion. A life cycle impact assessment attempts to establish a linkage between the system or process and its potential impacts.

Material: Anything that serves as crude or raw matter to be used or developed**.** A material is the basic matter (as metal, wood, plastic, fiber) from which the whole or the greater part of something physical (as a machine, tool, building, fabric) is made. Chemicals are the constituents of materials. For example, human-made materials like petroleum-based plastics are synthesized from chemicals.

Materiel solution: Correction of a deficiency, satisfaction of a capability gap or incorporation of new technology that results in the development, acquisition, procurement or fielding of a new item necessary to equip, operate, maintain and support military activities without disruption as to its application for administrative or combat purposes. In the case of a family of systems and system of systems approaches, an individual materiel solution may not fully satisfy a necessary capability gap on its own.

Mission critical: Any function for which if compromised would degrade the system effectiveness in achieving the core mission for which it was designed. See Glossary, Part II, of DoDI 5200.44.

Mission Task (MT): Any general task to be performed or effect to be achieved (e.g., hold targets at risk, provide countermeasures against surface-to-air missiles) derived directly from the capability requirements identified in the ICD or CDD. See 6.1.1 of the *Air Force Analysis of Alternatives (AoA) Handbook: A Practical Guide to Analyses of Alternatives*.

Noise: unwanted or disturbing sound.

Non-renewable energy: Energy from a source that cannot be replenished naturally within human timescales (e.g., 100 years).

Office of Cost Assessment and Program Evaluation (CAPE): CAPE provides independent analytic advice to the Secretary of Defense on all aspects of the Defense program, including alternative systems and force structures, the development and evaluation of defense program alternatives, and the cost-effectiveness of defense systems.

Operations and Support (O&S): A life cycle phase in the Integrated Defense Acquisition, Technology, and Logistics Life Cycle Management System that falls within the Sustainability Analysis study boundary discussed in this guidance. This phase includes activities such as system operations, support for the system, sustainment, and disposal.

Operational space: Land use that includes, but is not limited to, areas where military operations are conducted (e.g., theater). This type of land should not be included in the evaluation of alternatives using LCA methods for assessing impact to land.

Potentially Disappeared Fraction (PDF) of species: Usually associated with a unit of area (m^2, acre, etc.) and time (years), this metric characterizes the fraction of species expected to disappear on a specified area of earth surface, as a result of exposure to stressors, over a specified period of time. PDF is a measure of impact to biodiversity. For example, an environmental health score of 0.2 PDF/m^2/yr implies the loss of 20% of species, from exposure to a system release, on one squared meter of earth surface in one year.

Production: A life cycle stage of the Production and Deployment phase in the Integrated Defense Acquisition, Technology, and Logistics Life Cycle Management System that falls within the Sustainability Analysis study boundary discussed in this guidance.

Raw material acquisition: A life cycle stage typically included within LCA, and sometimes Sustainability Analysis. Raw material acquisition includes harvesting and processing natural resources from the environment.

Recycle: A substance is considered recyclable if it is captured as waste and reprocessed to create a new product for a new application.

Renewable energy: Energy from a source that can be replenished naturally within a relatively short period of time. Renewable energy comes from renewable sources that are captured from on-going natural processes, including, but not limited to: sunlight, wind, tidal dynamics, photosynthesis, and geothermal heat flows.

Reuse: A chemical, material, or object that is used for another application, usually after refurbishing, once the lifespan of the original application is exhausted.

Scoring Factor: An indexed unit that allows the analyst to quickly estimate the level of impact for a given impact category by multiplying that factor by the quantity of a specified resource input or emission output. A scoring factor combines the aggregation of all relevant emission factors needed to estimate outputs from a specified procurement cost (upstream impacts) or input quantity (downstream impacts) and the characterization factor needed to convert that output to appropriate impact indicator units. Endpoint scoring factors are also used to translate midpoint impacts into endpoint impacts.

Stressor: Any substance that flows through the work or natural environment and causes stress to resource availability, human health, or environmental health. Exposure to stressors is caused by human activities (e.g., emissions and resource consumption).

Sustainable acquisition: Acquisition conducted in a manner that results in a system design that minimizes impacts on resource availability, human health, and the environment while meeting performance parameters.

Sustainability: The durable and self-sufficient balance between social, economic, and environmental factors. In the context of the DoD acquisition process, sustainability involves the wise use of resources and the minimization of corresponding impacts and costs during the life cycle.

Sustainability Analysis: Within the context of this document, a Sustainability Analysis comprises both a Life Cycle Assessment, which evaluates human health and environmental impacts, as well as Life Cycle Costing, which captures life cycle costs of a system, product, or process.

Sustainability-related cost: Any cost (internal, external, or contingent) over a system's life cycle that is associated with the consumption of resources or the resulting impacts from such consumption, as identified by a Sustainability Analysis. Sustainability-related costs and sustainment costs are intertwined. A Sustainability Analysis helps uncover additional sustainability-related costs that may not have been considered using traditional sustainment costing methods.

Sustainable design: Implementation of sustainable elements in new product systems. These elements may include the use of low-impact materials, optimization of system-wide energy and water consumption, minimization of waste products through closed-loop design, and reduction of pollution emissions throughout the life cycle of the system.

Sustainment: Sustainment involves the supportability of fielded systems and their subsequent life cycle product support - from initial procurement to supply chain management (including maintenance) to reutilization and disposal. It includes sustainment functions such as initial provisioning, cataloging, inventory management and warehousing, and depot and field level maintenance.

Support system: Any system or subsystem that supports the system of interest in a manner that ensures that the function is met.

Support activity: Any activity tied to a specified support system that falls within the established system boundary.

System: Any weapon system, equipment, or platform acquired by the DoD to achieve a capability requirement, as defined by the ICD or CDD.

System activity: Any activity tied to a specified system element that falls within the established system boundary.

System boundary: A set of criteria specifying which activities are included as part of an acquired system's life cycle. The system boundary comprise the unit processes or activities that will be included within a Sustainability Analysis and should be consistent with the stated goal of the assessment.

System element: Any element composing the system of interest; including subsystems, components, parts and resource inputs.