Department of Defense Guidance

Sustainability Analysis Guidance:

Integrating Sustainability into Acquisition Using Life Cycle Assessment

Supplemental: Superstructure Alternatives Example

Current Version

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Acronym Listing

C&M	Chemicals and Materials
CAS	Chemical Abstracts Service
ft^2	square foot/feet
kg	kilogram(s)
kWh	kilowatt-hour(s)
LCAP	Life Cycle Activity Profile
LCC	life cycle cost
LCCA	life cycle cost analysis
LCI	Life Cycle Inventory
OMB	Office of Management and Budget
SA	Sustainability Analysis
SLCA	streamlined lifecycle assessment
SLD	Straight-Line Depreciation

Supplemental: Superstructure Alternatives Example

Introduction

This document provides a hypothetical example developed to illustrate each step of the Sustainably Analysis (SA) described in the U.S. Department of Defense's (DoD's) Sustainability Analysis Guidance: *Integrating Sustainability into Acquisition Using Life Cycle Assessment*, Version 5.0. Although this notional example is intended to be realistic in nature, it should be noted that the main intent of this example is to demonstrate all aspects of completing a streamlined lifecycle assessment (SLCA), including less common analytical nuances such as the use of allocation methods for quantifying the value of land use impacts, recycled content and differences in system life. As such, some design and operational elements have been altered or exaggerated to more clearly demonstrate these nuances.

An example SLCA model (see excel sheet) was developed to complement the steps discussed in this alternative example. The excel file model provides a structured template for (1) defining key study parameters, (2) organizing life cycle inventory (LCI) data, (3) calculating impacts and associated external costs, (4) quantifying life cycle internal and external costs and discounting those costs to base year dollars for equal comparison, and (5) visually presenting analytical results. All data and calculations in the SLCA model mirror the written explanations contained herein. Throughout the written example in this supplement, the sections below frequently draw reference to specific elements in the SLCA model to provide supporting visual examples to enhance the overall explanation. All data elements in the example model are labeled with a unique row and column number for easy reference.

Step 1 - Define the Scope of the Analysis

Goal

The goal of this example is to perform an integrated SA, including both a streamlined life cycle assessment (SLCA) and a life cycle cost analysis (LCCA), to compare two material alternatives for a noncombat ship's superstructure. The superstructure includes the parts of a ship that project above the ship's main deck.

Functional Unit and Reference Flow

The superstructure provides shelter while the ship transports passengers across the ocean. For comparative purposes, the system's function is characterized as the transport of 220 passenger cabins, 270 days per year, over the ship's expected life of 25 years. The reference flow for both alternatives is one unit of ship superstructure, and all LCI data for this study are normalized to this unit.

Alternatives

In this example, two alternatives are considered, an all-metal (metal) superstructure and a composite superstructure. The metal alternative mainly comprises a coated aluminum and steel exterior facing with interior steel support. The composite alternative comprises a sandwich composite construction also supported by an internal steel structure. Due to differences in weight between the aluminum-based and composite-based exterior, the composite alternative requires less steel support, further reducing the overall weight of the structure when compared to the metal alternative. In this model, this weight change is assumed not to affect the ship structure itself, though it does affect fuel consumption.

Performance Requirements

For this demonstration, it is assumed both alternatives equally meet all performance requirements.

Assumptions

The following assumptions are considered for both alternatives:

- 20 ships (parent system) are being considered for acquisition.
- The superstructure is for a non-combat vessel. Therefore, no armoring is needed.
- Each alternative considered makes the identical number and type of trips and carries identical loads.
- The total square footage (ft^2) of the exterior facing for each ship is assumed to be 101,325 ft^2.
- The ships are produced in Connecticut.
- Ship sustainment occurs in Virginia.
- The ships are used for transatlantic travel.
- The reference year for this study is 2014, which is the year ship construction was finalized.
- All operations begin in year 2015.
- A corrosion resistant coating is applied to the steel-based structural support during manufacturing. The internal steel structural support for both alternatives is not exposed to the harsh saltwater conditions, and thus periodic recoating is assumed to be unnecessary.
- The same assembly processes are used to join the metal superstructure and the composite superstructure to the ship's hull.
- In accordance with Office of Management and Budget (OMB) Circular A-94, Appendix C, a 25-year real internal discount rate of 2.8% is applied to internal costs occurring in out years.[1] See section 3.2.1 of the SA for additional guidance.
- A real social discount rate of 3.0% is applied to external costs occurring in out years. See section 3.2.1 of the SA for additional guidance.

The following additional assumptions are considered for the metal alternative:

- The useful life of the metal superstructure is 25 years.
- The metal superstructure consists of steel support (850,000 kilograms [kg]) with a steel (1,200,00 kg) and aluminum (310,000 kg) exterior facing.
- The exterior facing of the metal superstructure must be recoated every 5 years, resulting in 4 coating replacements during sustainment to satisfy the functional unit.

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[1] Discount rates reported by Appendix C of OMB Circular A-94 are updated annually. The discount rate used in this example reflects real discount rate reported in FY2014. Per the guidance in the circular, the discount rate of 25 years was estimated by taking the average of the reported 20-year and 30-year discount rates.

- The exterior facing of the metal superstructure must be power washed once per week, resulting in 52 washes per year, or 1,300 washes to satisfy the functional unit.
- The aluminum used in the exterior facing of the metal superstructure (310,000 kg) is purchased as virgin aluminum and assumed to be recycled at the end of the ship's life. The value of the recycled aluminum in a secondary market results in revenue and the recycled content offsets impacts associated with the primary production of aluminum. The monetary value received for the recycled aluminum in the secondary market, referred to as market value, and all offset impacts are credited back to the system using a system expansion/displacement allocation method based on monetary value (e.g., revenue). Revenue received from the sale of the aluminum scrap in a secondary market and the impact reduction associated with the recycled aluminum are recorded as a negative impact and cost (credit) in the last year of the life cycle cost (LCC) model.

The following additional assumptions are considered for the composite alternative:

- The useful life of the composite superstructure is 30 years, which is an additional 5 years of life when compared to the metal alternative. This additional life displaces the need to purchase a new system for 5 years beyond the functional unit lifetime, thus offsetting the impacts and associated costs of its primary production. Since the functional unit is capped at 25 years, the remaining 5 years of additional life occurs outside of the system boundaries and is therefore counted as residual value. This residual value, and its associated impacts, is calculated using a system expansion/displacement allocation method based on monetary value and recorded as a negative cost (credit) in the last year of the LCC model.
- The composite superstructure is a sandwich composite construction (total mass of 1,246,050 kg) that consists of two glass fiber-reinforced polymer (FRP) laminate on each side of a core of lightweight polyvinyl chloride (PVC) foam with steel support (696,000 kg).
- The composite superstructure must be power washed once per month, resulting in 12 washes per year, or 300 washes to satisfy the functional unit.
- A new thermoforming facility is required for the composite alternative to mold the composite material during production. The new 1,000,000-ft^2 facility, which is an expansion of the existing ship manufacturing facility, is assumed to be built in Connecticut on acres of temperate broadleaf forest. The facility construction and land use impacts associated with this facility will be allocated across the 20 acquired ships, therefore only an area of 50,000 ft^2 (1,000,000 ft^2 /20 ships) will be allocated to the functional unit. Additionally, land occupation impacts compound over time, and thus the duration of land use by the facility is also required. The facility is expected to occupy the land for 30 years to support the sustainment of the composite superstructure over its useful life. However, the functional unit is only 25 years, so only 25 years of land occupation is considered for the study. The facility's resulting total land use occupation per functional unit is therefore 1,250,000 ft^2-years (50,000 ft^2 x 25 years).

Life Cycle Activity Profile (LCAP)

An LCAP was completed for each alternative (see Tables 2 and 3 below) to streamline 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, climate change, human health, and ecosystem quality.

Completion of an LCAP 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 and costs

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 result in the greatest impact and cost.

Alternatives can be classified into one of four activity descriptor groups (Table 1 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 1. Examples of systems organized by energy activity descriptors

Activity Descriptor Group	Stationary	Mobile
Active	Heating, ventilation and air conditioning (HVAC) System, Water Purification System	Aircraft, Ground Vehicle, Ship
Passive	Satellite Dish, Barricade Infrastructure	Trailer, Satellite, Bomb

Per the definitions above, the ship superstructure is a stationary and passive system. However, the superstructure is a component of a larger parent system (the ship) that is classified as an active and mobile system. Since the system boundaries are extended to the ship (see detailed discussion in System Boundaries section), the activity descriptors assigned to the ship are used to inform the LCAP.

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.

- Energy: Active 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. Whereas passive systems typically consume little to no energy during operation, and thus energy use is dominated by upstream manufacturing and downstream sustainment activities.

  Superstructure Example: Both alternatives in this example are components of an active and mobile parent system (ship), implying that differences in energy use will be dominated by the use stage.

- Chemicals and Materials (C&M): The largest inventory (number) and amount (quantity) of C&M are typically consumed during manufacturing and sustainment, regardless of the activity descriptor classification. Systems exposed to harsh operating conditions that lead to significant wear and tear (e.g., active or mobile systems) or have a longer lifespan will typically require greater use of chemicals and materials during sustainment.

  Superstructure Example: Both alternatives have significant, yet different, C&M requirements in the manufacturing stage. For example, both alternatives require coated steel for the internal structure, but the composite alternative requires less steel support due to its lightweight exterior. The C&M requirements for the two alternatives are also considerably different in the sustainment stage. For example, the exterior facing of the metal superstructure requires periodic recoating, whereas the exterior facing of the composite alternative does not.

- Water: Active systems typically consume the most water for operation, cleaning or maintenance purposes, whereas water consumption for passive systems is typically dominated by manufacturing. 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 or sustainment (e.g., cleaning or maintenance) is often dominated by manufacturing.

  Superstructure Example: Both alternatives in this example are components of an active and mobile parent system (ship), implying that differences in water use will be dominated by the sustainment stage. Water requirements for the two alternatives are different in the sustainment stage in that the aluminum exterior of the metal alternative requires more frequent power washing than the composite alternative.

- Land: For most systems, regardless of their activity descriptors, incremental land use requirements are typically greatest during manufacturing, operations and sustainment. 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. Land requirements during operations and sustainment are typically more relevant for active or mobile systems.

  Superstructure Example: Both alternatives in this example are components of an active and mobile parent system (ship) that requires incremental land use at all porting locations.

However, this incremental land use during operations and sustainment is equivalent across the two alternatives and thus excluded from this comparative analysis. There is a difference in land requirements between the two alternatives in the manufacturing stage, where a new thermoforming facility is required for the composite alternative to mold the composite material during production.

- Noise: Active systems typically produce some level of noise during operation, whereas passive systems typically do not. Furthermore, sound-producing stationary systems generate noise that is concentrated in a particular location, whereas the noise produced by mobile systems travels during the operation of the system.

  Superstructure Example: Both alternatives in this example are components of an active and mobile parent system (ship) that does produce noise during operation. However, the noise generated by the ship does not result from the components being evaluated (superstructure) and thus is excluded from boundaries of this comparative analysis. There is a difference in noise between the two alternatives in the sustainment stage, where the metal alternative requires more frequent power washing than the composite alternative. This difference in noise from power washing is included in the analysis.

3. Identify activities that likely have dominant contributions to impacts

Tables 2 and 3 demonstrate the use of a standard template for completing the LCAP. As demonstrated, the activities identified above are recorded in the cell that corresponds to the appropriate inventory element and life cycle stage. After entering all activities into the table, each cell has been qualitatively classified as High, Medium (Med.), Low, or No Impact with respect to likely importance for the analysis (i.e., most likely to result in greater impact and associated costs). These classifications are listed at the bottom of each cell in parenthesis.

Once completed, the LCAP template guides data collection by identifying when resources are consumed, chemicals are released and noise is emitted; as well as which activities drive those results. Doing so focuses data collection efforts on activities that are most material in terms of total impact and associated costs.

Table 2. Qualitative LCAP for Metal Superstructure

LCI Element	**Life Cycle Stage: Production & Deployment (Investment)**	**Life Cycle Stage: Operation (Including Support Systems)**	**Life Cycle Stage: Sustainment**	**Life Cycle Stage: Disposal**
Energy	Electricity for metal working and coating application (Min. Impact)	Fuel oil combustion in ship (parent system) (High Impact)	Electricity for coating removal and application and power washing (Min. Impact)	N/A, equivalent across alternatives (N/A)
Water	Metal working (Min. Impact)	N/A, equivalent across alternatives (N/A)	•Coating removal and application •Power washing (Low Impact)	Hazardous water generated during manufacture and sustainment (Med. Impact)
Chemicals & Materials	•Steel, aluminum, paint, primer, air filters, and personal protective equipment •Emissions from metal working and coating application (Min. Impact)	N/A, equivalent across alternatives (N/A)	•Paint, primer, air filters, cleaning solution for power washing, and personal protective equipment •Emissions from metal working and coating application (Med. Impact)	Hazardous waste generated during manufacture and sustainment (e.g., air filters, personal protective equipment) (Low Impact)
Land Use	N/A, no incremental land (N/A)	N/A, no incremental land (N/A)	N/A, no incremental land (N/A)	N/A, equivalent across alternatives (N/A)
Noise	N/A, equivalent across alternatives (N/A)	N/A, equivalent across alternatives (N/A)	Power washing (Min. Impact)	N/A, equivalent across alternatives (N/A)

Table 3. Qualitative LCAP for Composite Superstructure

LCI Element	Life Cycle Stage: Production & Deployment (Investment)	Life Cycle Stage: Operation (Including Support Systems)	Life Cycle Stage: Sustainment	Life Cycle Stage: Disposal
Energy	Electricity for metal working and coating application (Min. Impact)	Fuel oil combustion in ship (parent system) (High Impact)	Electricity for coating removal and application and power washing (Min. Impact)	N/A, equivalent across alternatives (N/A)
Water	Metal working and thermoforming (Min. Impact)	N/A, equivalent across alternatives (N/A)	Power washing (Low Impact)	N/A, no incremental disposal (N/A)
Chemicals & Materials	•Steel, paint, primer, air filters, mineral wool, glass fiber, polyester, epoxy, polyurethane foam, and personal protective equipment •Emissions from metal working, thermoforming and coating application (Min. Impact)	N/A, equivalent across alternatives (N/A)	Cleaning solution for power washing (Med. Impact)	N/A, no incremental disposal (N/A)
Land Use	New thermoforming facility (Low Impact)	N/A, no incremental land (N/A)	N/A, no incremental land (N/A)	N/A, equivalent across alternatives (N/A)
Noise	N/A, equivalent across alternatives (N/A)	N/A, equivalent across alternatives (N/A)	Power washing (Min. Impact)	N/A, equivalent across alternatives (N/A)

System Boundaries

The primary design difference between the two alternatives is the materials used and the resulting manufacturing and sustainment processes required to construct and maintain the superstructure. The difference in density between the alternatives causes the ship's weight to vary, leading to a difference in fuel efficiency. Therefore, the system boundaries for the study are expanded to the parent system (the ship) to capture these differences in fuel consumption during operation. In addition, superstructures made of different materials require different sustainment activities. To compare the material differences across the alternatives, the activities associated with producing, using, and disposing of these materials and the resulting differences in sustainment activities are also considered in the analysis. All other activities and inputs associated with ships' life cycles are assumed to be equivalent for both alternatives and are therefore excluded from the system boundaries.

Figure 1 provides an illustration of the system boundaries for the metal superstructure. During production, the superstructure's exterior facing is assembled using procured pre-fabricated steel and aluminum components that are joined to the interior steel support. The assembly process includes metal working activities such as drilling, grinding and joining (e.g., welding). A corrosion inhibiting powder coating system, including primer and paint, is applied to the exterior of the superstructure during production to provide corrosion protection. Mineral wool batts are also installed to provide fire, thermal, and acoustic insulation. During operation, residual fuel oil (No. 6) is combusted to power the ship. During sustainment, the superstructure's exterior coating, which is exposed to harsh saltwater conditions, must be removed and reapplied every 5 years. To prevent corrosion and the need for additional coating applications, power washing of the exterior facing is required once a week. During disposal, the exterior aluminum facing is recycled and sold in secondary market and all other components are treated as waste sent to landfill.

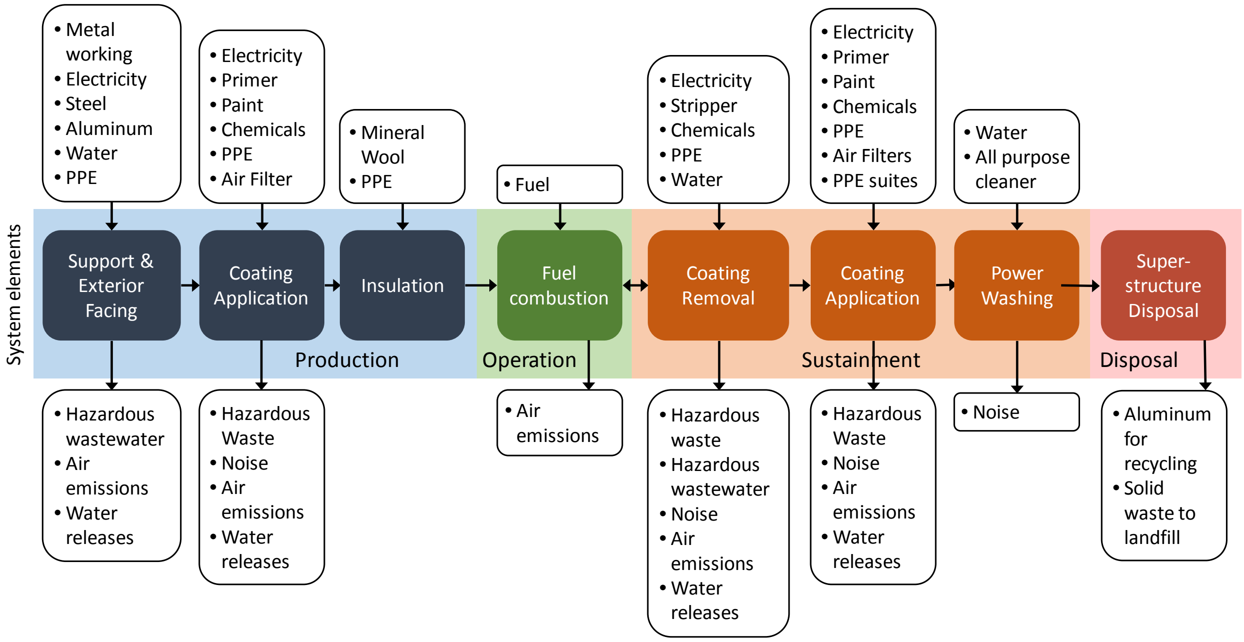

Figure 1. System Boundaries for the Metal Superstructure

The metal superstructure's recycled aluminum results in revenue generation and reduced impacts. The system boundary is expanded to include the reduction of impacts and costs associated with the market value of the recycled aluminum. The monetary value received for the recycled aluminum in the secondary market, referred to as market value, and all offset impacts are recorded as credits (negative impacts and costs) and subtracted from the alternative's system total impacts and costs using a monetary allocation method (see Box 1 for further explanation of how to allocate impacts and costs of reused or recycled materials).

As Figure 2 demonstrates, the system boundaries for the alternative composite system differ from the baseline metal superstructure in the production, sustainment and disposal stages of the life cycle. During production, the superstructure's composite exterior facing is manufactured using a newly constructed thermoforming facility, whose construction and resulting use of land is included in the boundary. The assembly process for the composite alternative requires fewer metal working activities when compared to the metal superstructure, including less intensive drilling and grinding to fasten the composite exterior facing to the internal steel support, as well as less joining (e.g., welding) due to reduced steel support required for the interior structure. Like the steel superstructure, the composite alternative requires the installation of mineral wool batts to provide fire, thermal, and acoustic insulation. Unlike the steel superstructure, the composite alternative does not require the application of a corrosion resistant coating for the exterior facing in the manufacturing or sustainment stages. During operation, the reduction in weight compared to the steel superstructure results in greater fuel efficiency and a reduction in residual fuel oil (No. 6) combustion. During sustainment, the composite alternative does require power washing once a month, but this is much less than its steel counterpart. Lastly, all components for the composite alternative are treated as waste and set to landfill during disposal.

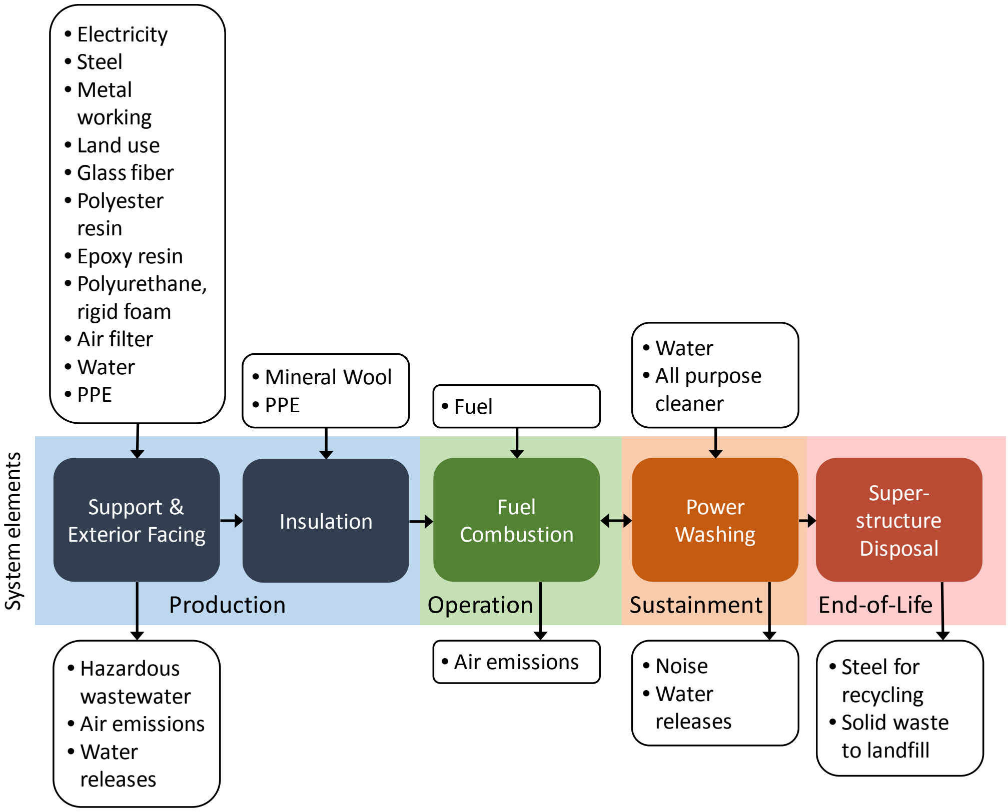

Figure 2. System Boundaries for the Composite Superstructure

As stated in the assumptions section, the composite superstructure has an expected life of 30 years. This additional life displaces the need to purchase a new system, thus offsetting the impacts and associated costs of its primary production. Since the functional unit is capped at 25 years, the remaining 5 years of additional life occurs outside of the system boundaries and is therefore counted as residual value (impact and cost credit) recorded in the last year of the LCC model (see Box 2 for further explanation of how to allocate impacts and costs associated with system life that occurs outside of the system boundaries).

Box 1: Allocating benefits from reused and recycled material

Reused or recycled system components and waste streams result in hidden value. The activity generating the reusable or recyclable material should be given a credit to offset impacts and costs associated with that value. Reusing and recycling material alleviates the need to harvest virgin material or purchase the material altogether, thus displacing the impacts and costs associated with raw material extraction and processing, though impacts and costs associated with collection and reprocessing of reused material must be included. However, modeling the benefits of reuse and recycling is susceptible to double counting. For example, double counting would occur if a credit were given to both the original system that contains reusable or recyclable materials and the unknown second system that uses that material as a system input. Properly dividing impacts between the original system—the system that is the focus of the SA—and the unknown second system can be challenging. There are two waste management allocation errors to avoid:

1) Not incorporating an impact or cost benefit for reuse and recycling
2) Overvaluing the benefit of reuse and recycling by effectively allocating away impacts and costs to an unknown second system.

All credits associated with reused or recycled material should be allocated back to the original system to avoid these common errors and maintain consistency in results across alternatives. To avoid overvaluing the benefits of recycling and reuse, the market (monetary) value of the waste material is used to distribute these benefits back to the original system.

Market value for reused or recycled system components and resulting waste is quantified as the monetary value of the material in a secondary market. For example, system A produces plastic water bottles that are recycled at the end of life. System B uses the recycled plastic to make another product. The market value of recycled water bottles will be the value of plastic resin in the secondary materials market. Impacts resulting from the production of plastic resins used in system B represent the displaced impacts—not the impacts associated with the actual production of the plastic water bottles. This same procedure should be used for all reused or recycled material to ensure consistency in the analysis. To accurately account for the impacts of recycled materials, the analyst should research the industry sector for which the reused or recycled materials are displacing production. The industry sectors will vary according to type of plastics, metals, glass, etc.

When the market value for reused or recycled material is unknown, it can be estimated as the remaining value of the material after depreciation. When the appropriate depreciation method is unknown, use the Straight Line Depreciation method to approximate the market value (see note in Box 2 for further explanation). Impacts are allocated and displaced according to an allocation partitioning factor, which is calculated by dividing the market value by the material's initial value. Impacts associated with the material's market value—calculated by multiplying the material's life cycle impacts by the allocation partitioning factor—should be subtracted from the system's total life cycle impacts. For costing purposes, the resulting impacts and associated costs should be recorded in the year the reuse or recycling occurs and discounted back to the reference year.

Box 2: Allocating benefits from system life occurring outside of the system boundaries

Alternatives within a study often have different life spans. Ideally, the functional unit will represent the lowest common denominator for the life spans across all alternatives. However, it is not always possible to find a lowest common denominator for all alternatives. As such, the life span of some systems will exceed the study period and fall outside the study boundaries. If an alternative has value beyond the study period, an impact and cost credit should be granted to that alternative.

A hybrid method of system expansion/displacement and allocation using monetary value is most appropriate when the life span of a system extends beyond the study period. In this case, the additional useful life (residual value) of the system displaces the need to purchase a new system, thus offsetting the impacts and associated costs of its primary production. The residual value of the system is used to calculate the allocation partitioning factor, which is calculated by dividing the residual value by the system's initial value. The residual value is estimated as the remaining value of the system at the end of the study period, after accounting for depreciation. Impacts are allocated and displaced according to the allocation partitioning factor. For costing purposes, the resulting impacts and associated costs should be recorded in the final year of the analysis and discounted back to the reference year.

NOTE: When the appropriate depreciation method is unknown, use the Straight-Line Depreciation method to approximate the residual value. The Straight-Line Depreciation (SLD) method simply reduces the value of the system each year by a depreciation factor equal to the initial system value divided by its expected life. For example, a system with an initial value of $1,000,000 and an expected life of 10 years would depreciate $100,000 each year [$1,000,000 / 10 years]. Using this example, the remaining value of the system after 8 years would then be $200,000 [$1,000,000 – ($100,000 * 8 years)]. Using the SLD, the resulting allocation partitioning factor for this example would then be 0.2 [$200,000/$1,000,000].

The allocation partitioning factor using the SLD method can also be derived without know the value of the system. In such cases, the number of years of residual life can be divided by the total expected system life to derive the allocation partitioning factor. In the example above, this calculation would also result in an allocation partitioning factor of 0.2 [2 years of residual life / 10 years of expected system life].

Step 2 – Develop a Life Cycle Inventory (LCI)

The LCI is created by recording all relevant inputs and outputs of the system and their associated costs in a structured data table for use during the Life Cycle Impact Assessment and Life Cycle Cost Analysis. When developing the LCI, these inputs, outputs and associated costs should be normalized to the functional unit and allocated to the appropriate system element and corresponding activities occurring within that system element (see Tables 2 and 3 in Step 1).

A recommended format for the LCI and sample data entries can be found in the example SLCA model (see the "Step 2 - LCI" worksheet in excel file). A description of each data element recorded in the example SLCA model is provided in the sections below.

System Descriptors:

System descriptor data are used to properly classify inventory data and allocate such data to the appropriate alternative and system element within that alternative. System descriptor data can be used for data disaggregation, chart building and other reporting functions. The system descriptor data elements and their column location in the example SLCA model (see the "Step 2 - LCI" worksheet in excel file) are described below.

- Alternative (column 1): Identifies the alternative for which the inventory item is associated.
- Life Cycle Phase (column 2): Identifies the life cycle phase for which the inventory item is associated.
- System Element (column 3): Identifies the system element (see Figures 1 and 2 in Step 1) that requires the inventory item.

Activity Data:

Activity data are used to define the activity for which each inventory item composes and drives how much of the inventory item is needed to satisfy the functional unit. Activity data can be used for data disaggregation, chart building and other reporting functions.

To simplify calculations required for the Life Cycle Impact Assessment (Step 3) and the Life Cycle Cost Analysis (Step 4), it is recommended that all inventory item data be normalized to an amount per year. This is achieved by defining the *Number of Activity Instances Required in a Year* (see below for further explanation) necessary to satisfy the functional unit. Doing so allows the analyst to multiply this amount by the inventory data (further explained in the Inventory Item Data section) to calculate the total amount of the inventory item required in a year. As discussed in greater detail in Steps 3 and 4, this data normalization allows the analyst to record impacts and their associated external costs in time, which can then be discounted back to base year currency; creating a fair comparison across alternatives.

The activity data elements and their column location in the example SLCA model (see the "Step 2 - LCI" worksheet in excel file) are described below.

- Activity (column 4): Describes the underlying activity requiring the inventory item input or releasing the inventory item output.
- Activity Reference Flow (column 5): Describes the activity-level reference flow for the activity for which the inventory item is required/released (see section 3.2.2 of the SA guidance).
- Activity Reference Flow Amount (column 6): Clarifies the amount of the activity, in reference flow units, required by the relevant system element for a single activity instance.
- Activity Reference Flow Unit (column 7): Identifies the unit of measure for the activity-level reference flow.
- Number of Activity Instances Required in a Year (column 8): Identifies the number of instances the system element requires in a year.
- Number of Activity Instances Required for the Functional Unit (column 9): Identifies the number of instances the system element requires over the functional unit, which can be calculated by multiplying the "Number of Activity Instances Required in a Year" by the study period.

Inventory Item Data:

Inventory item data are used to define each process input or output of interest and allocate inputs and outputs to the appropriate system activities. In these fields, the analyst first defines the input or output by providing a user-defined item description, and then quantifies how much of the item is required to meet the activity-level reference flow. The total amount of each input or output per functional unit can therefore be calculated as the amount per activity-level reference flow multiplied by the amount of the activity required to satisfy the functional unit.

Next, the analyst then matches that item data to the model data provided in the Scoring Factor Database. In this step, key characteristics of the inventory item (e.g., *inventory element, item classification, relevant industry, CAS number, location and environmental compartment*) are used to match preprocessed model data (scoring factors) to the observed input or output. This step also requires unit conversions for physical flows and currency conversions for item prices to ensure proper translation of scoring factors into impacts during the life cycle impact assessment (see Step 3) and external and internal costs during the LCCA (see Step 4).

The inventory item data elements and their column location in the example SLCA model (see the “Step 2 - LCI” worksheet in the excel file) are described below.

- User Defined Item Description (column 10): Describes the inventory item of interest, in terms understood by the analyst conducting the study.
- Inventory Element (column 11): Describes the inventory grouping for which the inventory item belongs (e.g., energy, chemicals and materials, water, land, noise, other). This designation should match the inventory element for the model data used from the scoring factor database.
- Item Classification (column 12): Clarifies whether the inventory item is a system input or output, which is used to select the appropriate scoring factors in the scoring factor database.
- Relevant Industry (column 13): Matches the most relevant industry associated with the inventory item if the item is procured from a supplier. This field is also used to identify the industry for which primary production is offset because of recycled or reused items. This field is not relevant (marked with “<n.a.>”) for non-procured items, such as direct natural resource consumption and releases, or residual value calculations. The value in this field is used to identify appropriate inflation rates that are used to inflate/deflate prices of procured items when the reported price is not in the base year currency.
- NAICS (column 14): An optional field that identifies the “North American Industry Classification System” code associated with the inventory item’s relevant industry. This code is often provided to the analyst as primary data and can be used to identify the closest matching industry designation and associated scoring factors in the scoring factor database.
- CAS (column 15): Identifies the unique “Chemical Abstracts Service” registry number for chemicals used as system inputs or released to the environment. This code is often provided to the analyst as primary data and can be used to identify the closest matching chemical and associated scoring factors in the scoring factor database.
- Location (column 16): Clarifies the location of where the inventory item is consumed or released. The location designation should be used to identify the closest matching location and scoring factors in the scoring factor database.

- Compartment (column 17): Clarifies the environmental compartment from which a natural resource is extracted (natural resource) or to which an output is released (air, water, soil). This field is not relevant (marked with “<n.a.>”) for procured items that require supply chain scoring factors. The compartment designation should match the environmental compartment of the chosen scoring factors in the scoring factor database.
- Reported Item Quantity per Activity Instance (column 18): Represents the amount of the inventory item, in units reported in the original dataset, required to satisfy the activity-level reference flow.
- Reported Inventory Item Unit (column 19): Clarifies the unit of measure originally provided to the analyst for measuring the amount of the inventory item. This unit is not always the same as the unit of measure required by the chosen scoring factors in the scoring factor database. As such, a unit conversion is required to properly model impacts and external costs associated with the inventory item. This topic is addressed in greater detail in Step 3.
- Reported Per-Unit Cost (column 20): Represents the per-unit cost, or procurement price, of the inventory item in the reported inventory item and cost units. This field is not relevant for non-procured items that require natural resource or release scoring factors, as these inputs and outputs do not create a direct cost. As such, the reported per-unit cost for natural resources and emissions should be recorded as zero.
- Reported Cost Unit (column 21): Clarifies the currency of the inventory item’s reported per-unit cost. This currency is not always the same as the base year currency (USD2014) required for the life cycle impact assessment and LCCA. As such, a currency conversion using an inflation factor is required to properly model impacts and internal/external costs associated with the inventory item. This topic is addressed in greater detail in Step 3.

Example LCI

In the hypothetical SLCA example model, LCI data was collected in accordance with the system boundaries established in Step 1. In this example inventory, inputs and outputs were assigned to the appropriate alternative and life cycle phase and then allocated to the appropriate system element and underlying activity. A short explanation of the all inputs and outputs, grouped by life cycle stage, system element and relevant activity, are provided in Tables 4 (metal superstructure) and 5 (composite superstructure). These tables also provide the frequency of each activity required to satisfy the functional unit. All LCI data (e.g., physical quantities, unit costs, amounts per activity-level reference flow, relevant industries, etc.) can be found in the “Step 2 - LCI” worksheet in the excel file, with reference to the specific row numbers for each line item identified in the “Rows” column of Tables 4 and 5.

Table 4. Explanation of Inputs and Outputs for the Metal Superstructure

Description	Item	Activity Frequency	Rows	Explanation
Production – Exterior Facing, Metal Working: Input	Aluminum (virgin)	Once during production	47	Used as material input for production of exterior facing
Production – Exterior Facing, Metal Working: Input	Steel (low alloy)	Once during production	45-46	Used as material input for production of interior support and exterior facing
Production – Exterior Facing, Metal Working: Input	Electricity (CT)	Once during production	42	Consumed from Connecticut electric grid during metal working processes
Production – Exterior Facing, Metal Working: Input	Personal protection equipment	Once during production	48	Used during metal working processes (e.g., welding shields)
Production – Exterior Facing, Metal Working: Input	Water (procured)	Once during production	67	Procured to support metal working processes
Production – Exterior Facing, Metal Working: Input	Water consumed by system and not returned	Once during production	68	Consumed during metal working processes
Production – Exterior Facing, Metal Working: Output	Chromium VI	Once during production	78	Released to onsite wastewater stream during metal working processes
Production – Exterior Facing, Metal Working: Output	Arsenic, ion	Once during production	82	Released to onsite wastewater stream during metal working processes
Production – Exterior Facing, Metal Working: Output	Vanadium, ion	Once during production	86	Released to onsite wastewater stream during metal working processes
Production – Exterior Facing, Metal Working: Output	Arsenic	Once during production	79	Emitted to air during metal working processes
Production – Exterior Facing, Metal Working: Output	Cadmium	Once during production	81	Emitted to air during metal working processes
Production – Exterior Facing, Metal Working: Output	Mercury	Once during production	87	Emitted to air during metal working processes
Production – Exterior Facing, Metal Working: Output	Methane	Once during production	85	Emitted to air during metal working processes

Description	Item	Activity Frequency	Rows	Explanation
Production – Exterior Facing, Metal Working: Output	Particulates, < 2.5 um	Once during production	83	Emitted to air during metal working processes
Production – Exterior Facing, Metal Working: Output	Sulfur dioxide	Once during production	84	Emitted to air during metal working processes
Production – Exterior Facing, Metal Working: Output	Zinc, ion	Once during production	80	Emitted to air during metal working processes
Production – Exterior Facing, Waste Disposal: Input	Hazardous Wastewater Permit	Once during production	76	Acquired to be in compliance with hazardous wastewater management requirements
Production – Exterior Facing, Waste Disposal: Output	Hazardous Wastewater	Once during production	71	Generated during the production of the exterior facing (specifically metal working processes)
Production – Coating, Coating Application: Input	Paint	Once during production	53	Used as material inputs for corrosion resistant coating system for application on exterior facing
Production – Coating, Coating Application: Input	Primer	Once during production	52	Used as material inputs for corrosion resistant coating system for application on exterior facing
Production – Coating, Coating Application: Input	Electricity (CT)	Once during production	41	Consumed from Connecticut electric grid during coating application
Production – Coating, Coating Application: Input	Personal protection equipment	Once during production	54	Used during coating application (e.g., disposable protective suits)
Production – Coating, Coating Application: Input	Air Filter	Once during production	55	Used to filter facility air during coating application
Production – Coating, Coating Application: Output	1-Butanol	Once during production	88+	Released to onsite wastewater stream and emitted to air during coating application

Description	Item	Activity Frequency	Rows	Explanation
Production – Coating, Coating Application: Output	Acetone	Once during production	90+	Released to onsite wastewater stream and emitted to air during coating application
Production – Coating, Coating Application: Output	Benzyl alcohol	Once during production	92+	Released to onsite wastewater stream and emitted to air during coating application
Production – Coating, Coating Application: Output	Chromium VI	Once during production	94+	Released to onsite wastewater stream and emitted to air during coating application
Production – Coating, Coating Application: Output	Xylene	Once during production	96+	Released to onsite wastewater stream and emitted to air during coating application
Production – Coating, Coating Application: Output	Noise from paint sprayer	Once during production	112	Emitted from paint sprayer during coating application
Production – Coating, Waste Disposal: Output	Air Filter Hazardous Waste	Once during production	62	Generated during coating application
Production – Coating, Waste Disposal: Output	Personal protection equipment Hazardous Waste	Once during production	63	Generated during coating application
Production – Insulation, Installation: Input	Mineral Wool	Once during production	49	Used as material input for installed superstructure insulation (mineral wool batts)
Production – Insulation, Installation: Input	Electricity (CT)	Once during production	51	Consumed from Connecticut electric grid during insulation installation
Production – Insulation, Installation: Input	Personal protection equipment	Once during production	50	Used during insulation installation (e.g., non-disposable masks and protective suits)
Operation – Ship Fuel, Fuel Combustion: Input	Residual Fuel Oil (No. 6)	Continuous over 25 years	40	Combusted during ship operation

Description	Item	Activity Frequency	Rows	Explanation
Sustainment – Coating, Coating Removal: Input	Electricity (VA)	Once every 5 years	44	Consumed from Virginia electric grid during coating application
Sustainment – Coating, Coating Removal: Input	Stripping agent	Once every 5 years	59	Procured to support the stripping of the existing coating on the exterior facing
Sustainment – Coating, Coating Removal: Input	Personal protection equipment	Once every 5 years	61	Used during coating removal (e.g., disposable protective suits)
Sustainment – Coating, Coating Removal: Input	Water (procured)	Once every 5 years	69	Procured to support coating removal processes
Sustainment – Coating, Coating Removal: Input	Water consumed by system and not returned	Once every 5 years	70	Consumed during coating removal processes
Sustainment – Coating, Coating Removal: Output	Benzyl alcohol	Once every 5 years	98+	Released to onsite wastewater stream and emitted to air during coating removal
Sustainment – Coating, Coating Removal: Output	D-Limonene	Once every 5 years	100+	Released to onsite wastewater stream and emitted to air during coating removal
Sustainment – Coating, Coating Removal: Output	Noise from paint stripping	Once every 5 years	114	Emitted during paint stripping process
Sustainment – Coating, Coating Application: Input	Paint	Once every 5 years	57	Used as material inputs for corrosion resistant coating system for application on exterior facing
Sustainment – Coating, Coating Application: Input	Primer	Once every 5 years	56	Used as material inputs for corrosion resistant coating system for application on exterior facing
Sustainment – Coating, Coating Application: Input	Electricity (VA)	Once every 5 years	43	Consumed from Virginia electric grid during coating application

Description	Item	Activity Frequency	Rows	Explanation
Sustainment – Coating, Coating Application: Input	Personal protection equipment	Once every 5 years	60	Used during coating application (e.g., disposable protective suits)
Sustainment – Coating, Coating Application: Input	Air Filter	Once every 5 years	58	Used to filter facility air during coating application
Sustainment – Coating, Coating Application: Output	1-Butanol	Once during production	102+	Released to onsite wastewater stream and emitted to air during coating application
Sustainment – Coating, Coating Application: Output	Acetone	Once during production	104+	Released to onsite wastewater stream and emitted to air during coating application
Sustainment – Coating, Coating Application: Output	Benzyl alcohol	Once during production	106+	Released to onsite wastewater stream and emitted to air during coating application
Sustainment – Coating, Coating Application: Output	Chromium VI	Once during production	108+	Released to onsite wastewater stream and emitted to air during coating application
Sustainment – Coating, Coating Application: Output	Xylene	Once during production	110+	Released to onsite wastewater stream and emitted to air during coating application
Sustainment – Coating, Coating Application: Output	Noise from paint sprayer	Once during production	113	Emitted from paint sprayer during coating application
Sustainment – Coating, Waste Disposal: Input	Hazardous Wastewater Permit	Once every 5 years	75	Acquired to be in compliance with hazardous wastewater management requirements
Sustainment – Coating, Waste Disposal: Output	Air Filter Hazardous Waste	Once every 5 years	64	Generated during coating removal and application

Description	Item	Activity Frequency	Rows	Explanation
Sustainment – Coating, Waste Disposal: Output	Personal protection equipment Hazardous Waste	Once every 5 years	65	Generated during coating removal and application
Sustainment – Coating, Waste Disposal: Output	Hazardous Wastewater	Once every 5 years	66	Generated during coating removal
Sustainment – Exterior facing, Power Washing: Input	Water (procured)	Once weekly over 25 years	72	Procured to support power washing of exterior facing
Sustainment – Exterior facing, Power Washing: Input	Nontoxic Cleaning Agent	Once weekly over 25 years	74	Procured to support power washing of exterior facing
Sustainment – Exterior facing, Power Washing: Input	Water consumed by system and not returned	Once weekly over 25 years	73	Consumed during power washing of exterior facing
Sustainment – Exterior facing, Power Washing: Output	Noise from power washing	Once weekly over 25 years	115	Emitted from power washer during power washing of exterior facing
End-of-Life – Exterior facing, Landfilling: Output	Landfilled solid waste	Once at end of study period	77	Landfilled superstructure components after decommissioning
End-of-Life – Exterior facing, Recycling Allocation: Output	Aluminum (recycled and sold on secondary market)	Once at end of study period	116	Recycled after being sold on the secondary market

Table 5. Explanation of Inputs and Outputs for the Composite Superstructure

Description	Item	Activity Frequency	Rows	Explanation
Production – Exterior Facing, Metal Working: Input	Electricity (CT)	Once during production	2	Consumed from Connecticut electric grid during metal working processes
Production – Exterior Facing, Metal Working: Input	Steel (low alloy)	Once during production	5	Used as material input for production of interior support
Production – Exterior Facing, Metal Working: Input	Personal protection equipment	Once during production	4	Used during metal working processes (e.g., welding shields)
Production – Exterior Facing, Metal Working: Input	Water (procured)	Once during production	18	Procured to support metal working processes

Description	Item	Activity Frequency	Rows	Explanation
Production – Exterior Facing, Metal Working: Input	Water consumed by system and not returned	Once during production	19	Consumed during metal working processes
Production – Exterior Facing, Metal Working: Output	Chromium VI	Once during production	27	Released to onsite wastewater stream during metal working processes
Production – Exterior Facing, Metal Working: Output	Arsenic, ion	Once during production	31	Released to onsite wastewater stream during metal working processes
Production – Exterior Facing, Metal Working: Output	Vanadium, ion	Once during production	36	Released to onsite wastewater stream during metal working processes
Production – Exterior Facing, Metal Working: Output	Arsenic	Once during production	28	Emitted to air during metal working processes
Production – Exterior Facing, Metal Working: Output	Cadmium	Once during production	30	Emitted to air during metal working processes
Production – Exterior Facing, Metal Working: Output	Mercury	Once during production	38	Emitted to air during metal working processes
Production – Exterior Facing, Metal Working: Output	Methane	Once during production	35	Emitted to air during metal working processes
Production – Exterior Facing, Metal Working: Output	Particulates, < 2.5 um	Once during production	33	Emitted to air during metal working processes
Production – Exterior Facing, Metal Working: Output	Sulfur dioxide	Once during production	34	Emitted to air during metal working processes
Production – Exterior Facing, Metal Working: Output	Zinc, ion	Once during production	29	Emitted to air during metal working processes
Production – Exterior Facing, Thermoforming: Input	Epoxy resin	Once during production	11	Used as material inputs for production of exterior facing
Production – Exterior Facing, Thermoforming: Input	Glass fiber	Once during production	9	Used as material inputs for production of exterior facing
Production – Exterior Facing, Thermoforming: Input	Polyester resin, unsaturated	Once during production	10	Used as material inputs for production of exterior facing

Description	Item	Activity Frequency	Rows	Explanation
Production – Exterior Facing, Thermoforming: Input	Polyurethane, rigid foam	Once during production	12	Used as material inputs for production of exterior facing
Production – Exterior Facing, Thermoforming: Input	Air Filter	Once during production	13	Used to filter facility air during thermoforming
Production – Exterior Facing, Thermoforming: Input	Electricity (CT)	Once during production	3	Consumed from Connecticut electric grid during thermoforming
Production – Exterior Facing, Thermoforming: Input	Natural gas	Once during production	26	Combusted in thermoforming facility during thermoforming
Production – Exterior Facing, Thermoforming: Input	Water (procured)	Once during production	16	Procured to support thermoforming
Production – Exterior Facing, Thermoforming: Input	Water consumed by system and not returned	Once during production	17	Consumed during thermoforming
Production – Exterior Facing, Thermoforming: Input	Thermoforming Facility	Once during production	14	Construction and occupation of new thermoforming facility built to support exterior facing production. Inventory data (e.g., square feet of building construction and acre years of land occupation) are allocated to a single ship produced, using an allocation partitioning factor of 0.05 (1 ship under study / 20 ships in total delivered).

Description	Item	Activity Frequency	Rows	Explanation
Production – Exterior Facing, Thermoforming: Input	Land occupation for thermoforming facility	Once during production	15	Construction and occupation of new thermoforming facility built to support exterior facing production. Inventory data (e.g., square feet of building construction and acre years of land occupation) are allocated to a single ship produced, using an allocation partitioning factor of 0.05 (1 ship under study / 20 ships in total delivered).
Production – Exterior Facing, Thermoforming: Output	Particulates, < 2.5 um	Once during production	32	Emitted to air during thermoforming
Production – Exterior Facing, Waste Disposal: Input	Hazardous Wastewater Permit	Once during production	24	Acquired to be in compliance with hazardous wastewater management requirements
Production – Exterior Facing, Waste Disposal: Output	Landfilled solid waste	Once during production	37	Landfilled waste products from thermoforming
Production – Exterior Facing, Waste Disposal: Output	Hazardous Wastewater	Once during production	20	Generated during the production of the exterior facing (waste water from metal working and thermoforming could not be separated, thus total output is reported)
Production – Insulation, Installation: Input	Electricity (CT)	Once during production	8	Used as material input for installed superstructure insulation (mineral wool batts)

Description	Item	Activity Frequency	Rows	Explanation
Production – Insulation, Installation: Input	Mineral Wool	Once during production	6	Consumed from Connecticut electric grid during insulation installation
Production – Insulation, Installation: Input	Personal protection equipment	Once during production	7	Used during insulation installation (e.g., non-disposable masks and protective suits)
Production – Superstructure, Residual Value: Output	Residual value of 5 years of extra composite superstructure life	Once during production	117	Production credit allocated to the composite alternative according to the proportion of total production impacts and costs associated with 5 years of remaining life beyond the study scope. The allocation partitioning factor for calculating this credit is 0.167 (5 years of residual life / 30 year system life).
Operation – Ship Fuel, Fuel Combustion: Input	Residual Fuel Oil (No. 6)	Continuous over 25 years	1	Combusted during ship operation
Sustainment – Exterior facing, Power Washing: Input	Water (procured)	Once weekly over 25 years	21	Procured to support power washing of exterior facing
Sustainment – Exterior facing, Power Washing: Input	Nontoxic Cleaning Agent	Once weekly over 25 years	23	Procured to support power washing of exterior facing
Sustainment – Exterior facing, Power Washing: Input	Water consumed by system and not returned	Once weekly over 25 years	22	Consumed during power washing of exterior facing
Sustainment – Exterior facing, Power Washing: Output	Noise from power washing	Once weekly over 25 years	39	Emitted from power washer during power washing of exterior facing
End-of-Life – Exterior facing, Landfilling: Output	Landfilled solid waste	Once at end of study period	25	Landfilled superstructure components after decommissioning

Step 3 – Estimate Life Cycle Impacts

After completing the LCI, inventory data are translated into midpoint and endpoint impacts using impact factors available in in the Scoring Factor Database. During this step, model data (impact factors) are matched to all inventory items and used to calculate life cycle impacts per the functional unit. All processes associated with this step are describe in the sections below. These explanations also reference an example LCIA completed in the example SLCA model (see the "Step 3 - LCIA" worksheet in the excel file) to further demonstrate the process.

Match Impact Model Data to Inventory Items

As described in section 3.4 of the SA Guidance and specified in the scoring factor database, each inventory item can be translated into impacts across midpoint impact categories and endpoint impact categories. These impact factors are based on scientific models relating to procurement, natural resource use and releases, and represent total impacts within an impact category per-unit of input or output. The scoring factor database provides a unique impact factor for each inventory item and impact category combination. As demonstrated in columns 31–50 of the LCIA worksheet in the example SLCA model, the best-matching set of scoring factors should be identified and recorded for each inventory item to facilitate the translation of inventory items into midpoint and input impacts.

The best-matching set of impact factors for each inventory item is determined by identifying and recording model data provided in the scoring factor database that most closely matches the inventory item data according to the following characteristics:

- Scoring Factor Classification (column 22): Describes the type of scoring factor used to model the impacts associated with a specified inventory item. There are four types of impact factors available in in the scoring factor database: (1) supply chain, (2) natural resource, (3) release, and (4) activity. Details for each type of factor are provided below.
  - Supply chain factors represent upstream impacts that are embedded in the procurement of items and services and should be matched to inventory items that are purchased and used as inputs for the system. Examples of procured items include a wide range of products from steel and aluminum to electronic components to plastic and rubber. Procured services may range from engineering services to construction to utilities (electricity and water). Multiplying supply chain factors, which are in units of impact per dollar of spend, by an inventory item's total cost per functional unit yields that item's total impacts relative to the functional unit.
  - Natural resource factors represent downstream impacts per physical quantity of natural resource use and measure changes to resource availability. These factors should be matched to inventory items that are natural resource inputs such as minerals, water, and land. Multiplying natural resource factors, which are in units of impact per physical unit of input, by an inventory item's total physical input quantity yields that item's total impacts relative to the functional unit.
  - Release factors represent downstream impacts per physical quantity of the release and model impacts from the transport and exposure of the release. These factors should be matched to inventory items that are direct releases of chemicals and materials to air, water, and soil or noise outputs. Multiplying release factors, which are in units of impact per physical unit of output, by an inventory item's total physical output quantity yields that item's total impacts relative to the functional unit.

  - Activity factors are hybrid factors that assess both upstream and downstream impacts per quantity of activity-level reference flow. Activity factors combine supply chain, natural resource use, and release impacts into a single impact factor. These factors should be matched to inventory items that quantify a level of activity, such as fossil fuel combustion by a specified combustion technology, electricity consumption drawn from a specified power grid, or mass-distance traveled using a specified mode of transport. Multiplying activity factors, which are in units of impact per activity-level reference flow (e.g., 1 kilowatt-hour [kWh] of electricity consumed), by an inventory item's total activity output (e.g., total kWh of electricity consumed) yields that item's total impacts relative to the functional unit.

- Scoring Factor Inventory Item (column 23): Identifies the name of the inventory item assigned to the best-matching set of scoring factors provided in the scoring factor database used to model the impacts associated with a specified inventory item in the LCI. When modelling an inventory item that represents recycled material, the *scoring factor inventory item* should represent the industry of primary production for which the recycled content offsets. For example, the *scoring factor inventory item* chosen for the recycled aluminum in the metal superstructure is "Alumina refining and primary aluminum production (33131A)" because this is the industry of primary aluminum production that is offset as a result of the recycling activity (see row 121 of the "LCIA" worksheet in the example SLCA model for further details).
- Scoring Factor Compartment Description (column 24): Identifies the specific environmental compartment of the *scoring factor inventory item* assigned to the best-matching set of scoring factors provided in the scoring factor database used to model the impacts associated with a specified inventory item in the LCI. A *scoring factor inventory item* can have multiple environmental compartments (e.g., a chemical can be released to urban air, rural air, freshwater, or soil), and a different set of impact factors associated with those compartments. Matching the appropriate compartment to the inventory item is critical for ensuring accurate impact estimates.
- Scoring Factor Inventory Item Unit (column 25): Clarifies the unit of measure required by the set of impact factors used to model impacts associated with the chosen *scoring factor inventory item*. Supply chain factors are normalized to units of currency, whereas natural resource, release and activity factors are normalized to physical units.

Convert Inventory Item Data to Model Data Units

Inventory data composing the LCI (see Step 2) are often provided in different units than the units required by the scoring factors used to model the impacts of inventory items. In these instances, the following unit conversions are required before scoring factors can be used to translate LCI data into impacts:

- **Physical Quantities:** The physical amount of an inventory item must be converted from the *reported inventory item unit* recorded in the LCI (see Step 2) to the *scoring factor inventory item unit*.
- **Per-Unit Cost:** The per-unit cost of an inventory item must be converted to a cost per *scoring factor inventory item unit* and then inflated to a per-unit cost in the base year currency.

As demonstrated in the example SLCA model (see the "Step 3 - LCIA" worksheet in the excel sheet), these conversions occur over a series of calculations using the following variables:

- Inventory Unit Conversion Factor (column 26): A factor used to convert the amount in the *reported item quantity per activity instance* field to the amount in the *model item quantity per activity instance* field required by the chosen set of scoring factors to properly model impacts associated with the inventory item. For example, fuel oil combustion reported in gallons must be converted to liters using a conversion factor of 3.78 liters per gallon (L/gal) before fuel oil combustion activity scoring factors, for which impacts are provided per liter, can be used to model impacts. This specific example is demonstrated in row 1 of the example SLCA model. When unit conversion is not required, a value of 1 should be recorded in this field.

- Model Item Quantity per Activity Instance (column 27): Represents the amount of the inventory item required to satisfy the activity-level reference flow in units required by the scoring factors in the scoring factor database to properly model impacts associated with the inventory item. This field is calculated by multiplying the *reported item quantity per activity instance* by the *inventory unit conversion factor*.
- Model Per-Unit Cost (USDyr) (column 28): Represents the per-unit cost, or procurement price, of the inventory item in units consistent with the *model inventory item unit* and currency consistent with the *reported per-unit cost.* This field is calculated by dividing the *reported per-unit cost* by the *inventory unit conversion factor*.
- Inflation Factor (column 29): A factor used to convert the amount in the *model per-unit cost (USDyr)* field to an amount in the base year currency (USD2014), which is required for the life cycle impact assessment and LCCA. All inflation factors are provided in the scoring factor database and are assigned by relevant industry. The appropriate inflation factor can be found by cross-referencing the industry recorded in *relevant industry* field and the currency reported in the *reported per-unit cost* field. When an inflation factor is not required (e.g., natural resources and releases), a value of 1 should be recorded in this field.
- Model Per-Unit Cost (USD2014) (column 30): Represents the per-unit cost, or procurement price, of the inventory item in units consistent with the *model inventory item unit* and currency consistent with the base year (USD2014). This field is calculated by multiplying the *model per-unit cost (USDyr)* by the *inflation factor*.

Calculate Life Cycle Midpoint and Endpoint Impacts

Life cycle midpoint and endpoint impacts for inventory items are calculated using assigned impact scoring factors in combination with inventory item requirements per functional unit. For inventory items using natural resource, release or activity impact factors, the total impact of a specific impact category is calculated by multiplying the *model item quantity per activity instance* by the *number of activity instances required for the functional unit*, and then multiplying that result by the assigned impact scoring factor (see equation 1 below). Columns 51–70 of the “Step 3 - LCIA” worksheet in the example SLCA model provide examples of this calculation for each factor type.

(1) (Model Item Quantity / Activity Instance) x (Activity Instances / Functional Unit) x Impact Factor

Supply chain factors are unique, as impacts are normalized per dollar of spend and not per physical unit. As equation 2 demonstrates below, equation 1 must be modified to translate the model item quantity into a cost before multiplying that amount by the appropriate supply chain impact factor. Columns 51–70 of the “Step 4 - LCCA” worksheet in the example SLCA model provide examples of this calculation.

(2) (Model Item Quantity / Activity Instance) × (Activity Instances / Functional Unit) × (Cost / Model Item Unit) × Impact Factor

Calculating Impact Credits Associated with Residual Value

Explained in section 3.2.6 of the SA Guidance and Box 2 above, impact credits associated with residual value must be calculated separately. As row 117 of the "Step 3 - LCIA" worksheet in the example SLCA model demonstrates, impact factors for residual value calculations do not exist in the scoring factor database (see columns 31–50 of the "Step 3 - LCIA" worksheet in the example SLCA model). Instead, the total impacts in the production stage allocated to the remaining years of system life using the allocation partitioning factor (see the Box 2 for further discussion) should be recorded as an impact credit (negative value) in the model.

The SLD method is used in this example. This method requires that all production-related life-cycle impacts[2] that occur in the base year are allocated to the 5 years of residual life according to the allocation partitioning factor (5 years of residual life / 30 years of system life). Equation 3 below summarizes this calculation and columns 51–70 in row 117 of the "LCIA" worksheet in the example SLCA model provides a working example.

(3) Sum of (Production Impacts per Functional Unit x (Year of Residual Life / System Life))

Step 4 – Estimate Life Cycle Costs

After completing the LCIA, annual internal and external costs for each inventory item are calculated, forecasted over the study period and discounted back to a net present value for equal comparison of costs across alternatives. All processes associated with this step are describe in the sections below. These explanations also reference an example LCCA completed in the example SLCA model (see the "Step 4 - LCCA" worksheet in the excel sheet) to further demonstrate the process.

Calculate and Forecast Annual Internal Costs

The annual cost for each inventory item is calculated as the product of the *model item quantity per activity instance*, the *number of activity instances required in a year*, and the *model per-unit cost (USD2014)*. Equation 4 below summarizes this calculation.

(4) (Model Item Quantity / Activity Instance) × (Activity Instances / Year) × (Cost / Model Item Unit)

Once annual internal costs are calculated for all inventory items (see column 32 of the "Step 4 - LCCA" worksheet in the example SLCA model), those annual costs should be recorded in all years over the study period for which the inventory item's assigned activity occurs. Using columns 36–61 of the "Step 4 - LCCA" worksheet in the example SLCA model as an example, a unique cost schedule was used for each of the following activities:

- Production, All Activities: All production-related costs are recorded in the base year 2014.
- Operation, All Activities: All operational-related costs are recorded in operational years (2015 to 2039).

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[2] It is important to note that all land occupation occurring as a result of production should not be included in this calculation because land use is an annual impact that is already credited back to the system by not including the residual life in the system boundaries.

- Sustainment, Power Washing: Power washing costs are recorded in operational years (2015 to 2039).
- Sustainment, Coating Removal/Application: Coating removing and application costs for the metal superstructure are recorded every five years during the operation period (2020, 2025, 2030 and 2035).
- End-of-Life, All Activities: All end-of-life costs are recorded in the final year of the study period 2039.

Calculate and Forecast Annual External Costs

Inventory data must be translated into external costs using external cost factors available in in the Scoring Factor Database. Using the same model data matched to inventory items from Step 3, the external cost factor from the best-matching set of scoring factors should be recorded for each inventory item (see column 31 in the "Step 4 - LCCA" worksheet in the excel sheet). External cost factors are then used to translate inventory data into annual external costs. As described below, this calculation is slightly different depending on the type of scoring factors matched to the inventory item.

For inventory items using natural resource, release or activity impact factors, the annual external cost associated with an inventory item is calculated by multiplying the total annual quantity of the inventory item (*model item quantity per activity instance* x *number of activity instances required in a year*) by the best-matched external cost factor, which represent dollars of external costs in USD2014 per *scoring factor inventory item unit*. Equation 5 below summarizes this calculation and column 33 of the "Step 3 - LCCA" worksheet in the example SLCA model provides an examples of this calculation for each factor type.

(5) (Model Item Quantity / Activity Instance) × (Activity Instances / Year) × External Cost Factor

Supply chain external cost factors are unique, as external costs are normalized per dollar of spend and not per physical unit. As equation 6 demonstrates below, equation 5 must be modified to translate the model item quantity into a cost before multiplying that amount by the appropriate supply chain impact factor. Column 33 of the "Step 4 - LCCA" worksheet in the example SLCA model provides an example of this calculation.

(6) (Model Item Quantity / Activity Instance) × (Activity Instances / Year) × (Cost / Model Item Unit) × External Cost Factor

Once annual external costs are calculated for all inventory items (see column 33 of the "Step 4 - LCCA" worksheet in the example SLCA model), those annual costs should be recorded according to the cost schedule outlined in the internal cost section above.

Calculating Cost Credits Associated with Residual Value

Like the process used in Step 3, internal and external cost credits associated with residual value must be calculated separately. As row 117 of the "Step 4 - LCCA" worksheet in the example SLCA model demonstrates, the total internal and external costs in the production stage must be allocated to the remaining years of system life using the allocation partitioning factor (see the Box 2 for further discussion). Equation 7 below summarizes this calculation and columns 32–33 in row 117 of the "Step 4 - LCCA" worksheet in the example SLCA model provide a working example. The results from this calculation should be recorded as cost credit (negative value) in the last year of the LCCA model.

(7) Sum of (Production Costs per Functional Unit x (Years of Residual Life / System Life))

Calculating Life Cycle Internal and External Costs

To fairly compare all alternatives evaluated in the study, all out-year internal and external costs should be discounted to the base year and aggregated as a net present value. Forecasted costs should be discounted using the discount factors specified in Step 1. The sum of these net present values for each alternative represent the alternatives total internal and external LCCs. Equation 8 below provides an equation for calculating the net present value of each inventory item's forecasted costs, and columns 34 and 35 of the "Step 4 - LCCA" worksheet in the example SLCA model provide working examples of this calculation.

(8) $\sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0$

(8) Sum, from t = 1 to T, of ((Ct / (1+r)t) - C0

Where:

C_t = the net cost during year t
C_0 = the total investment/production cost in the base year
r = the internal or social discount rate
t = the number of years comprising the study period

Step 5 – Synthesize Results and Iterate

With Steps 1–4 completed, impact and cost results can be synthesized and display visually to facilitate comparisons across the evaluated alternatives. Using the data structure outlined in Steps 1-4, the results of the SA can be presented in a myriad of ways to compare alternatives at three different levels: (1) midpoint impacts, (2) endpoint impacts, and (3) total LCCs. These presentation levels are summarized below, along with example output comparative charts. Detailed references for the example results provided in the "Step 5 – Example Results" worksheet in the example SLCA model.

- Midpoint impacts: Midpoint impacts provide the analyst with a clear understanding of the relative potency, in terms of physical units, of each system's aggregated resource consumption and resulting 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 (e.g., greenhouse gases, energy, and water).

  Figure 3 provides an example output of midpoint impact results. This spider chart shows the relative differences across the midpoint impact categories. In this example, the composite alternative outperforms the metal superstructure in all categories.

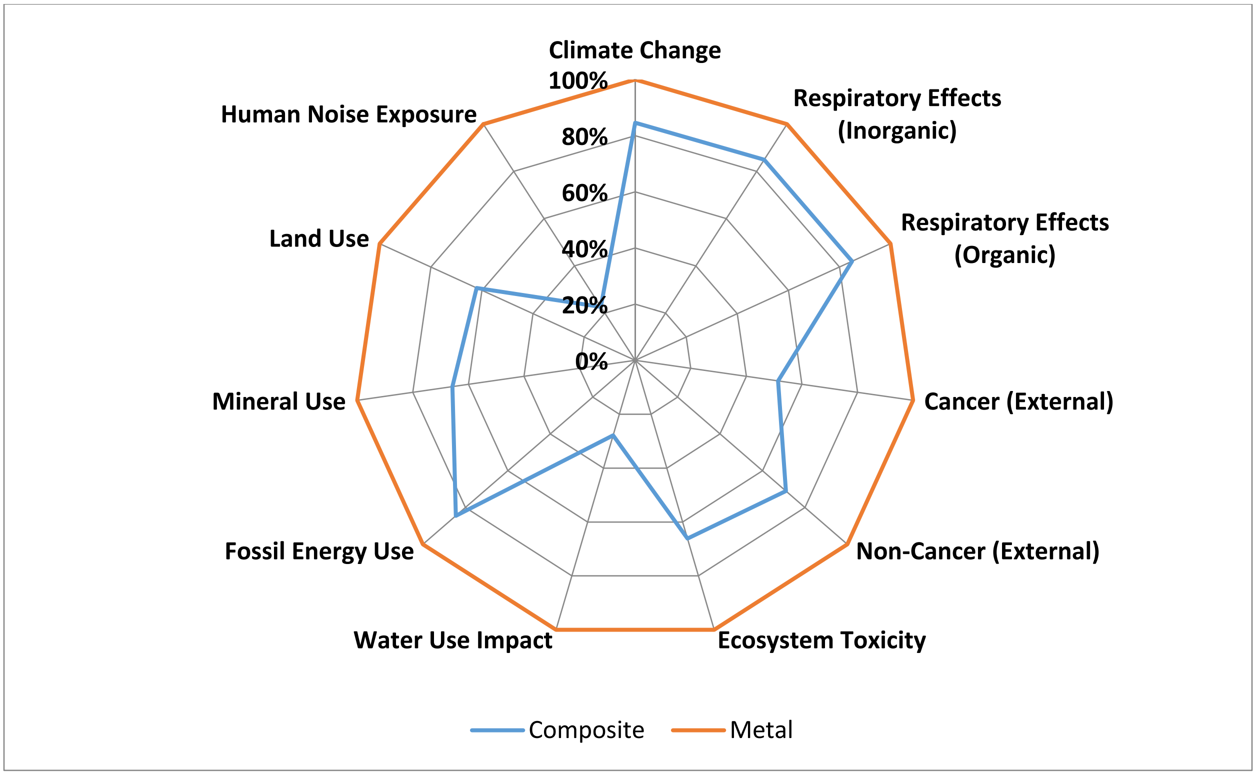

Figure 3. Spider Chart Summary of Midpoint Impacts

- Endpoint impacts: 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.

  Figure 4 provides an example output of endpoint impact results. This bar chart shows the relative differences across the endpoint impact categories. In this example, the composite alternative outperforms the metal superstructure in all categories.

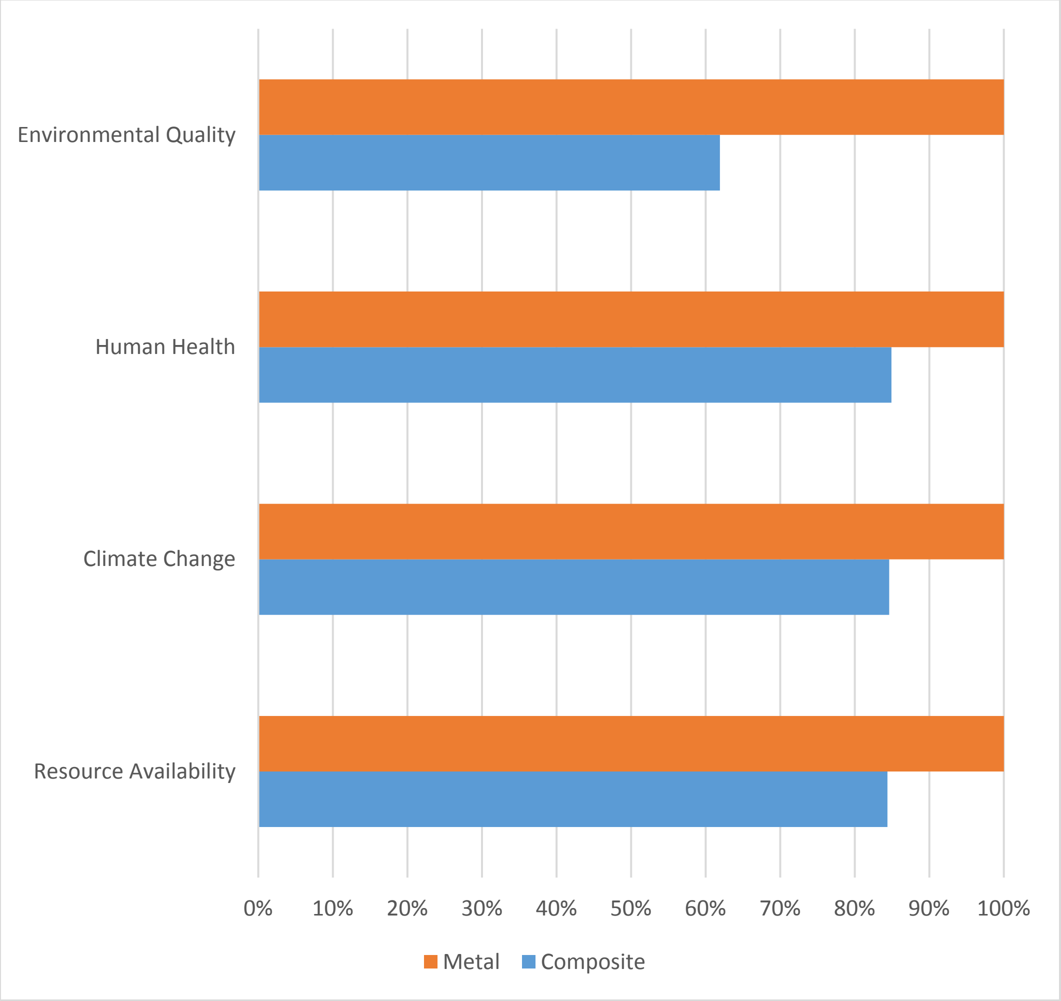

Figure 4. Bar Chart Summary of Endpoint Impacts

- Total LCCs: Presenting impacts in terms of LCC better communicates the overall importance of a particular impact. Furthermore, LCC can directly inform investment decisions, budget models, 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.

  Figures 5, 6, and 7 provide an example outputs of LCC results. The column chart in Figure 5 compares the total life cycle internal and external costs across the evaluated alternatives. In this example, the composite alternative results in lower internal and external costs than the metal superstructure. Figure 6 is a variation of Figure 5, breaking down LCCs by inventory element. This chart shows that energy is by far the largest driver of impact. Figure 7 further breaks the results in Figure 6 by activity, and shows that the majority of the energy impacts are driven by fuel oil combustion during operation.

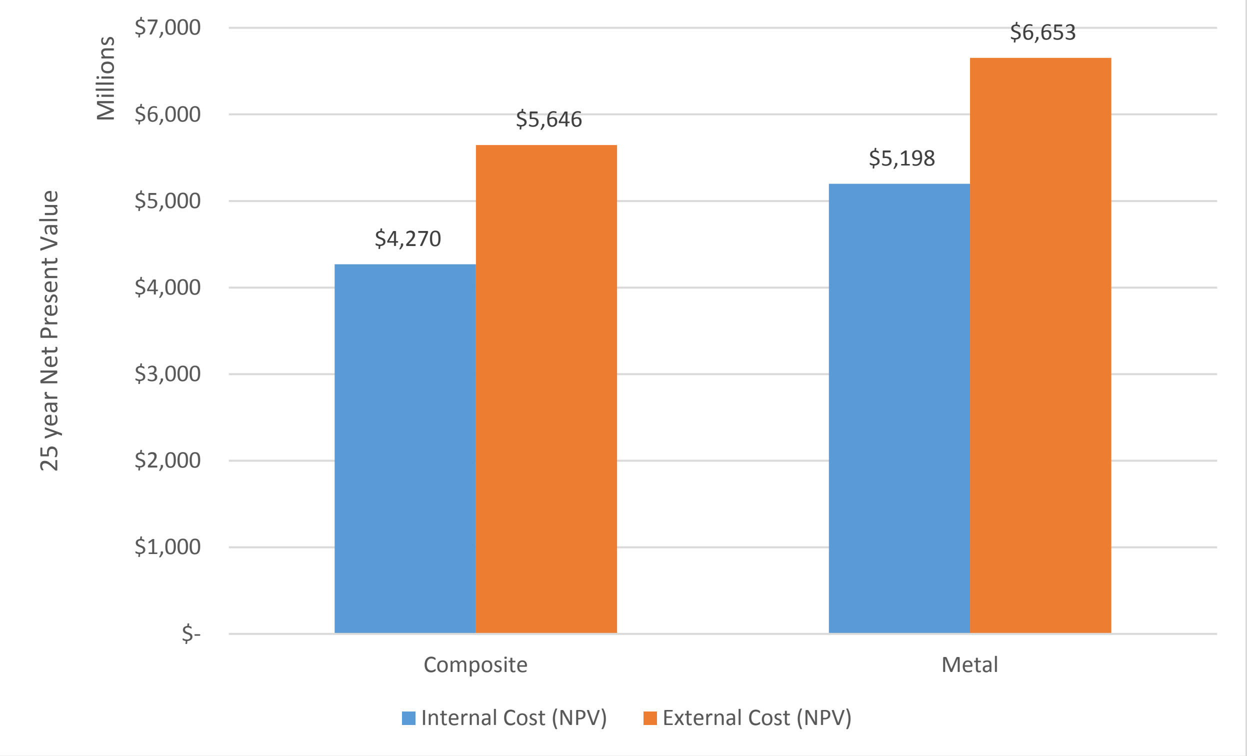

Figure 5. Comparing Total Life Cycle Internal and External

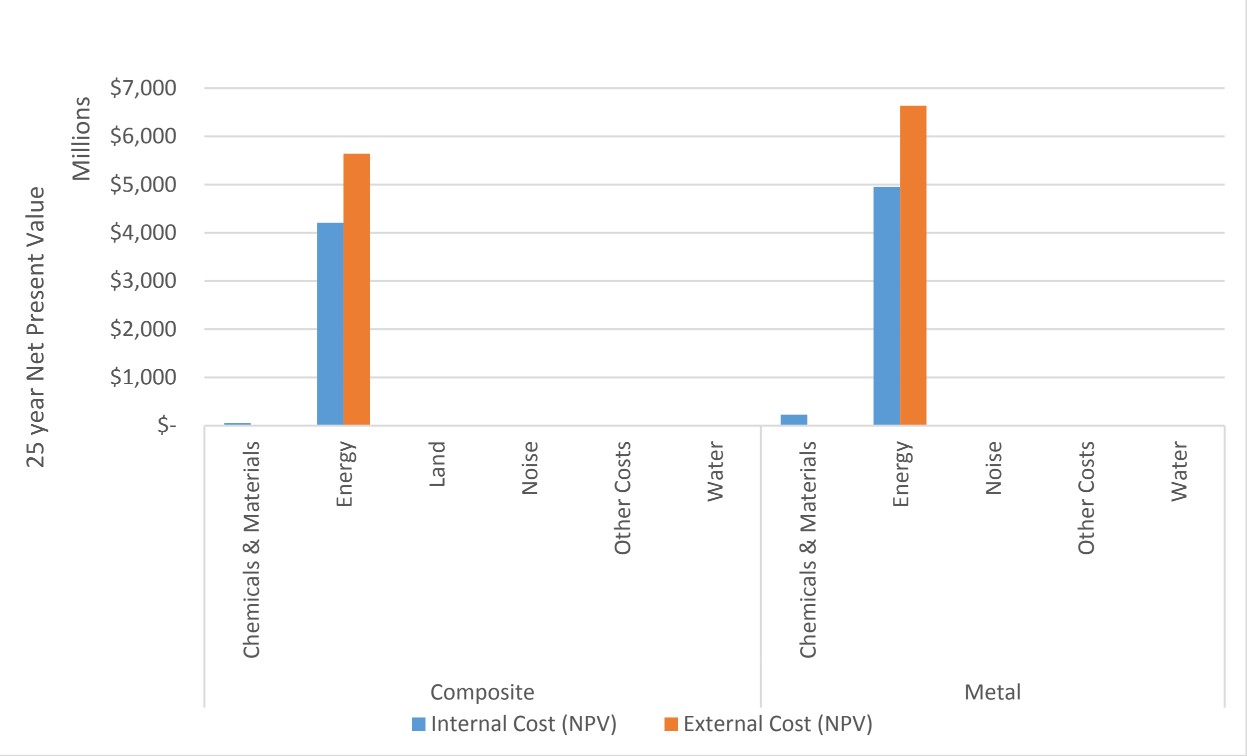

Figure 6. Comparing Life Cycle Internal and External Costs by Inventory Element

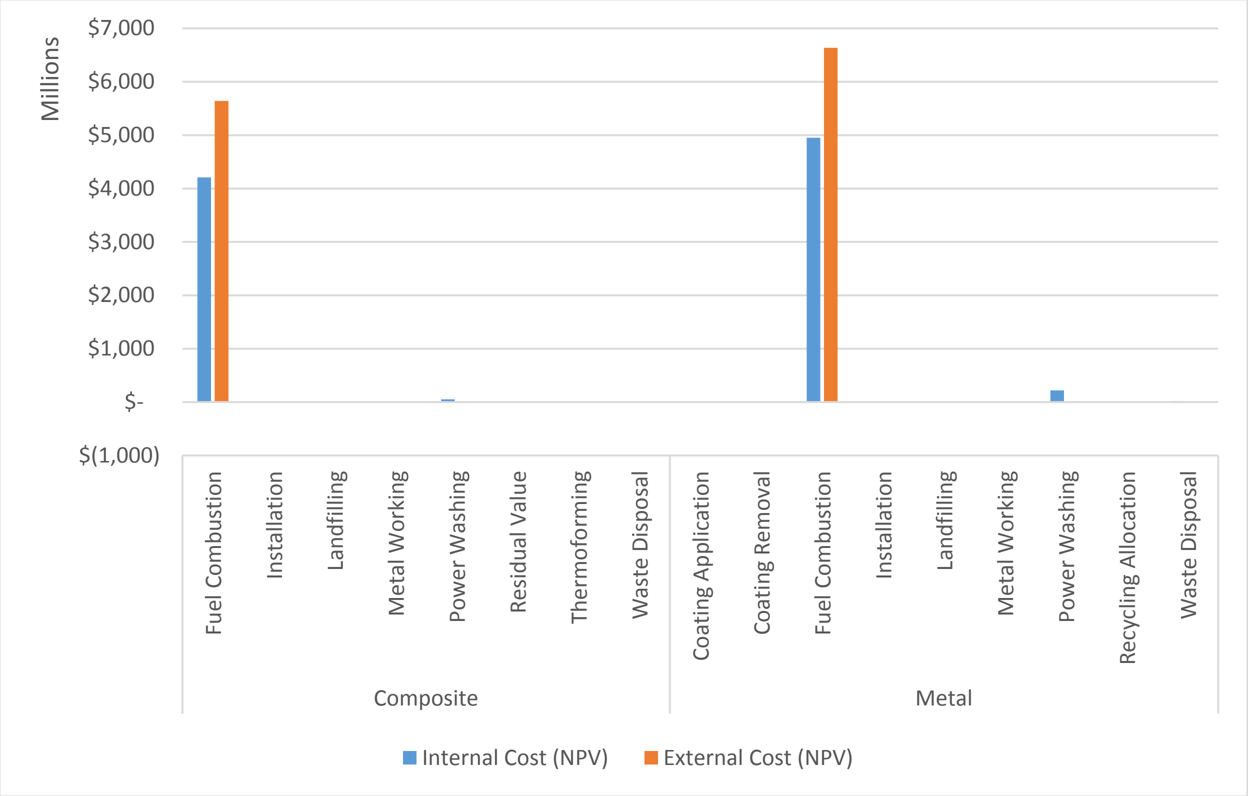

Figure 7. Comparing Life Cycle Internal and External Costs by Activity

Discussion

Results Summary

The SA is intended to identify each system's largest sources of impact and cost and uncover the drivers of those impacts and costs. In the superstructure example provided in this supplement, it is very clear that fuel consumption during the operation of the ship is the largest source of impact and cost difference. This difference is driven by the material used for the superstructure. Since the composite is lighter than the aluminum exterior facing, less support is required and the reduction in total ship weight leads to a significant reduction in fuel consumption.

It is important to note that the results provided in the superstructure were simplified for demonstration. SA results often present tradeoffs across alternatives and impact categories evaluated. In these instances, such results should be considered in the trade space to optimize system design and reduce downstream impact and cost burdens during operational or sustainment activities.

Limitations and Sources of Uncertainty

In addition to presenting summary results, it is also recommended that analytical limitations be discussed to inform decision making and future iterations of the analysis. In the superstructure example provided in this supplement, the use of supply chain factors for inventory items such as material inputs and services like waste management use industry average data and thus may not accurately reflect the unique conditions of the specific items and services procured for the evaluated system. For example, the overall composition, and related environmental impacts, of material inputs can vary substantially from industry averages. Likewise, the exposure pathway of releases come with varying degrees of uncertainty, which could be tested further using scenario analysis or simulated uncertainty analyses. Such methods were not employed for this simplified example.