A SunCam online continuing education course

Sustainability Comparisons for All Engineers

by

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Course Outline:

What is Sustainability?

It is increasingly common for engineers to consider sustainability when designing a product, process, or facility. Sustainability strives to meet the needs of the present without compromising the ability to meet future needs. It is based on the principle that it is our responsibility to protect the people and environment that may be affected by the item being designed.

Sustainability can be achieved when the human health and natural environment can be maintained or improved over time, without exceeding the ecological capabilities that support them. In terms of design, this involves consideration for the long term impact on the community and environment.

Sustainability is commonly evaluated by considering the following three categories:

1. Economic: Maximize value, wealth, and profits in the economically viable dimension.
2. Environmental: Provide cleaner products with less raw material consumption and waste generation in the environmentally compatible dimension.
3. Social: Have more socially benign products, services, and impact in the socially responsible dimension.

These three categories are referred to as the “triple bottom line” or the three P’s: profit, planet, and people. The categories are depicted in Figure 1 with the overlap of the three being defined as sustainable.

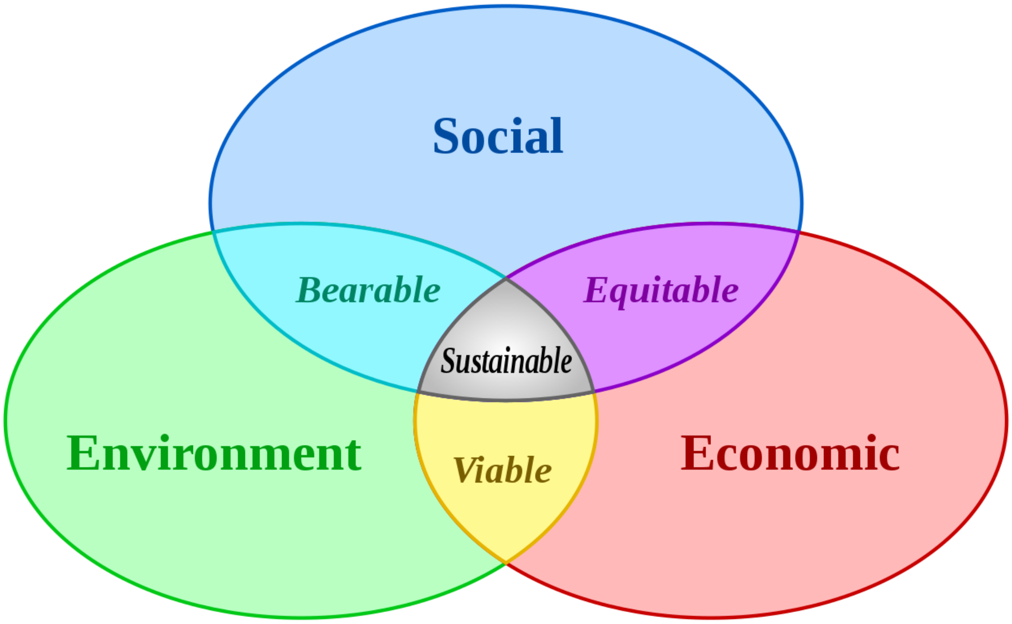

Figure 1: Triple Bottom Line for Sustainable Development

Within each category, there are a number of criteria (also called indicators) that can be used to numerically assess the sustainability of the item being considered. This allows an engineer to compute the triple bottom line of the item. This general approach to sustainability applies to every field of engineering.

Trends in Sustainability

Our understanding of sustainability has evolved over time for the following reasons:

- The world is ever-changing, both in terms of human society and the natural environment.
- New knowledge of the human impact on the world around us.
- Changes in our core values.

This means that what was considered sustainable in the past may not be considered sustainable today or in the future. To help capture current viewpoints, engineers should consider recent trends in sustainability. The following approaches are currently widespread and continue to grow in popularity.

Life Cycle Assessment

Determining the long term impact of a product, process, or service can be accomplished with a Life Cycle Assessment (LCA). Life Cycle Assessment is the investigation and evaluation of the environmental impacts of a given product or service caused by its existence. This is also called the “cradle-to-grave” approach.

Figure 2: Important Stages for a Lifecycle Assessment

LCA is commonly used for the following business purposes:

- Support and promote business strategy,
- Research and development,
- Product or process design,
- Education, and
- Labeling or product declarations.

Procedures for performing an LCA are specified in ISO 14000 - Environmental Management Standards. Software that assists with life cycle assessment and costing includes GaBi Software developed by PE International and SimaPro developed by PRé Consultants.

Lifecycle Cost

Lifecycle Cost refers to the total cost of ownership over the life of an asset. This whole-life costing includes costs incurred after an asset has been constructed or acquired, such as maintenance, energy usage, operation, and disposal. These life cycle evaluations help quantify sustainability for use in decision-making.

The lifecycle cost can be calculated using the present worth approach. The formula is as follows:

$$Lifecycle\ Cost = Capital\ Cost + Annual\ Maintenance * PWF - Salvage\ Value$$

where:

$$PWF = Present\ Worth\ Factor = \frac{(1+i)^T - 1}{i*(1+i)^T}$$

$$i = interest\ rate$$

$$T = number\ of\ years$$

Renewable Energy

Energy use/consumption has emerged as one of the most important considerations for sustainable design. Energy use tends to have a significant impact on all three categories of sustainability. In the future, energy prices are expected to rise, and this impacts the economic aspect of sustainability. Nonrenewable forms of energy are being depleted so that future generations will need to utilize other forms of energy, and this impacts the societal aspect. Nonrenewable forms of energy include nuclear power and fossil fuels such as coal, petroleum, and natural gas. Obtaining power from fossil fuels has an impact on the environmental aspect of sustainability since there is a release of greenhouse gases into the atmosphere, which contributes to climate change.

For these reasons, renewable energy, also called sustainable energy, is becoming more popular. Renewable energy sources include plant matter, solar power, wind power, wave power, geothermal power, and tidal power. Electricity provided by utility companies is derived from a combination of nonrenewable and renewable sources which differs for each region.

Figure 3: A 10 MW solar power plant providing renewable energy.

Precautionary Principle

The precautionary principle is as follows:

> *When an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically.*

The precautionary principle is already incorporated into many international environmental agreements and European environmental policies. It is applied in various contexts, including potentially hazardous materials and chemicals, materials selection, preventing environmental destruction such as threats to biodiversity, pollution prevention, reduction in greenhouse gas emissions, and food safety.

Engineers and project managers often use the precautionary principle as part of a risk assessment. A risk matrix may be created where the likelihood and severity of each risk is tabulated, scored, and alternatives approaches are compared. This is especial important when loss of human life is a possibility.

Greenhouse Gases
Scientists inform us that certain gases in the atmosphere can trap heat and these are called greenhouse gases (GHGs). Scientists nearly unanimously agree that increases in the concentrations of heat-trapping GHGs can be linked to the increase in the Earth's average surface temperature and other aspects of climate change. Naturally occurring GHGs include water vapor, carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), and Ozone (O3). Other greenhouse gases, mostly from industrial sources, include several classes of halogenated substances that contain fluorine, chlorine, or bromine.

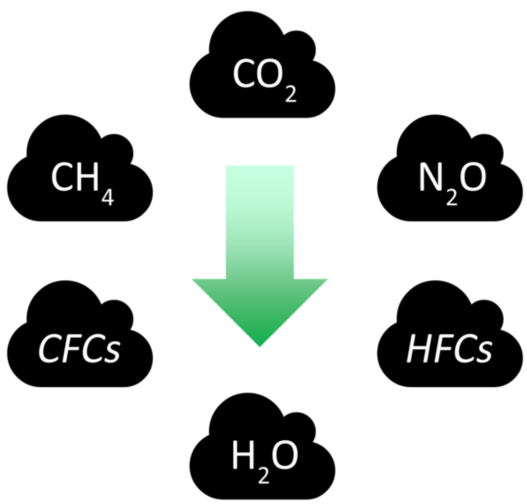

Figure 4: Chemical formulas of common greenhouse gases. The CFCs (chlorofluorocarbons) and HFCs (hydrofluorocarbons) are man-made gases.

Since the release of these gasses is considered to harm the environment, their minimization is an important aspect of sustainability. It is common to express the amount of greenhouse gases released as the “carbon footprint”. Net Zero Emissions (NZE) is an approach to reducing GHG emissions and capturing carbon such that there is net zero carbon footprint for an organization, country, or the whole world.

Public Reporting

Public reporting on sustainability performance is an important way for organizations to manage their triple bottom line impact. Sustainability reporting is a form of value reporting where an organization publically communicates its economic, environmental, and social equity performance. Reporting leads to improved sustainable development because it allows organizations to measure, track, and improve their performance on specific issues.

The Global Reporting Initiative (GRI) is a network-based organization that has pioneered the development of the most widely used sustainability reporting framework. Thousands of companies report each year using the GRI framework.

LEED Certification

The U.S. Green Building Council is a non-profit community of leaders with a goal of making green buildings available to everyone through its Leadership in Energy and Environmental Design (LEED) programs. LEED provides independent third-party verification that a facility has met a threshold for sustainability measurements.

LEED Certification refers to buildings that have been designed, built, and maintained using green building and energy efficiency best practices. LEED certification requires earning credits through measurement and verification in the following areas:

1. Sustainable Sites – Location and land use
2. Water Efficiency – Indoor and outdoor water use
3. Energy Efficiency – Energy Use
4. Material Resources – Sustainability of materials used
5. Indoor Environmental Quality – Ventilation and air quality

LEED certification offers the following benefits related to sustainability:

- Reduced energy and water usage
- Lower operating costs
- Less construction waste

- More durable (long-lasting) buildings
- Supports the local economy
- Greater resale value
- Improved indoor air quality
- Increased employee productivity

Figure 5: LEED recognition plaque in a Silver certified building. There are four levels of certification in order from lowest to highest rating: Certified, Silver, Gold, and Platinum.

Note that LEED certification can be expensive and can increase the design time, so it is not always pursued. Many engineers chose to become LEED accredited to show their ability to apply sustainability practices. The following accreditation tiers are available:

- LEED Green Associate
- LEED AP with Specialty
- LEED Fellow

Comparing Sustainability

It is now relatively common to compare the sustainability of alternatives during the preliminary design stage to facilitate decision making. This provides long term value to the project, society, and the environment.

At a glance, it would appear difficult to compare the sustainability of alternatives because the social and environmental categories seem vague and subjective. However, commonly accepted methodologies have been developed to calculate sustainability with reduced subjectivity.

Often there are challenges in quantifying aspects of sustainability and in combining the data to directly compare the alternatives. Multi-criteria assessment software is available. However, such software tends to be either too broad or too focused on specific industries, providing limited benefit to a design engineer.

Eco-Efficiency Analysis

Eco-Efficiency Analysis™ is a tool to assess the environmental impact versus the cost-effectiveness. It was established by BASF Corporation in 1996. The Eco-Efficiency Analysis methodology has been validated by NSF International. It also follows ISO standards for environmental life cycle assessments and life cycle costs. The environmental impact and economic impact of alternatives can be plotted to help select a balanced path forward.

Envision

Envision™ Sustainable Infrastructure is an approach developed by the Institute for Sustainable Infrastructure (ISI). Envision provides a consistent approach for evaluating and rating infrastructure projects in terms of community, environment, and economic impact. The approach encourages ongoing assessment of the sustainability indicators over the course of the project's life cycle. There is an option for third-party project verification. Envision includes 64 sustainability and resilience indicators, called 'credits'. The credits are grouped into five categories:

- Quality of Life,
- Leadership,
- Resource Allocation,
- Natural World, and
- Climate & Resilience

Worksheets

Some municipalities have adopted multi-criteria decision making worksheets that are tailored for local values for sustainability. For example, the Milwaukee Metropolitan Sewerage District (MMSD) has developed a standard sustainability scoring worksheet that is required for evaluating alternatives during the preliminary design stage. And the Green Bay Metropolitan Sewerage District (GBMSD) has presented a similar worksheet with sustainability indicators and weights that can be utilized for comparing design alternatives. Such worksheets make it relatively easy for an engineer to fill in quantities for each alternative and be given scoring results with clear rankings for sustainability.

However, in the absence of software or an adopted worksheet, the design engineer will need to perform a project-specific sustainability comparison. This is typically done with a multi-criteria scoring approach, which engineers have been using for decades to compare alternatives in a variety of contexts. The next section explains common techniques for comparing alternatives with an emphasis on the multi-criteria scoring approach.

Approaches for Comparing Alternatives

It is important to understand common approaches engineers use to compare alternatives, as these same approaches can be utilized for comparing sustainability as well. Engineers are accustomed to analyzing and comparing alternatives as part of the design process. The following are common approaches to comparing alternatives:

- Advantages Table
- Qualitative Comparison
- Quantitative Comparison
- Multi-Criteria Scoring

A risk assessment may also be performed to identify and compare the potential for severe impact risks or high probability risks. This is especially important if any of the alternatives have a significant probability of causing the loss of human life. See the References section at the end for more information on risk assessments.

Advantages Table

The simplest approach to comparing alternatives is with an Advantages Table, as shown in Table 1. Each alternative is listed with perceived advantages and disadvantages.

Table 1: Example Advantages Table

Alternative No.	Description	Advantages	Disadvantages
1	Asphalt Shingle Roof	Fast installation Low cost Color selection	Short life span
2	Clay Tile Roof	Aesthetically pleasing Long life span Storm resistant	Expensive
3	Metal Roof	Long life span Storm resistant Color selection	Expensive

With this approach, there is a lot of flexibility in choosing what to include in the advantages and disadvantages columns. For example, Alternative 1 has an advantage of “fast installation”, so for Alternatives 2 and 3, “slow installation” could be added as a disadvantage. It is up to the engineer creating the table to make judgment decisions as to what to include. Overall, this approach is fast and simple, but has a lot of subjectivity and may not result in choosing the best alternative.

Qualitative Comparison
An improved approach is creating a qualitative comparison table, as shown in Table 2. This type of table lists several criteria (also called indicators), with a comparison of the alternatives for each criterion. In this case, six criteria are presented: Installation Time, Construction Cost, Color Selection, Aesthetics, Life Span, and Storm Resistance. And the qualitative terms “Best, Average, Worst” are used to compare each alternative for each criterion. Alternately, terms such as “Good, Fair, and Poor” may be used.

Table 2: Example Qualitative Comparison

Alt. No.	Description	Installation Time	Constr. Cost	Colors Available	Aesthetics	Life Span	Storm Resist-ance
1	Asphalt Shingle Roof	**Best**	**Best**	Average	Worst	Worst	Worst
2	Clay Tile Roof	Worst	Worst	Worst	**Best**	**Best**	Average
3	Metal Roof	Average	Average	**Best**	Average	Average	**Best**

Note how Table 2 provides significantly more information than Table 2. It also has less subjectivity since alternatives must be compared for each criterion. Often, this type of comparison table is sufficient to allow selected of an alternative.

Quantitative Comparison

The previously discussed alternatives table and qualitative comparison table are commonly used for design decisions with relatively simple and low-cost systems. However, a quantitative approach is more common for complex and high-cost systems. A quantitative comparison takes more effort but provides more information to make a more informed choice of alternatives.

A quantitative comparison includes numerical values instead of comparative advantage terms. For example, dollar values are to be listed for the estimated construction cost of each alternative. See Table 3 for an example of a quantitative comparison table. The best values for each criterion are in bold.

Table 3: Example Quantitative Comparison

Alt. No.	Description	Installation Time (days)	Constr. Cost (USD)	Colors Available (number)	Aesthetics (1 to 10 scale)	Life Span (years)	Storm Resist-ance (mph)
1	Asphalt Shingle Roof	**3 days**	**$10,000**	20	4	15	110
2	Clay Tile Roof	7 days	$60,000	10	**10**	**50**	125
3	Metal Roof	5 days	$40,000	**100**	6	40	**150**

These types of tables are common for engineering reports with alternatives comparisons. Having numerical values and seeing them in a single table is very helpful.

Multi-Criteria Scoring

The multi-criteria scoring approach uses the numerical values for each criterion to calculate a single total score for each alternative. The scoring approach minimizes subjectivity and provides transparency in showing how the best alternative is chosen. See Table 4 for an example of a scoring table.

Table 4: Example Multi-criteria Scoring Table

Indicator	Weight Factor	Asphalt Shingle		Clay Tile Roof		Metal Roof	
		Normal. Index	Weighted Index	Normal. Index	Weighted Index	Normal. Index	Weighted Index
Installation Time	10	1.0	10	0.4	4	0.6	6
Constr. Cost	30	1.0	30	0.2	6	0.3	9
Colors Available	10	0.2	2	0.1	1	1.0	10
Aesthetics	10	0.4	4	1.0	10	0.6	6
Life Span	20	0.3	6	1.0	20	0.8	16
Storm Resist.	20	0.7	14	0.8	16	1.0	20
Aggregated Index		-	66	-	57		**67**
Final Score (Normalized to 1)		-	0.99	-	0.85		**1.0**

The final score is the normalized aggregated index, with the best score being 1. In this example, the metal roof alternative has the best score and is the winner of this comparison. Note that for a sustainability comparison, the calculations are typically done with the lowest score being the best and the highest score of 1.0 being the worst.

The scoring technique must take into account that some criteria (also called indicators) are more important than others. In this example, construction cost is three times as important as installation time, so it is given three times the “weight” when calculating the final score. In this case, a small change in the weight factors can result in a different alternative having the best score.

The next section provides detailed instructions on how to do a scoring comparison.

Steps for Multi-Criteria Scoring

The following figure shows the recommended steps to score and compare alternatives.

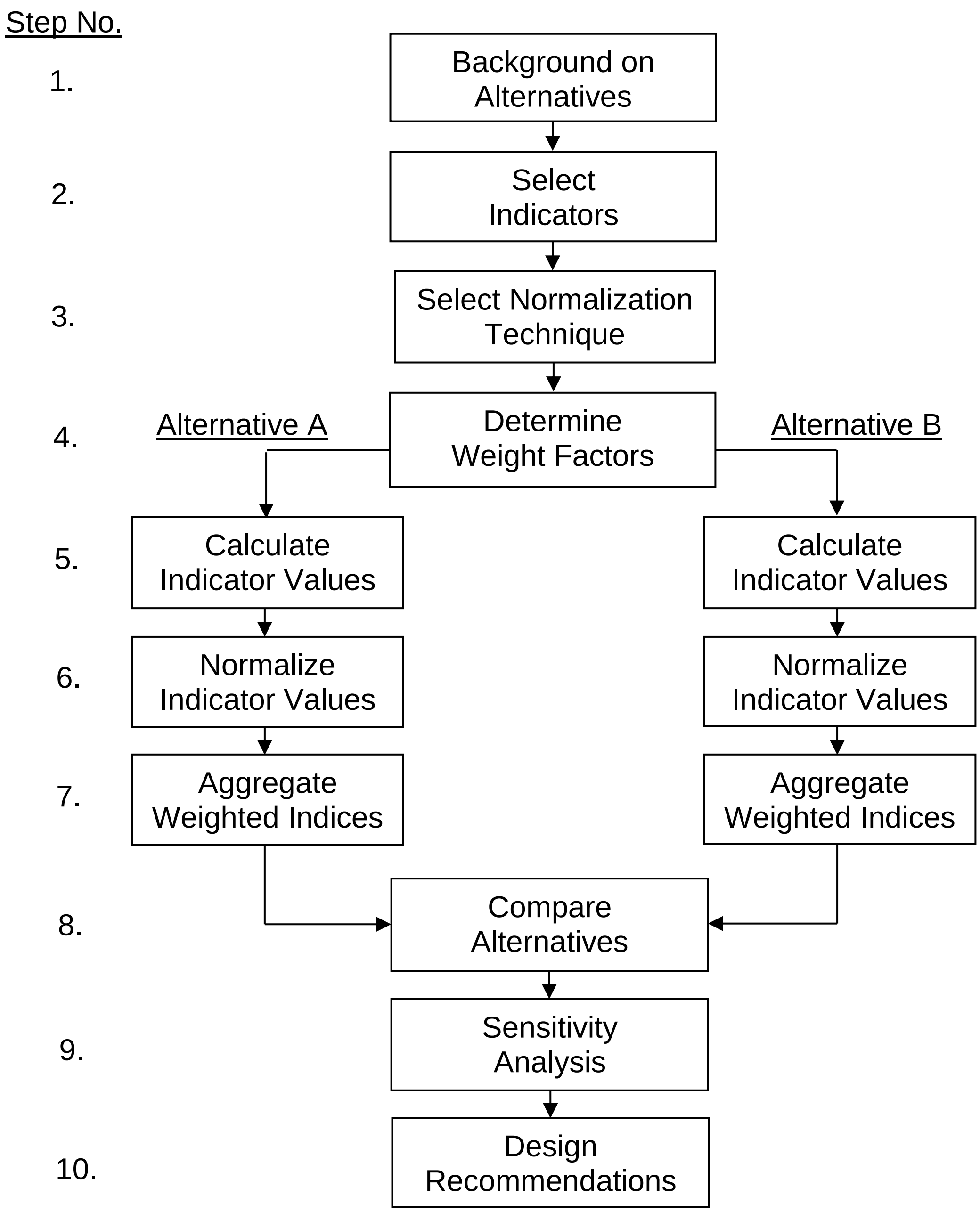

Figure 6: Framework for multi-criteria scoring of alternatives. Additional alternatives can be considered in Steps 5, 6, and 7.

Each step in the multi-criteria scoring framework is described below.

Step 1: Background on Alternatives

The first step is to gather background information on each alternative being considered. Define each system and list the inputs and outputs (energy, water, wastewater, materials, product, gas emissions, solid waste, etc). List significant lifecycle impacts including operation and maintenance requirements.

Step 2: Select Indicators

A good next step is to select the indicators that will be used for the comparison. Consider indicators and metrics used in reference materials and standards set by relevant organizations. An engineer may be justified in creating one or more unique indicators due to project specifics. For a sustainability comparison, indicators should be selected in the ecological, economic, and societal categories. See the next Section for example indicators.

Step 3: Select Normalization Technique

Select how indicator values will be normalized. Normalization factors are multiplied by the indicator values to produce numbers with a maximum value of 1 to simplify the aggregation of values and allow a direct comparison of alternatives. There are three common techniques for determining the normalization factors: internal normalization, external normalization, and existing normalization. Internal normalization involves calculating the indicator values for each alternative and selecting the greatest indicator value as the normalization factor. External normalization uses a reference value that is common for the industry or representative of nearby facilities to account for local conditions. Existing normalization uses the indicator values of any existing processes as the normalization factors for the alternatives. The example in Table 4 uses internal normalization with higher values being "better" than lower values.

Step 4: Determine Weight Factors

Determine the indicator weight factors, which typically vary for each project. Consideration may be given to reference materials, however project specific input from stakeholders is often preferred. In the absence of such input, one approach is to give equal weight for each of the three categories of sustainability (approximately 33.3% each) to ensure each is equally represented in the final scoring.

To reduce subjective bias, consider calculating weight factors with the Analytic Hierarchy Process (AHP) as listed in the References section. In AHP, direct comparisons are made for each pair of indicators, which breaks down the task of creating weight factors into less subjective inputs. Indicator comparison inputs can be obtained from those with a vested interest in the project, such as engineers, owners, operators, local authorities, and community members.

Step 5: Calculate Indicator Values

Calculate the indicator values for each alternative. Ensure indicator values have the same units for each alternative. For sustainability comparisons, the larger the indicator value, the greater the negative ecological, economic, or societal impact. Thus smaller indicator values indicate greater sustainability and a smaller “footprint”.

Step 6: Normalize Indicator Values

Divide each indicator value by the indicator normalization factor to obtain a set of normalized indices.

Step 7: Aggregate Weighted Indices

Multiply each normalized index by the weight factor and sum these weighted indices to obtain an overall aggregated index for each alternative. These can be normalized by dividing each aggregated index by the largest aggregated index value. The normalized aggregated indices represent the “final scores” for each alternative. These final scores have a scale of 0 to 1. Depending on the choices made in Step 3, a value of 1 may be the best or worst score.

Step 8: Compare Alternatives

Compare the results for each alternative. Highlight the best alternative and calculate the percent difference from the next best alternative. A radar plot of the normalized indices for each alternative provides a visualization of the results before applying weights. The area encompassed by each alternative is representative of the sustainability, with smaller areas indicating increased sustainability.

Step 9: Sensitivity Analysis

A sensitivity analysis shows if small changes in the calculations can result in a different alternative being chosen as the winner. Start by determining the impact of any assumptions and uncertainties on the indicator values and potential changes in the weight factors of 10% or more. Scores should be recalculated for each extreme in the range of indicator values and weights. Compare the new results to the original results and assign a plus or minus variance range to each final score. If the ranges overlap for two or more of the best alternatives, there should be decreased confidence in declaring a winning alternative.

Step 10: Design Recommendations

Use the comparison results to consider opportunities to improve the design of the alternatives. For any design changes, recalculate the indicator values and aggregated indices.

Proper documentation should be maintained at each of these steps, so a quality review can be performed. There are many opportunities to make mistakes with math or logic, and a brief review by another Engineer can confirm the results and any conclusions.

Indicator Selection

The selection of indicators, also called criteria, is an important part of the sustainability assessment. Typically an engineer will select a unique set of indicators based on the project specifics. Ideally, the indicators will reflect the potential sustainability impacts of all the alternatives.

The following are potential indicators to consider, organized according to the triple bottom line categories of sustainability:

1. Economic
    a. Capital Cost
    b. Construction Cost
    c. Operating Cost
    d. Lifecycle Cost
    e. Litigation Risk
    f. Life Span

2. Environmental
    a. Potable Water Consumption
    b. Stormwater Management
    c. Solid Waste Produced
    d. Wastewater Produced
    e. Energy Consumption (nonrenewable)
    f. Recycling / Beneficial Reuse
    g. Greenhouse Gas Emissions (non-biogenic)
    h. Air Pollution
    i. Water Pollution
    j. Impact to Natural Areas (forests, wetlands, coastlines, etc)
    k. Impact to Protected Species

3. Social
    a. Employee Productivity
    b. Safety
    c. Chemical Use
    d. Regulatory Acceptance
    e. Partnership Potential

f. Stakeholder Support
g. Aesthetics
h. Land Use
i. Job Creation

To keep the analysis manageable, indicators are chosen to reflect the *significant* sustainability impacts, and minor or insignificant impacts are neglected. The chosen indicators should be independent of each other so that an impact is not counted more than once and so indicators and weights can be easily adjusted during the evaluation process.

Societal indicators can be difficult to quantify. For example, aesthetics can be a very important factor in the design and selection of an alternative, yet it is challenging to quantify aesthetics because each individual has a different perspective and opinion on what is tasteful and beautiful.

Example 1: Roof Type

Kai Alana is a structural engineer working on the design of a new maintenance garage for a client. For the roof, Kai asked the client what materials they prefer. The client said that either an asphalt shingle roof or metal roof would be accepted. The client asked that Kai pick whichever is more sustainable. Kai decided to use the 10 steps presented in Figure 6 to compare the sustainability of the two alternatives.

Step 1: Background on Alternatives

The maintenance garage has an area 2,600 square feet with a gable roof, as shown in Figure 7. The property is located just outside of Lincoln, Nebraska.

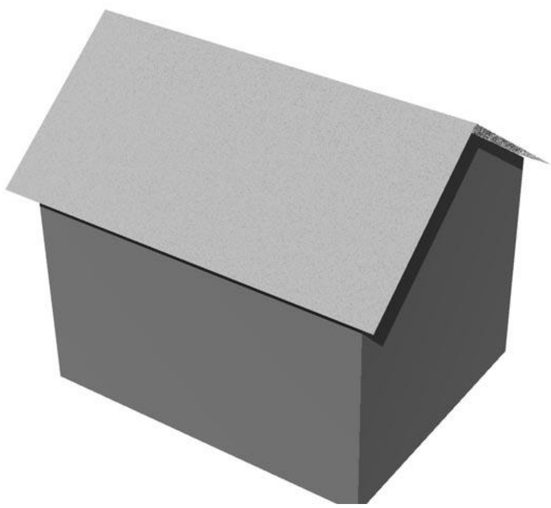

Figure 7: 3D model of a garage with a gable roof.

Source: https://commons.wikimedia.org/wiki/File:Gable_roof.jpg (c) by Wikiwikiyarou; used under CC BY-SA 3.0

As first step in understanding the alternatives, Kai discussed the application with a local roof supplier and requested a quote for each roof type. Also, Kai researched the following qualities for each roof type:

- Roof maintenance
- Life span
- Falling hazards
- Fire protection
- Origins of materials and manufacturing process
- Impact on heating and cooling of the house

Step 2: Select Indicators

Next, Kai reviewed potential indicators for the comparison. He chose the following indicators, organized according to the triple bottom line categories of sustainability:

1. Economic
    a. Lifecycle Cost

2. Environmental
    a. Solid Waste Produced
    b. Non-Recycled Content
    c. Pollution from Manufacturing
    d. Energy Loss

3. Social
    a. Safety (Fall Hazard and Fire Protection)
    b. Aesthetics

Step 3: Select Normalization Technique

Kai chose the internal normalization technique since this is a direct comparison between the two roof types, without an existing roof or industry standard for comparison. Kai decided that lower values will be more sustainable, with a typical scoring range of 0 to 1.

Step 4: Determine Weight Factors

Kai decided to give equal weight for the three categories of sustainability to ensure each is strongly represented in the results. And for simplicity, equal weight is given to the indicators within each category, as shown in Table 5.

Table 5: Weight Factors for Roof Type Sustainability Comparison	
Indicator	Weight Factor
Economic (34%)	
- Lifecycle Cost	34
Environmental (32%)	
- Solid Waste Produced	8
- Non-Recycled Content	8
- Pollution from Manufacturing	8
- Energy Loss	8
Social (34%)	
- Safety	17
- Aesthetics	17
Total (100%)	100

Step 5: Calculate Indicator Values

For this sustainability comparison, the larger the indicator value, the greater the negative ecological, economic, or societal impact. For indicators that are scaled from 1 to 10, the number 1 represents the most sustainable value possible.

For calculating the lifecycle cost, Kai used the present worth approach. He chose a time period of 40 years and an interest rate of 5%. Thus the present worth factor is as follows:

$$PWF = \frac{(1+0.05)^{40}-1}{0.05*(1+0.05)^{40}} = 17.16$$

The asphalt roof requires replacement every 15 years, which will be included in the annual maintenance as $10,000 divided by 15, which is $670 per year. This will be in addition to the $200 per year of normal roof maintenance for both options.

The asphalt shingle roof lifecycle cost is calculated as follows:

$$Lifecycle\ Cost = \$10{,}000 + 870 * 17.16 = \$24{,}900$$

The metal roof lifecycle cost is calculated as follows:

$$Lifecycle\ Cost = \$40{,}000 + 200 * 17.16 = \$43{,}400$$

After calculating all the indicators, Kai input the values in Table 6.

Step 6: Normalize Indicator Values

Kai calculated the normalized indices by setting the largest value as 1 and dividing the smaller value by the larger value. Kai input the normalized index values in Table 6 and made the more sustainable values bold. It can be seen that the asphalt shingle roof is more sustainable in two indicators, and the metal roof is more sustainable in four indicators.

Table 6: Weight Factors for Roof Type Sustainability Comparison

Indicator	Units	Asphalt Shingle		Metal	
		Value	Norm. Index	Value	Norm. Index
Lifecycle Cost	$	24,900	**0.57**	43,400	1
Solid Waste Produced	Scale 1 to 10	8	1	4	**0.50**
Non-Recycled Content	%	90	1	20	**0.22**
Pollution from Manufacturing	Scale 1 to 10	8	1	4	**0.50**
Energy Loss	1 / R Value	2.5	**0.25**	10	1
Safety	Scale 1 to 10	5	1	5	1
Aesthetics	Scale 1 to 10	6	1	4	**0.68**

Step 7: Aggregate Weighted Indices
Kai multiplied the each normalized index by the associated weight factor to obtain the weighted index. He then summed the weighted indices to obtain an overall aggregated index for each alternative, as shown in Table 7. Kai normalized the aggregated indices to get a final score for each alternative.

Table 7: Final Scoring for Roof Type Sustainability Comparison

Indicator	Weight Factor	Asphalt Shingle		Metal Roof	
		Normal. Index	Weighted Index	Normal. Index	Weighted Index
Lifecycle Cost	34	0.57	19	1	34
Solid Waste Produced	8	1	8	0.50	4
Non-Recycled Content	8	1	8	0.22	2
Pollution from Manufacturing	8	1	8	0.50	4
Energy Loss	8	0.25	2	1	8
Safety	17	1	17	1	17
Aesthetics	17	1	17	0.68	12
Aggregated Index		-	**79**	-	81
Final Score (Normalized to 1)		-	**0.98**	-	1.0

Step 8: Compare Alternatives
Kai observed that the asphalt shingle roof has a lower score, and thus it is the “winner” of his sustainability comparison. The asphalt shingle scored 2% lower than the metal roof, which is a very small difference. The metal roof scored slightly better in the environmental and social categories, but the asphalt shingle roof scored significantly better in the economic category.

Step 9: Sensitivity Analysis

With only a 2% difference in the score of the two alternatives, Kai had a low level of confidence in declaring the asphalt shingles more sustainable. He noted that a slight change in any of the calculated indicator values or weight factors could change the outcome.

Step 10: Design Recommendations

In the process of evaluating these alternatives, Kai identified the following design modifications that would result in increasing the sustainability of the roof design:

- Use recycled fiberglass shingles which also have a high fire resistance
- Use a high energy star rated product
- Add solar panels on the roof
- Add anchor points on the roof
- Coordinate the architectural design of the house and roof to maximize the aesthetic appeal
- Add a downspout to a rain barrel for stormwater management

Kai had his coworker review his work, and then he presented his findings to the client. The client agreed to proceed with asphalt shingle roof. Several of the design recommendations were integrated into the design to make the roof more sustainable.

Example 2: Odor Control Systems

Ivy Ganley is an environmental engineer working for the City of Fremont, Delaware. There have been several complaints of a bad smell in one of the neighborhood parks. The odors were tracked to a nearby sewer structure. Ivy has been asked to compare the sustainability of two alternatives to remove the odors.

The two odor control alternatives are a biofilter bed system and an activated carbon system. Ivy decided to use the multi-criteria approach to compare the two alternative odor control systems and to discover ways to improve the sustainability of each system.

Step 1 - Background on Alternatives

Ivy started by reviewing the design of each odor control system. She developed a preliminary size and layout of each system, as summarized below.

Activated Carbon System

The activated carbon system functions by blowing odorous air through activated carbon media which adsorbs the hydrogen sulfide, H_2S, and other odorous pollutants. An exhaust pipe discharges treated air directly to the atmosphere. A schematic of the system is shown in Figure 8.

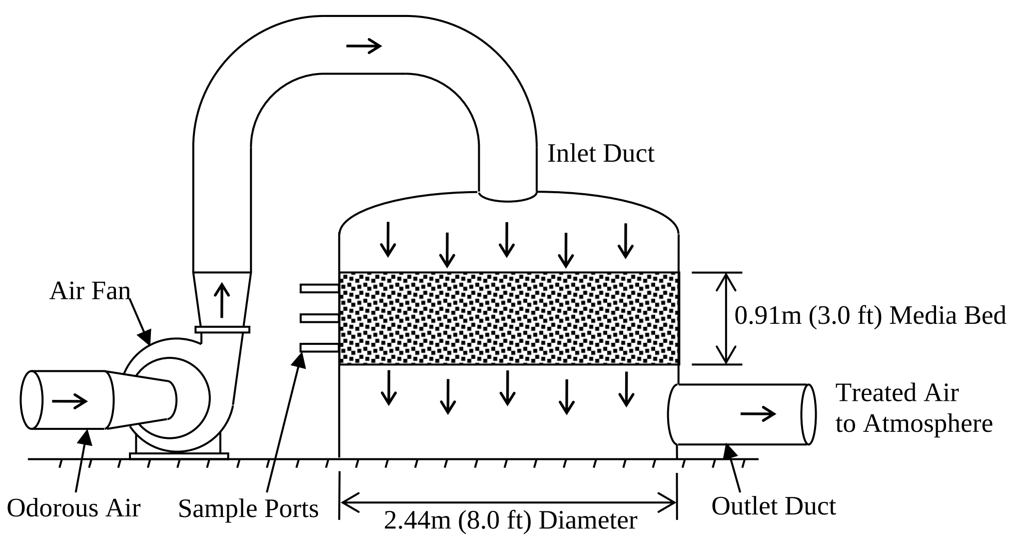

Figure 8: Schematic diagram of the activated carbon system.

Components of the activated carbon system are as follows:

- Air fan with a 5.6 kW (7.5 HP) motor and control panel
- Cylindrical fiberglass enclosure
- Bed of pelletized activated carbon contained by the enclosure
- Inlet and outlet air ducts

The carbon media is virgin, pelleted, caustic impregnated bituminous coal. It can be regenerated a limited number of times using an in-situ caustic solution treatment. Often operators will choose media replacement over regeneration to avoid hazardous chemical handling. The lifespan of the activated carbon is calculated as the adsorption capacity divided by the H_2S load. In this case, the capacity is 597,940 g H_2S, and the load 61.4 g H_2S/h, resulting in a lifespan of 406 days, or 1.11 years.

Biofilter Bed System

The biofilter bed system also uses a blower to draw air from the sewer structure. The odorous air is forced through a buried biofilter bed which removes the odor compounds and emits treated air to the atmosphere. A schematic of the system is shown in Figure 9.

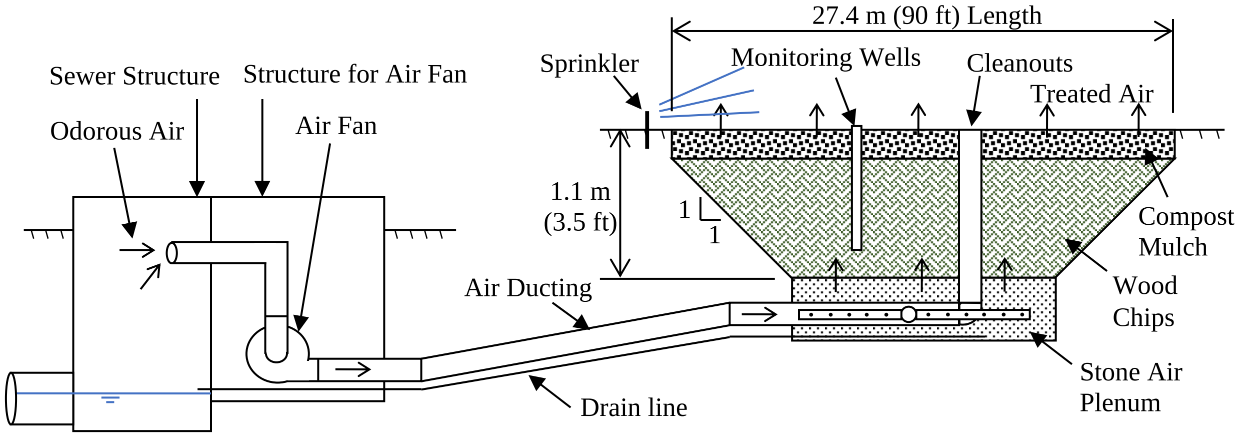

Figure 9: Schematic diagram of the biofilter bed system.

Components of the biofilter bed system are as follows:

- Air fan with a 14.9 kW (20 HP) motor and control panel
- Inlet and outlet air ducts
- A network of perforated pipes at the bottom of the bed in a stone plenum
- Biofilter bed composed of wood chips

- Moisture is maintained by an automatic spray irrigation system
- Monitoring wells
- Surface layer of compost that can sustain a flower bed

Odor removal is accomplished by bacteria living on the surface of the wood chips. The bacteria convert H_2S to sulfuric acid. To keep the bacteria active in removing odors, the media must remain moist, and so daily irrigation is required. Ordinary wood chips obtained from local residents are acceptable.

Step 2 – Selection of Indicators

To help select the indicators, Ivy reviewed a reference paper on sustainability metrics and an example sustainability assessment. She made a list of potential indicators and considered which were most relevant to the activated carbon and biofilter bed systems. Ivy chose the following six indicators for the comparison:

1. Economic
    a. Lifecycle Cost

2. Environmental
    a. Energy Use
    b. Water Use
    c. Solid Waste
    d. Greenhouse gas (GHG) emissions

3. Social
    a. Aesthetics

Step 3 - Selection of Normalization Technique

Ivy chose the internal normalization technique since the study is a direct comparison between the biofilter bed and activated carbon systems.

Step 4 - Determination of Weight Factors

Ivy decided to gain the input of three of her coworkers in determining the weights for the six indicators. She also decided to use the Analytic Hierarchy Process (AHP). Ivy made a survey to give each of her coworkers. The survey listed each combination of two indicators and asked the respondent to choose the more import indicator from each pair, along with the level of importance, called the intensity. The survey feedback was averaged, and are shown in Table 8.

Table 8: Direct comparisons of Indicators for AHP Calculation			
Indicator A	Indicator B	More Important Indicator	Intensity (0 to 9)
Energy Use	Aesthetics	Energy Use	6
Energy Use	GHG Emissions	Energy Use	4
Energy Use	Lifecycle Cost	Equal	2
GHG Emissions	Aesthetics	Equal	3
GHG Emissions	Lifecycle Cost	Lifecycle Cost	6
Lifecycle Cost	Aesthetics	Lifecycle Cost	6
Solid Waste	Aesthetics	Solid Waste	3
Solid Waste	Energy Use	Energy Use	4
Solid Waste	GHG Emissions	Solid Waste	2
Solid Waste	Lifecycle Cost	Lifecycle Cost	4
Solid Waste	Water Use	Solid Waste	2
Water Use	Aesthetics	Water Use	2
Water Use	Energy Use	Energy Use	3
Water Use	GHG Emissions	Equal	1
Water Use	Lifecycle Cost	Lifecycle Cost	4

Ivy used the intensity results in Table 8 to calculate weight factors using the AHP approach. She entered the intensities in a matrix with each indicator as a row and column, and performed algebra to obtained averaged weight factors. Table 9 shows the completed matrix with the average values on the right being the weight factors with a scale of 0 to 1. These weight factors are multiplied by 100 to be shown as a percent.

For more information on performing AHP calculations, see the References section.

Table 9: AHP Matrix with Resulting Weight Factors							
	Aesthetics	Cost	GHG	Energy	Water	Waste	**Weight**
Aesthetics	0.046	0.065	0.025	0.043	0.042	0.034	**0.042**
Cost	0.292	0.410	0.425	0.450	0.366	0.375	**0.387**
GHG	0.138	0.072	0.075	0.074	0.085	0.061	**0.084**
Energy	0.292	0.246	0.275	0.270	0.254	0.375	**0.285**
Water	0.092	0.095	0.075	0.090	0.085	0.051	**0.081**
Waste	0.138	0.112	0.125	0.074	0.169	0.102	**0.120**

Step 5 - Calculation of Indicator Values

Ivy calculated the indicator values for each of the two systems based on a 20-year lifecycle. Here work is summarized below.

Energy Use

The activated carbon system has an air fan motor that will consume approximately 4500 W continuously, resulting in an energy use per unit airflow is 1.02 W/(m^3/h). The biofilter bed system has an air fan motor that will consume an average of 13,400 W continuously, resulting in an energy use per unit airflow is 2.63 W/(m^3/h).

Water Use

The activated carbon unit only uses water for cleaning operations, requiring an estimated 5 L/d (1.32 gpd), which totals 1825 L/yr, or 0.415 (L/yr)/(m^3/h). The biofilter bed spray system runs twice a day at one hour each time, from spring until fall. The rotor heads release approximately 1800 L/d (475 gpd) for 200 days per year, for an average 360,000 L/yr, or 70.6 (L/yr)/(m^3/h).

Solid Waste

The only waste produced by the activated carbon system is the annual landfill disposal of spent media, which results in a waste quantity of 2460 kg/yr (5420 lb/yr), or 0.559 (kg/yr)/(m^3/h). For the biofilter bed, media needs to be replaced approximately every five years, with spent media disposed of at a landfill. The weight of disposed wood chips and compost is 12,835 kg/yr (28,300 lb/yr). The weight of the replacement wood chips is subtracted since they are from recycled yard waste that is saved from disposal. Therefore the biofilter bed solid waste is 4066 kg/yr (8963 lb/yr), or 0.797 (kg/yr)/(m^3/h).

Lifecycle Cost

Lifecycle cost is calculated as the present worth of capital costs and annual operation costs, using a present worth factor. A timeframe of 20 years is assumed, with an interest rate of 5%, resulting in a present worth factor of 12.46. For the activated carbon system, capital costs are $116,300 and operation costs are $19,100 per year, resulting in a present worth cost of $354,300 or $80.52/($m^3$/h). For the biofilter bed system, capital costs are $65,200 and operation costs are $18,700, resulting in a present worth cost of $298,200 or $58.47/($m^3$/h).

GHG Emissions

The activated carbon system does not have a significant impact on direct GHG emissions in the air stream during operation; however, there are indirect GHG emissions resulting from the initial carbonization and activation of the media, and the system electrical energy use. The initial carbonization and activation of the carbon media has been reported to emit 560 g of carbon dioxide and 54 g of methane per kg of media, resulting in the emission of 1377 kg CO_2/yr and 133 kg CH_4/yr. The Global Warming Potential, GWP, of methane is 25 CO_2 equivalents (CO_2e) based on a 100-year time horizon. So the methane emission is 3325 kg CO_2e/yr, for a total GHG emission of 4702 kg CO_2e/yr. Also, there are GHG emissions due to electrical energy consumption, which is calculated to be 27,950 kg CO_2e/yr using the United States regional emissions factor of 0.7094 kg CO_2e/kWH. Therefore the activated carbon system GHG emissions are 7.42 (kg CO_2e/yr)/(m^3/h).

Biofilter beds have been found to remove methane gas due to the natural presence of methanotrophic bacteria. The methane loading rate is estimated at 10.94 g/(m^2h), which corresponds to a methane removal rate of 35%. The result is the removal of 16,250,000 kg CO_2e/yr. GHG emissions due to electrical energy consumption are 83,280 kg CO_2e/yr using the same regional emissions factor. Therefore the biofilter bed GHG emissions are a net reduction of 3170 (kg CO_2e/yr)/(m^3/h).

Aesthetics

The aesthetic impact is scored using a ratio of negative to positive attributes. The activated carbon system has four negative attributes (requires enclosure/building, exposed ductwork, visually unnatural, limited configurations available) and one positive attribute (small footprint), resulting in a score of 4. The biofilter bed has two negative attributes (large footprint, air fan requires enclosure/building) and two positive attributes (bed can be below ground, visually natural) giving it a score of 1.

Step 6 - Normalization of Indicator Values

Ivy normalized the results as shown in Table 10. For GHG emissions, the biofilter bed system has a negative indicator value, but a normalized index of 0 is assigned since that is the minimum allowed value for aggregation. The activated carbon system has lower values in energy use, water use, and solid waste. The biofilter bed has lower values in lifecycle cost, GHG emissions, and aesthetics. Ivy double checked that lower values indicate an increase in sustainability for all indicators.

Table 10: Summary of Indicators and Normalized Indices

Indicator	Units	System	Indicator Value	Normalized Index
Energy Use	$\frac{W}{m^3/h}$	Carbon	1.02	0.388
		Biofilter	2.63	1.000
Water Use	$\frac{L/yr}{m^3/h}$	Carbon	0.415	0.005
		Biofilter	70.60	1.000
Solid Waste	$\frac{kg/yr}{m^3/h}$	Carbon	0.559	0.701
		Biofilter	0.797	1.000
Lifecycle Cost	$\frac{\$}{m^3/h}$	Carbon	80.52	1.000
		Biofilter	58.47	0.726
GHG Emissions	$\frac{kg\ CO_2e/yr}{m^3/h}$	Carbon	7.42	1.000
		Biofilter	-3170	0.000
Aesthetics	$\frac{Negative}{Positive}$	Carbon	4	1.000
		Biofilter	1	0.250

Step 7 – Aggregation of Weighted Indices

Ivy calculated the weighted indices for each indicator by multiplying the normalized index by the weight factor, as shown in Table 11. The indices were summed to provide an aggregated index and final score for each alternative. The lower value is considered more sustainable.

Table 11: Final Scoring for Odor Control Sustainability Comparison					
Indicator	Weight Factor	Activated Carbon		Biofilter Bed	
		Normalized Index	Weighted Index	Normalized Index	Weighted Index
Energy Use	28.5	0.388	11.058	1.000	28.500
Water Use	8.1	0.005	0.041	1.000	8.100
Solid Waste	12.0	0.701	8.412	1.000	12.000
Lifecycle Cost	38.7	1.000	38.700	0.726	28.096
GHG Emissions	8.4	1.000	8.400	0.000	0.000
Aesthetics	4.2	1.000	4.200	0.250	1.050
Aggregated Index		-	**70.811**	-	77.746
Final Score (Normalized to 1)		-	**0.911**	-	1.000

Step 8 – Comparison of Alternatives

Ivy reviewed the results which indicate that the activated carbon system is overall slightly more sustainable with a score that is 8.9% lower than the biofilter bed system. Ivy observed that each system has three indicators in which they are considered more sustainable, so the weight factors have a significant influence on the overall outcome.

The lifecycle cost indicator has the greatest weight, and the biofilter bed has a lifecycle cost that is 15.8% lower than the activated carbon system due to relatively low capital costs. The energy use indicator has the next greatest weight, and the activated carbon system uses 61.2% less energy, so it gains a significant advantage. Ivy concluded that the lower energy use is the single biggest reason the activated carbon system won the comparison.

Ivy made the radar diagram displayed in Figure 4 to view the normalized indicator values graphically. This plot assumes equal indicator weights. The area encompassed by each system represents the unsustainable impact of the system, with a smaller area indicating increased sustainability. The biofilter bed has a slightly smaller area and without the weight factors it would be considered 2.9% more sustainable.

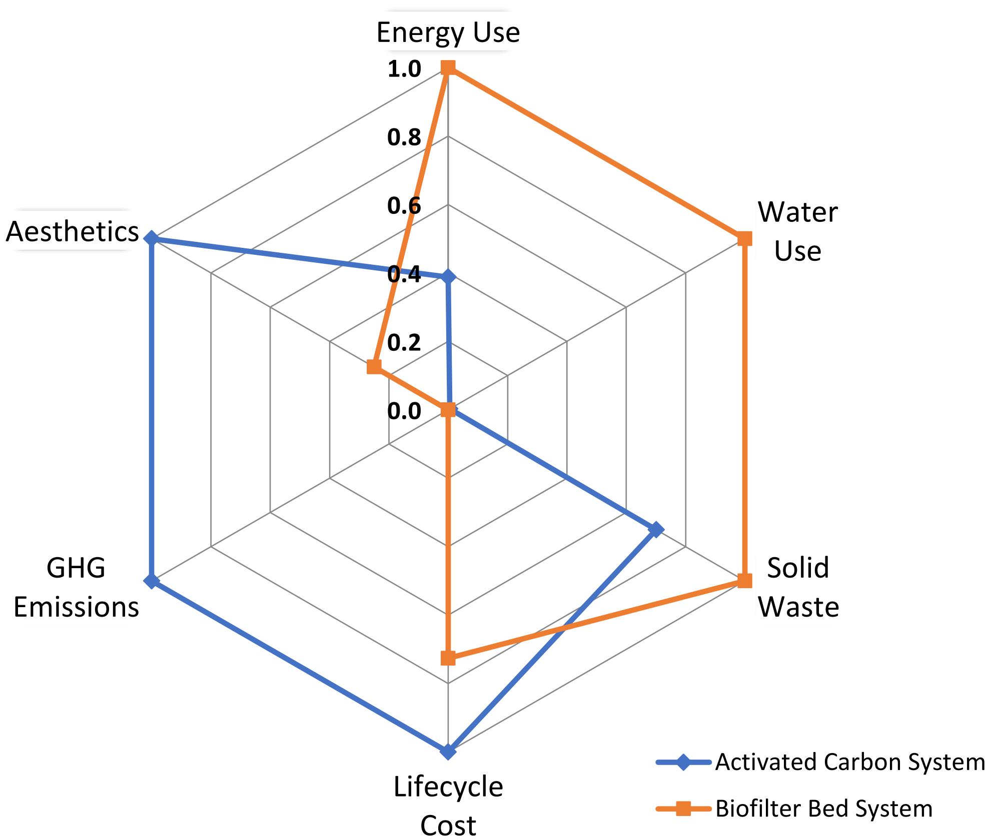

Figure 4: Radar diagram of normalized indices for each alternative. A smaller area corresponds with a smaller footprint and being more sustainable.

<u>Step 9 – Sensitivity Analysis</u>

Ivy reviewed her indicator value calculations and realized that the energy use, water use, and GHG emission values for the biofilter bed included assumptions and could vary greatly due to operating conditions. She recalculated the scores for the range of assumptions, and concluded that energy use is the only indicator that would have a significant impact on the final score. For example if the biofilter bed energy use were 25%

lower, the final score would of the two systems would be very similar, however the activated carbon system would still be the winner.

Ivy noted that the values for aesthetics for both systems will vary by location; however, with such a small weight value, aesthetics does not have a great effect on the comparison results. There appears to be no calculation assumption that would change the final result that the activated carbon system is slightly more sustainable.

Ivy wondered if selected different indicators would impact the results. She found two reference comparisons that used different indicators and weights. She recalculated the scores with the different indicators and weights. The first reference did not include aesthetics and results in the activated carbon system being 14.9% more sustainable. The second reference did not include water use and gave much less weight to energy use, and results in the biofilter bed system being 14.5% more sustainable. These results confirm that importance given to energy use decides which of the two systems is more sustainable.

Step 10 – Design Recommendations

Ivy identified several design modifications that would increase sustainability. For the activated carbon system, both lifecycle costs and solid waste can be decreased significantly by using a recently developed surface-modified non-impregnated activated carbon which can be regenerated with water instead of caustic soda. This media has an added catalytic functionality which oxidizes H_2S and converts it to water-soluble sulfur compounds. The regeneration wastewater appears acceptable to release into the sewer system, and regeneration can be done 10 times before media replacement is required.

For the biofilter bed system, significant energy reduction can be achieved by using a variable frequency drive (VFD). Without the VFD, the operating point on the fan curve moves across a large range so that most of the time the air fan is running at low efficiency. With a VFD, the air fan speed can be slowed during low pressure to provide the same airflow rate with the benefits of power savings of nearly 50%, reduced sound, and increased air fan longevity. The VFD can be programmed to adjust the speed according to pressure gauge readings. The energy cost savings over the 20-year lifecycle would fully offset the initial cost of the VFD.

Ivy presented her findings to the City Manager and it was decided to proceed with an activated carbon system with water regeneration media.

Helpful References

Life Cycle Assessment Tools:

https://www.basf.com/us/en/who-we-are/sustainability/we-drive-sustainable-solutions/quantifying-sustainability/eco-efficiency-analysis.html

https://www.iso.org/standard/37456.html

ISI Envision Framework:

https://sustainableinfrastructure.org/envision/use-envision/

Indicator Selection and Calculations:

http://nbis.org/nbisresources/metrics/triple_bottom_line_indicators_process_industries.pdf

Sustainability Comparisons with Multi-Criteria Approach:

Martins, A.; Mata, T.; Costa, C.; Sikdar, S. (2007) Framework for Sustainability Metrics; *Industrial & Engineering Chemical Research*; Vol 46, 2962-2973.

Piluso, C.; Huang, Y.; Helen, H. (2008) Ecological Input-Output Analysis-Based Sustainability Analysis of Industrial Systems; *Industrial & Engineering Chemical Research*; Vol 47, 1955-1966.

Sikdar, Subhas (2003) Sustainable Development and Sustainability Metrics; *AIChE Journal*; 49 (8), 1928-1932.

Tugnoli, A.; Santarelli, F.; Cozzani, V. (2008); An Approach to Quantitative Sustainability Assessment in Early Stages of Process Design; *Environmental Science & Technology*; Vol. 42, 4555-4562.

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Saaty, Thomas L. (2001) Fundamentals of Decision Making and Priority Theory with the Analytic Hierarchy Process; RWS Publications; Pittsburgh, PA.

