**SUSTAINABILITY ROOT CAUSE ANALYSIS (SRCA)**

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**Introduction**

Over the past decades, many methodologies and indicators have been proposed to assess sustainability issues in the chemical and energy production systems. However, a major challenge is to identify the bottleneck issues in order to improve its sustainability effectively. The multi-dimensional nature of sustainability requires a more comprehensive accounting for the impacts of various factors. The complicated cause-and-effect relationships require the capacity of conducting a systematic sustainability root cause analysis method (SRCA) to identify the key steps towards sustainability improvement.

The study and application of SRCA techniques in sustainable manufacturing will encourage students to develop critical thinking skills. This education module is suitable for teaching seniors and graduate students. In this section, the motivation of Sustainability Root Cause Analysis (SRCA) and the basic techniques are presented. Root cause analysis (RCA) is originally a quality management concept. It is a powerful tool to pinpoint the obstacles to improvement. It is usually used in a reactive mode to determine the causes of problems which have already occurred. There are several tools that can be used to perform a root cause analysis, such as 5 Whys, the Pareto chart, and the Fish-bone diagram.

**Rationale: Sustainability Root Cause Analysis for ensuring Sustainable Engineering**

Due to the sophistication of processes, the fundamental causes leading to an inadequate sustainability performance may not be immediately apparent. The sustainability root cause analysis (SCRA) method described here can be used for chemical and energy production systems. Stemmed from RCA, the SRCA framework is built on the combination of Pareto chart and the Fishbone diagram, in conjunction with a set of sustainability metrics for conducting comprehensive sustainability assessment on complex chemical and energy production systems along each dimension of sustainability.

**Course Content: Sustainability Root Cause Analysis Methods and Applications**

The sustainability root cause analysis framework consists of the Pareto analysis and the Fish-bone diagram, along with a set of sustainability metrics. Due to the multi-dimensional nature of sustainability, a good root cause analysis method depends on an appropriate sustainability assessment system. A comprehensive sustainability assessment must consider each dimension of sustainability methodically. In the following sections, the Pareto analysis method, fish bone diagram and sustainability assessment methodologies are introduced respectively.

*The Pareto Analysis*

The Pareto analysis, also known as the 80-20 rule, is named after Vilfredo Pareto, an Italian economist. According to its principle, for most events, roughly 80% of the effects / problems come from 20% of causes. The Pareto analysis helps focus the attention on the most important causes and avoids the wastage of time and energy on minor causes.

A combination of a line and bar chart is produced to identify the top 20% of problems. The procedure to prepare the chart is outlined below:

(a) The first step is to prepare a table showing all causes with their impacts in percentage. An example is provided below.

Table 1. The Starting Table for Pareto Analysis

|  |  |
| --- | --- |
| Causes | Percentage Impact (%) |
| Cause 1 | 20 |
| Cause 2 | 15 |
| Cause 3 | 25 |
| Cause 4 | 30 |
| Cause 5 | 10 |

(b) The table is then sorted in descending order by percentage.

(c) As shown below, a third column is added to show cumulative percentage.

Table 2. A Completed Table for Pareto Analysis

|  |  |  |
| --- | --- | --- |
| **Causes** | **Percentage Impact (%)** | **Cumulative Percentage (%)** |
| Cause 4 | 30 | 30 |
| Cause 3 | 25 | 55 |
| Cause 1 | 20 | 75 |
| Cause 2 | 15 | 90 |
| Cause 5 | 10 | 100 |

(d) A line chart is prepared with the causes on the x-axis and their cumulative percentage values are on y-axis.

(e) On the same graph, a bar chart is added with causes on the x-axis and percent impacts on the y-axis. An example is shown in Figure 1.

Figure 1. The Initial Chart for Pareto Analysis

(f) A horizontal line is drawn at 80%. A vertical line is added at the intersection of the 80% line with curve.

(g) The point of intersection of the vertical line and x-axis separates the major causes to the left side and minor causes to the right side. An example is provided in Figure 2.

Figure 2. A Completed Chart for Pareto Analysis

This technique helps the users to identify the top causes that need to be addressed to resolve the 80% of the problems. Once the major causes are identified, the Fish-bone diagram can be used to illustrate the root causes of the problems. Then efforts can be made to remove the major obstacles in order to develop a more sustainable process.

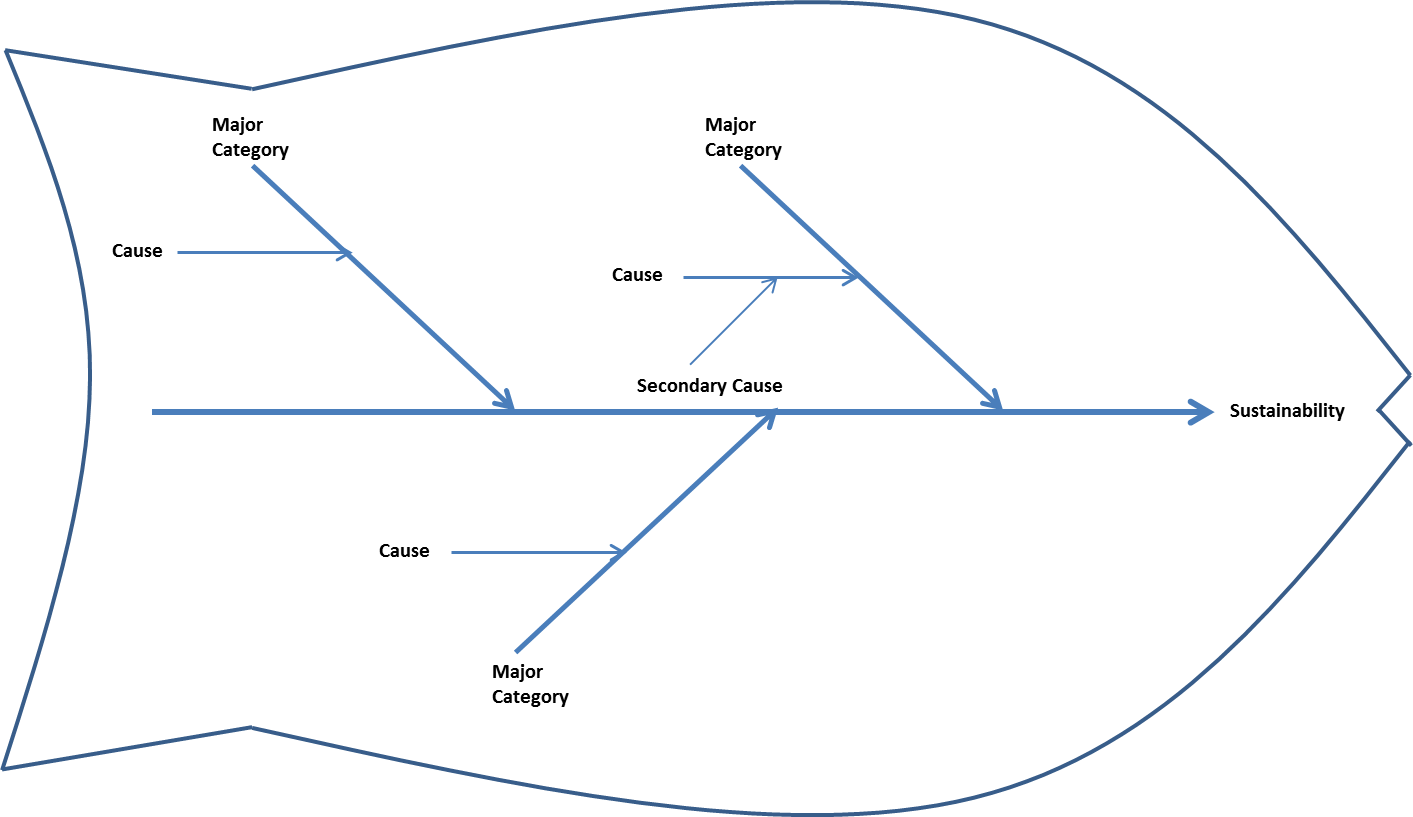


Figure 3. An example of the Fishbone Diagram

*The Fish-Bone Diagram*

The Fish-Bone diagram, as shown in Figure 3, also known as the Ishikawa diagram or cause-and-effect diagram, was developed by Kaoru Ishikawa as a quality control tool. The Fish-bone diagram represents the major problems in a process. In the case study considered here, the Pareto analysis results are used to prepare the Fish-Bone diagram. The Fish-bone diagram helps in visualizing and conveying important relationships between seemingly disconnected elements.

The economic analysis, the environmental impacts, and the societal concerns, which form the basis of sustainability assessment, are used as the major criteria to prepare the Fish-bone diagram and Pareto charts. Many different sustainability assessment methodologies have been proposed by different groups and societies. One assessment method is outlined below as an example.

***SUSTAINABILITY ASSESSMENT METHODOLOGY***

In sustainable development, measuring the economic, environmental and social impacts of an economic activity using specific and defined indicators is very important. The sub-categories considered in each of the dimensions are described below.

**Economic Criteria:** From extensive research [1, 2], it has been determined that the most appropriate economic sub-indices are profit, net present value (NPV) and internal rate of return (IRR) or discounted cash flow rate of return (DCFRR). Profit is calculated by subtracting the production cost from total sales. IRR and NPV include initial investment, annual profit and depreciation, salvage value, and interest on investment. A positive NPV indicates that the project is feasible. When choosing from alternatives, the project with the highest positive NPV is preferred.

NPV = -CTCI + ∑ CA,m / (1+r)m (1)

CTCI: Total capital investment before base year composed of total fixed capital cost, working capital cost

C A: Total annual income cash flow after base year m

r : The interest rate

x : The project life after base year

IRR reflects the highest, after-tax interest or discount rate at which the project can just break even. A project that yields a higher IRR is considered more profitable.

IRR = FV / (1+i)n = FV (1-d) (2)

FV : The nominal value of a cash flow amount in a future period

i : The interest rate

d : The discount rate

n : The time in years before the future cash flow occurs

Based on the need, the user can also choose other indicators, such as capital cost only, or operating cost only, or total cost.

**Environmental Criteria:** EPA’s waste reduction (WAR) algorithm [3] analyzes the environmental impacts at the manufacturing stage for the life cycle of the chemical process. The main impact categories are:

Table 3. Eight Categories of Environmental Impacts Defined by EPA

|  |  |  |
| --- | --- | --- |
| **General Impact Category** | **Impact Category** | **Measure of Impact Category** |
| Human Toxicity | Ingestion | LD50 |
| Inhalation/Dermal | OSHA PEL |
| Ecological Toxicity | Aquatic Toxicity | Fathead Minnow LC50 |
| Terrestrial Toxicity | LD50 |
| Atmospheric Impacts | Global Warming Potential | GWP |
| Ozone Depletion Potential | ODP |
| Regional Atmospheric Impacts | Acidification Potential | AP |
| Photochemical Oxidation Potential | PCOP |

The WAR algorithm provides a relative indication of the environmental friendliness or unfriendliness of a given process based on the potential environmental impacts of the chemicals. The PEI indexes use mass and energy balance to calculate environmental impacts of the process as shown in eq.3. The WAR software contains a database of relative environmental impact scores.

(3)

Where is the amount of potential environmental impact inside the system (chemical process plus energy generation process), and are the input and output rates of potential environmental impact to the chemical process, and are the input and output rates of potential environmental impact to the energy generation process, and are the outputs of potential environmental impact associated with waste energy (denoted by the subscript we) lost from the chemical process and the energy generation process, and where is the rate of generation of potential environmental impact inside the system.

There are other environment impact assessment methods available, such as the TRACI method (from EPA) [4] (http://www.earthshift.com/software/simapro/traci2), RECIPE method [5](http://lcia-recipe.net/), EcoTox method [6](http://www.epa.gov/med/Prods\_Pubs/ecotox.htm) etc. It is up to the user to decide which method to choose.

**Social Criteria:** Indicators of social sustainability should reflect the company’s treatment of its employees, suppliers, contractors and customers. In the early design stage, safety is the most appropriate indicator. Since established methods like HAZOP require detailed information like P&IDs, inherent safety [7-10] is used as the criterion to judge the social impact of a chemical production process in the early design stage. The Inherent Safety Index is the sum of chemical and process safety index. Chemical safety index considers flammability, explosiveness, toxicity, corrosiveness and quantity of all chemicals involved in the process. Process safety considers safety score and quantity of process equipment. The scores breakdown is shown in the tables in the Appendix 2.

**Connections to Existing Core Curriculum**

Root cause analysis method is currently taught in quality control courses, while the economic, environmental and social aspects of sustainability assessment are individually taught in Engineering Economics, Environmental Sciences and Process Safety courses respectively. This module can be used in a Process Analysis or Process Design course in undergraduate curriculum, or in a graduate level course.

**Case Study**

1. SRCA for Biodiesel Production Process
2. A steam methane reforming Process
3. A polygeneration Process
4. SRCA of a LNG Process

Aspen Plus process simulation file, problem statement and solution for these case study problems are provided.

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**Appendix 1**

**COMPUTER TOOLS**

**(a) Aspen Plus**

The process simulation software package Aspen Plus was used to simulate all these processes. Aspen Plus is very useful and convenient for the simulation of chemical plants. The simulator output provides the necessary data to conduct the sustainability assessment. A complete tutorial on Aspen Plus can be found at: http://web.ist.utl.pt/mcasquilho/acad/Aspen/AspUserGuide10.pdf. Aspen Plus version 7.1 was used in this project.

**(b) Aspen Economic Evaluator**

Aspen Economic Evaluator is used to estimate the capital cost of the two processes (Aspen Icarus 2006). The latest version can be activated from within the Aspen Plus window. It maps the equipment, sizes it, and provides a comprehensive estimate of capital cost, including operating costs and investment analysis. The integrated economics step-by-step video tutorial is available from Aspen Tech: http://tinyurl.com/c9lbvwb

**(c) WAR Algorithm**

WAste Reduction algorithm: The http://www.epa.gov/nrmrl/std/war/sim\_war.htm was developed by the EPA. The method is based on a potential environmental impact (PEI) balance for chemical processes. The result of the PEI balance is an impact (pollution) index that provides a quantitative measure of the impact of the waste generated in the process. Case studies can be conducted by directly importing data from Aspen Plus into WAR algorithm, which is quite convenient.

**Appendix 2:**

Tables used in the calculation of inherent safety index are listed below.

**Chemical Inherent Safety:**

Table 4a. Flammability

|  |  |
| --- | --- |
| **Flammability, IFL** | **Score** |
| Nonflammable | 0 |
| Combustible (flash point > 55 C) | 1 |
| Flammable (flash point <= 55 C) | 2 |
| Easily flammable (flash point < 21 C) | 3 |
| Very flammable (flash point < 0 C & boiling point <= 35 C) | 4 |

Table 4b. Explosiveness

|  |  |
| --- | --- |
| **Explosiveness (UEL-LEL) vol%, IEX** | **Score** |
| Non explosive | 0 |
| 0-20 | 1 |
| 20-45 | 2 |
| 45-70 | 3 |
| 70-100 | 4 |

*(Note: UEL and LEL denote the upper and lower explosive limit. The difference between the two serves as the indicator for explosive potential)*

Table 4c. Toxicity

|  |  |
| --- | --- |
| **Toxic Limit (ppm), ITOX** | **Score** |
| TLV > 10000 | 0 |
| TLV <= 10000 | 1 |
| TLV <= 1000 | 2 |
| TLV <= 100 | 3 |
| TLV <= 10 | 4 |
| TLV <= 1 | 5 |
| TLV <= 0.1 | 6 |

Table 4d. Corrosiveness

|  |  |
| --- | --- |
| **Corrosiveness, ICOR** | **Score** |
| Carbon steel | 0 |
| Stainless steel | 1 |
| Better material needed | 2 |

**Process Inherent Safety:**

Table 4e. Inventory

|  |  |
| --- | --- |
| **Inventory, II** | **Score** |
| 0-1 t | 0 |
| 1-10 t | 1 |
| 10-50 t | 2 |
| 50-200 t | 3 |
| 200-500 t | 4 |

Table 4f. Process Temperature

|  |  |
| --- | --- |
| **Process Temperature, IT** | **Score** |
| < 0 oC | 1 |
| 0-70 oC | 0 |
| 70-150 oC | 1 |
| 150-300 oC | 2 |
| 300-600 oC | 3 |
| >600 o | 4 |

Table 4g. Process Pressure

|  |  |
| --- | --- |
| **Process Pressure, IP** | **Score** |
| 0.5-5 bar | 0 |
| 0-0.5 or 5-25 bar | 1 |
| 25-50 bar | 2 |
| 50-200 bar | 3 |
| 200-1000 bar | 4 |

Table 4h. Equipment Safety

|  |  |
| --- | --- |
| **Equipment Safety, IEQ** | **Score** |
| Equipment handling nonflammable, nontoxic materials | 0 |
| Heat exchangers, pumps, towers, drums | 1 |
| Air coolers, reactors, high hazard pumps | 2 |
| Compressors, high hazard reactors | 3 |
| Furnaces, fired heaters | 4 |