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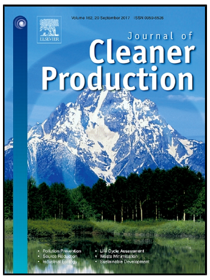

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New composite sustainability indices for Cradle-to-Cradle process design: Case study on thinner recovery from waste paint in auto industries

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LIST OF ABREVIATIONS

Abbreviation	Description
A	Equipment size in their corresponding units (e.g. heat transfer area in m^2 for heat exchangers)
AIChE	American Institute of Chemical Engineers
AHP	Analytical Hierarchical Process
AP	Acidification potential
ATM	Atmosphere
ATP	Aquatic toxicity potential
C_P	Equipment cost ($)
CSI	Composite Sustainability Index
f_i	Frequency of Accidents for Chemical *i*
GUI	Graphical User Interface1
GWP	Global warming potential
H_i	Hazard Effects of Chemical *i*,
HTPI	Human toxicity potential by ingestion
HTPE	Human toxicity potential by exposure dermal and inhalation
HV	Heating value of a fuel
$\dot{I}_e$	Rate of gas emissions to atmosphere in the form of heat or electricity consumption in a process unit
$\dot{I}_{gen}^{(t)}$	Rate of total PEIs generated or consumed by chemical reactions within the process.
$\dot{I}_{in}^{(t)}$	Rate of total potential environmental impacts existing in the input streams to the system
$\dot{I}_{out}^{(t)}$	Rate of total potential environmental impacts existing in the output streams from the system
I_{System}	Quantity of potential environmental impact inside the chemical process system

ISD	Inherently Safer Design
K_1, K_2 and K_3	Correlation parameters along with the minimum and maximum values of equipment size
LCA	Life Cycle Analysis
M_j	Chemicals Inventory (tonne)
MW_i	Molecular weight of component *i*
MW_j	Molecular weight of component *j*
η_k	Total efficiency of a process unit *k*
ODP	Ozone depletion potential
PEI	Potential Environmental Impacts
PCOP	Photochemical oxidation potential
$\dot{Q}_i$	Fraction of the heat flow attributed to component *i*
Q_1 *to* Q_6	Energy streams
$(R.I)^P$	Risk Index Associated with Product Streams
$(R.I)^T$	Sum of Risk Index of Product & Waste Streams
$(R.I)^W$	Risk Index Associated with Waste Streams
SI	Sustainability Index
TTP	Terrestrial toxicity potential
US EPA	US Environmental Protection Agency
x_i	Mass fraction of component *i*
$x_{i,j}$	Mass Fraction of Component *i* in Stream *j* ($i, j = 1, 2, \ldots$)
WAR Algorithm	WAste Reduction Algorithm
W/T	Waste thinner

***Abstract*:** In a conventional chemical process design, the main focus is on the process economy resulting in the generation of huge amounts of waste materials within the process. Such design approach demands end-of-pipe treatment, which is neither profitable due to the hefty costs of the installation and operation of large scale waste treatment facilities, nor environmentally conscious due to the potential impacts of the generated wastes within the process on the environment. The recent approach to sustainable process design has surmounted this challenge. This paper presents a new application of an already introduced composite sustainability index (*CSI*) that requires minimum amount of data to monitor the sustainability performance of a chemical process and troubleshoot, if necessary. Then, the *CSI* is applied to an existing process for the purpose of Cradle-to-Cradle design by significant reduction of the environmental impacts of the process, and the escalation of the plant profitability due to sustainable retrofitting of the plant. The *CSI* methodology can be applied to chemical, refinery, petrochemical, oil & energy, fuel and biofuel processes. The three main advocates have been considered in the *CSI*, which are the impacts of "energy" and "material" on the environment as well as "risk assessment". The *CSI* is technically imperative at all engineering stages of above process plants with the aim of source reduction and environmental protection. The *CSI* gives process and safety engineers a competitive edge, making their designed process stand out amongst other design array. The current study proves that the *CSI* methodology is a powerful tool for process and safety designers, and that the process sustainability and profitability are strongly linked. So, it is specifically decisive at managerial level pursuant to strategic planning towards company's sustainability.

Keywords: Sustainability indicators, cradle-to-cradle design, auto industry economy, inherently safer design, energy impacts index, material impacts index (WAR algorithm).

1. Introduction

Typical chemical and refinery process designs are based on economic objectives, such as net present value, capital investment and operating costs (Zhang et al., 2008). Hence, the environmental impacts of materials and energy associated with a manufacturing process are usually overlooked at primitive stages of conventional process design. Such negligence results in the intrusion of large quantities of waste materials and pollutants to the environment (EPA, 2012). Thus, the conceptual design stage is the best time for environmental performance assessment of chemical processes by employing simplified screening methodologies versus more accurate evaluations during detailed design (Adu et al., 2008). Sustainability has been defined in different ways. For example, in terms of products and services, sustainability is defined as the constant improvement of the products as well as services demanded by society at minimum adverse impacts upon the Earth (Cobb et al., 2007). As such, in terms of economy, sustainable development is defined as the economic advances at a standard pollution emission to environment and within acceptable resource depletion (Microsoft Encarta, 2004). It turns out that the concept of sustainability and sustainable development are based on three distinctive components: economy, environment and society.

The traditional approach to process design is being replaced by a sustainability outlook through the incorporation of environmental consciousness into process design. The sustainable development has become one of the main objectives of chemical manufacturing companies including refineries. Sustainable companies aspire to impinge delicately on the earth and natural resources, while developing products, services, technologies, and profits that influence larger societal efforts without compromising the meeting of future generations' needs

(Sneirson, 2009). For the sake of the evaluation of the sustainability performance of a corporation against profitability, environmental protection, safety, society & customer service, and technological improvement aspects, new indices have been developed by several researchers as will be discussed in succeeding section (Literature Review).

This paper provides a review of an already introduced Composite Sustainability Index (*CSI*) to be used at the conceptual design phase of a sustainable chemical process (Ordouei et al., 2015). Therefore, the main objectives of this study are:

- To introduce the proposed conceptual decision making model; i.e. *CSI* methodology, in brief.
- To utilize the competence of the *CSI* methodology in order to design a Cradle-to-Cradle process in auto industries, a case study on the recovery of thinner (as a chemical solvent) from painting sludge. The sludge (containing a mixture of paint and thinner) is generated and collected after washing of the remaining paint existing in storage tanks, pipes, hoses and pistols by thinner.
  The Cradle-to-Cradle design focuses on pollutant (source) reduction by employing the existing technologies used in chemical processes. And finally,
- To compare the painting unit of an auto manufacturing plant in a conventional design (standalone or base model) with a sustainable design (hybrid model) from material and energy impacts on environment, risk assessment and profitability perspectives.

2. Literature review

Sustainability indicators enable design engineers, investors, regulators and decision makers to simply understand, quantify and analyze complex data about a business, a product, and particularly a chemical manufacturing plant.

The concept of sustainability is now an inseparable part of current scientific investigations. Examples include (but not limited to) teaching (Carew and Mitchell, 2008); sustainable vehicle design (van Lante and van Til, 2008); and probability estimation of accidents, such as explosion, toxic release, risk reduction (Rathnayaka et al., 2014). Further examples are the development of a framework for local sustainability indicators within a regional setting (Mascarenhas et al., 2010); material balance environmental index for the evaluation of the impact of toxicities emitted to the environment (Torres et al., 2011); and evaluation settings (e.g. indicator methods), as well as sensitivity of economic and environmental assessment results with the aim to change in reaction routes, recycling configurations, and operating conditions as design alternatives (Sugiyama et al., 2009).

Methods for the evaluation of sustainability development have been proliferated during the last few years. Corporations treat the sustainability concept for strategic planning and external communications, supply chain, and decision making (Amimi and Bienstock, 2014). The sustainability performance of an organization can be determined at different levels, such as local, regional, public, private, profit, non-profit, industrial, agricultural, transportation, etc. (Ramos and Caeiro, 2010). There are few corporation methodologies, which apply sets of indicators with limited applications to measure the companies' performances. For instance, Dow Jones Sustainability Indices (2013) targets enhancement of the company in various fields of expertise, such as strategy, financial, customer and product, governance and shareholders, as well as human resource. Similarly, FTSE4Good Environmental Leaders Europe 40 Index (2015) serves investors in order to find European partnership in environmental management. And finally, the *AIChE* Sustainability Index (*SI*) is established on the basis of features that shape a merged Sustainability Index or *SI* (Cobb et al., 2007). The *SI* collects the required information from company's annual sustainability report, industrial performance rankings, government‘s pamphlet and newsletters. The *SI* has developed a score based metrics scaled from 0 - 7 and depicted the metrics on a spider chart. Unfortunately, the majority of the existing indicators (including the corporation sustainability indicators) cannot be employed at the early design stage of a chemical process due to two decisive constraints:

- As a matter of fact, the societal component of sustainability is associated with customer satisfaction and after sale services, which have business nature and demonstrate individual company's performance. Therefore, the societal element cannot be measured at the primary stage of a process and/or product design. However, the engineering codes and standards must be used in detailed design stage to protect society.
- At early design stage (i.e. conceptual design phase) detailed information of production rates, financial reports, process log sheets, customer satisfactions and products qualities are unavailable.

The *AIChE's SI* has tried to resolve the former limitation (Cobb et al., 2007); however, the *SI* is obliged to gather a large number of data, which differ from one corporation to another based on business performance. Besides, this obligation conflicts with the latter constraint, which is the unavailability of such detailed data at conceptual design stage of a chemical process. Above all, none of the existing indices can be used for prototype product and process designs.

Moreover, the existing sustainability methodologies in the fields of education, management, construction, and healthcare are not applicable to chemical process design; for instance, teaching (Carew and Mitchell, 2008), sustainable vehicle design (van Lante and van Til, 2008). Likewise, finding partnership as proposed by FTSE4Good Environmental Leaders Europe 40 Index (2015) has rather managerial nature than design applications.

Researchers have also made several attempts in many different ways to provide distinctive methodologies in order to design sustainable chemical processes; however, they cannot be employed at the conceptual design stage. For example, Life Cycle Assessment (*LCA*) has been widely used for the estimation of impacts of chemicals, processes and services on environment. This methodology evaluates the impacts from raw material (source) to disposal (e.g. land filling). Therefore, it is sometimes referred to as "Cradle-to-Grave" Analysis. The *LCA* is carried out by collecting of the records of material and energy inputs and emissions to the environment, assessment of potential environmental impacts of the identified inputs and outputs, as well as construing the outcomes for decision-making. The *LCA* is an important tool for the evaluation of the potential environmental impacts of a chemical compound over its entire life time from extraction to land filling. Therefore, the *LCA* requires a huge number of data for impacts evaluation that may not be available at the conceptual design step of a chemical process. Besides, the *LCA* has much wider application than a chemical process design itself. The WAste Reduction (*WAR*) algorithm is another methodology that can be used at the primitive stage of a chemical process design (Young and Cabezas, 1999). The US Environmental Protection Agency (*EPA*) has endorsed WAR algorithm and incorporated it into a user friendly software package (WAR GUI, 2008).

There are also other sustainability methods that may be used at the early design stage of a chemical process. For instance, Li et al. (2009) presented a methodology for integrating of environmental impacts into chemical process design, which can be applied at the initial design phases especially for separation processes. They estimated the impacts of "materials" and "energy" used in a chemical process on environment. The impacts of "energy" on environment is calculated based on the data provided by EPA (2008) and the environmental impact potential of "materials" (chemicals) on atmosphere, soil, water, and human are estimated similar to *WAR* algorithm. Hossain et al. (2011) developed an environmental and economic quantitative evaluation approach that can be applied to a chemical process at different levels of process synthesis and retrofit application through integrated environmental and cost potential (*IECP*). They introduced the concept of cradle-to-gate life cycle assessment by providing weighting factors for the environmental and economic indices using Aspen HYSYS to obtain required data for calculations. Khan et al. (2004) developed a composite index called life cycle indexing system (*LInX*) that can be implemented to conduct *LCA* analysis for the evaluation of chemical products and processes. The *LInX* encompasses four sub-indices; i.e. environment, health and safety (*EHS*); cost; technical feasibility; and socio-political. A pertinent weight is assigned to each sub-index using analytical hierarchy process (*AHP*), which are used to determine the overall value of the composite index. Above all, making results comprehensible and meaningful to public is also challenging but essential if evaluations are to be translated into policy and action (Becker, 2004).

The above mentioned methods are often time-consuming, expensive to conduct, unappealing and difficult tasks. Besides, these methodologies require reiteration and consist of only a crucial part of the assessment process (e.g. environment, or safety, or economy). For example, the *LCA* requires vast information about a material, process or service from extraction of raw materials, transportation, and manufacturing to landfilling of a substance. Li et al. (2009) used EPA (2008) for estimation of energy impacts on environment, the EPA uses the same emission factors for both of heat and power and ignores the efficiency factor of boiler and steam turbine, which have different contributions to the air pollution. Li et al. (2009) also estimated the environmental impact potential of material, which is time intensive but very similar to the *WAR* algorithm in terms of impacts categories. Hossain et al. (2011) presented a methodology, which requires data collections from pilot plant experiments or existing large scale plants. The pilot and/or large scale plants imply that the method cannot be used at the early stage of a process design. Besides, the environmental assessment of Hossain's methodology is limited to emissions from power plants not a chemical process itself. And finally, it is not clearly explained how to calculate weighting factors for environmental and economic evaluations? *LInX* method (Khan et al., 2004) is also time consuming and needs scores of information (similar to the *LCA*), which may not be available at the primitive step of a process design. Al-Sharrah et al. (2007) introduced a simple quantitative safety risk index, which combines four elements; frequency of accidents, hazards associated with chemical exposure, chemical inventory and plant size.

The study of the above mentioned frameworks and similar analyses necessitate to aggregate a set of different indices into a composite index that enables a comprehensive assessment of the sustainability of a process design. To answer to this important demand, the *CSI* integrates the *WAR* algorithm, which is underscored to be applicable merely in manufacturing step (Section 3.1.1), the new methodology presented by Ordouei et al. (2014 a) for evaluation of energy impacts on environment (Section 3.1.2) and the developed model of Al-Sharrah's methodology by Ordouei et al. (2014 b) for risk assessment (Section 3.1.3) into chemical process design.

3. The major elements of the new Composite Sustainability Index (*CSI*)

In preceding section, it was explained that the majority of the existing sustainability indicators cannot be applied to the conceptual design stage of a chemical process. Therefore, there is a high demand to such index to be simple and user friendly, quantitative, applicable at the early design phase, based on engineering principles, as well as engineering codes and standards, and finally to be acceptable by scientists and regulators.

The concept of sustainability has boosted a strong backbone for the *CSI* methodology by employing three core metrics commonly used in almost all chemical products and chemical process designs: the impacts of "Material" and "Energy" on the environment and "Risk" associated with process safety.

Although the above metrics can be used individually, the *CSI* methodology combines them in order to give deep insights of a chemical process and in order to rank process design alternatives at minimum available data such as heat & material balance, composition and condition of material streams. In succeeding section the above three metrics are discussed in details.
When one of the above mentioned metrics conflicts with others, analytical hierarchical process (*AHP*) will be employed in order to assign appropriate weighting for each metric (Saaty, 2008). In this case, aggregation of the indices will result in an individual value for the *CSI* associated with each and every design alternative. Ordouei et al. (2015) have presented a comprehensive case study (gasoline blends) using the *CSI*, which encompasses variety of conflicts among the gasoline blends, and used the *AHP* in order to rank the blends. Readers are cordially encouraged to read the reference to find out more about *AHP* methodology and its application to the case study.

The *CSI* methodology can be broadly used in chemical, refinery, petrochemical, oil & energy, fuel and biofuel processes. This implies that this methodology may not be applied to biochemical, pharmaceutical, food and beverage industries.

3.1. Sustainability indices

It is essential to pay attention that the Composite Sustainability Indicators (*CSI*) has purely technical concept, as it incorporates three generic components (as stated in preceding section), which are used for the ranking of a process design. It implies that economy factor is not part of sustainability indicators, even though profitability analysis of a process at design stage is a must. The rationale underlying the exclusion of economy index from the *CSI* is: (a) to avoid biased evaluation of the sustainability of a process design without compromising the process economy, and (b) to accomplish cost-benefit analysis.
The *CSI* is a robust tool for the evaluation and the ranking of a new product/process design and retrofit, in which three main metrics are involved:

- The impacts assessment of materials on environment by WAste Reduction (*WAR*) algorithm (Young and Cabezas, 1999; Young et al., 2000).
- The evaluation of energy impacts on environment by a methodology presented by Ordouei et al. (2014 a).
- The appraisal of risk to a product/process safety (inherent safer design or *ISD*) by a methodology published by Ordouei et al. (2014 b).

Auspiciously, it is possible to include other technical factors to the *CSI* based on a process and/or a product nature. For example, in an application of the *CSI* to gasoline blends (sustainable product design) the octane number and the mileage loss of the blends were added to the *CSI* in addition to material, energy and safety metrics (Ordouei et al., 2015).

3.1.1. Waste reduction (WAR) algorithm

The *WAR* algorithm, an existing quantitative sustainability methodology, estimates the impacts of chemical pollutants within a process on environment in Potential Environmental Impacts per hour (*PEI/h*). The *PEI* is defined as "the adverse outcome of a chemical component on environment should it be discharged into environment" (Young et al., 1999; Young and Cabezas, 2000). *PEI* balance is an analogous to material and energy balance:

$$dI_{System}/\,dt = \dot{I}_{in}^{(t)} - \dot{I}_{out}^{(t)} + \dot{I}_{gen}^{(t)} \qquad (1)$$

Where,
I_{System} = the quantity of the *PEI* inside the chemical process system,
$\dot{I}_{in}^{(t)}$and $\dot{I}_{out}^{(t)}$ = the rates of total *PEI* existing in the input and output streams from the system, respectively.
$\dot{I}_{gen}^{(t)}$ = the rate of total PEIs generated or consumed by chemical reactions within the process.

At steady state,

$$dI_{System}/\, dt = 0 \tag{2}$$

Thus,

$$\dot{I}_{in}^{(t)} - \dot{I}_{out}^{(t)} + \dot{I}_{gen}^{(t)} = 0 \tag{3}$$

The *PEI* can be calculated for both product and non-product streams. The *WAR* algorithm methodology employs two main impact categories, each one includes four sub-categories (totally eight environmental impact categories) for the assessment of *PEI* indices (Young et al., 2000) as follow:

- **Global atmospheric impacts:** The global atmospheric impacts contain Global warming potential (GWP), Ozone depletion potential (ODP), Photochemical oxidation potential (PCOP), and Acidification potential (AP).
- **Local toxicological impacts:** The local toxicological impacts contain Human toxicity potential by ingestion (HTPI), Human toxicity potential by exposure both dermal and inhalation (HTPE), Terrestrial toxicity potential (TTP), and Aquatic toxicity potential (ATP).

These impact categories can be calculated by a software package called Waste Reduction Algorithm Graphical User Interface (WAR GUI, 2008) and developed by the US EnvironmentalProtection Agency (EPA).

3.1.2. Energy impacts on the environment

The Composite Sustainability Index (*CSI*) has employed a new invented simple and quantitative index introduced by Ordouei et al. (2014a) in order to assess the impacts of energy on environment. The energy index established a relationship between generation (or consumption) of energy in the forms of heat or power to the rate of emissions (e.g. CO_2, NO_2 and SO_2) to atmosphere. The index is shown in the following equation:

$$\dot{I}_e = \sum_k \sum_j \sum_i x_i \times \left\{ \dot{Q}_{i,k} / \left(\eta_k \times HV \right) \right\} \times \left(MW_j / MW_i \right) \tag{4}$$

where

η_k = Total efficiency of the process unit *k* (e.g. heat exchanger, incinerator, electromotor etc.)

$\dot{Q}_i$ = The fraction of heat flow attributed to the component *i* in kJ/h (*i* = C, S and N)

HV = The heating value of a fuel (kJ/ kg fuel)

x_i = The mass fraction of the component i

MW_j = The atomic weight of the component i (kg/kgmol). Also, the superscripts j denotes gas emitted to atmosphere (j = CO_2, SO_2, NO_2).

$\dot{I}_e$ = The rate of gas emission to atmosphere in the form of the component j in kg of pollutant per hour due to either heat or power consumption in the process unit k.

Readers are prompted to refer to the detailed study of the existing methodologies made by Ordouei et al. (2014a). The above equation has a number of advantages over the existing methodologies, including (but not limited to):

- A simple index for the estimation of emission rates at any stage of a process design.
- Accurately estimates the impacts of all emission rates (i.e. CO_2, SO_2 and NO_2) from fossil fuel combustion on environment.
- Needs minimum data such as the composition and the heating value of a fossil fuel, in addition to electric power consumption from process equipment nameplates.

3.1.3. Evaluation of the risk to a process safety

The Composite Sustainability Index (*CSI*) has been established based on three main metrics; i.e. the impacts of material and energy used or generated within a process on environment and the risk associated with the process safety. The *CSI* methodology also indicates process designs, which are inherently safer. Inherently Safer Design (*ISD*) is a systematic tactic to minimize the risks to the safety of a process plant, human, environment and equipment during design and operation of the process (Hendershot, 2011).

Several attempts have been made in many different ways to present risk evaluation methodologies. However, they have one or more of the following disadvantages which make them undesirable for application at the early design phase of a chemical process, such as: qualitative, comprehensive, time-consuming, requiring detailed process data, and dependent on the quality of data collected (e.g. training and experience of safety managers). Besides, human risk analysis is the major missing part in most of these methodologies. Ordouei et al. (2014b) have justified for the above-mentioned shortcomings in the development of their *ISD* risk index. Ordouei's methodology is applicable to small, medium and large size complex process plants, such as chemical, refinery and petrochemical industries. The *ISD* risk index (Ordouei et al., 2014b) is an advancement to Al-Sharrah's risk index (2007), which evaluates risk associated with components of product and waste streams, instead of the entire process. The *ISD* risk index (Ordouei et al., 2014b) also mitigates the effect of obtaining unrealistic results for certain instances, and can be used at the primitive stage of chemical process designs, which are presented by the following equations:

$$(R.I)^P = \sum_i \sum_j M_j \times f_i \times H_i \times x_{i,j} \tag{5}$$

$$(R.I)^W = \sum_k \sum_l M_l \times f_k \times H_k \times x_{k,l} \tag{6}$$

where

$R.I$ = Risk Index defined as the number of affected people per year, which represents the maximum potential risks. The superscripts P and W stand for product and waste streams, respectively.

The subscripts i and k denote the chemical contents of product and waste streams, respectively. As such, the superscripts j and l designate the product and waste streams within a process, respectively.

M_j and M_k = Mass of chemicals in product and waste streams released to the environment, respectively (the maximum one month of plant inventory in tonne).

f_i and f_k = Frequency of accidents for chemical component i, k in number of accidents per year.

H_i and H_k = Hazard effects in the number of people affected per tonne of chemical components i, k released.

Thus, the total risk $(R.I)^T$ is defined as the summation of the risks associated with product and waste streams as follows:

$$(R.I)^T = (R.I)^P + (R.I)^W \tag{7}$$

The proposed *ISD* index is adaptable with four policies for inherent safer design introduced by Center for Chemical Process Safety (2009) and Manna et al. (2006), which follow:

- **Intensification**: Minimization of hazardous compound within a process plant.
- **Substitution**: Substitution of hazardous materials with benign compounds.
- **Moderation**: Handling and transporting of hazardous chemicals under reduced risks conditions (e.g. dilution, refrigeration, etc.).
- **Limitation**: Diminishing the probability of accidents and associated damages; e.g. applying interlocking commands for process control.

3.2. Process economy analysis

As stated earlier, three main elements of the composite sustainability indices (*CSI*) are evaluation of the impacts of material and energy used in a process on environment as well as the risk to the process safety. However, depending on the nature of a process or a product other metrics may be added to the *CSI*. The art of the *CSI* is that it does not compromise with process economy. Therefore, profitability assessment is not considered as a component of the *CSI* approach in order to prevent from obtaining biased results; however, the concept of cost-*CSI* analysis (analogous to cost-benefit analysis) is professionally maintained in the methodology.

The cost estimation and profitability analysis are implemented based on the correlations presented by Turton et al. (2012):

$$\log C_P^0 = K_1 + K_2 \log (A) + K_3 [\log (A)]^2 \tag{8}$$

where

C_P = equipment cost ($).

A = equipment size in their corresponding units (e.g. heat transfer area in m^2 for heat exchangers, shell mass in kg for pressure vessels, etc.).

K_1, K_2 and K_3 = correlation parameters along with the minimum and maximum values of equipment size.

Therefore, equipment sizing is imperative for the cost estimation of a chemical process. Then, the Bare module costs for each equipment and for entire process can be estimated. In parallel, the cost of fresh thinner can be estimated in each design to find out which design saves more money. And finally, the economic benefits of process design alternatives are compared in order to select the more economic process.

4. Illustrative case study

In this case study, the *CSI* methodology is applied to the painting unit of an automotive industry. The objectives of this section are; (a) to present an existing conventional (standalone) painting process typically used in automotive industries, (b) to design a hybrid painting process, where polluted thinner is recovered and reused in the painting unit of an auto manufacturing plant, (c) to compare both processes from the *CSI* outlook.

Automotive companies constitute of several units or steps for manufacturing of cars, including painting step where paint is blended with thinner (as a solvent) and applied on the cars. Painting is an important part of car industries from economic and environmental perspectives. Moreover, customers pay for their favorite colors when they purchase cars.

4.1. The concept of Cradle-to-Cradle design in auto industries

Cradle-to-Cradle design is an economic and industrial approach to establish an efficient and (ideally) waste free process. In conventional auto industries, thinner is received and used in painting unit for mixing with thick paint for diluting purpose and then, pumped into pistols through pipes and hoses in order to coat manufactured cars by the diluted paint. In a painting unit, fresh thinner is also used for flushing of the pipes and thinner receiver. In order to provide the end users with various options, the automotive companies manufacture cars with different colors; therefore, the manufacturers have to switch production lines time to time from one color to another. To do so, the painting facilities; e.g. painting tanks, pumps, pipes, hoses and pistols, have to be cleaned up first. This is why fresh thinner has to be pumped into (and recirculated through) the equipment involved until the inside of all equipment are completely cleaned from residual paints, while waste (flushed) paint is generated and collected in waste tanks. Therefore, in an auto manufacturing factory a large quantity of waste paint (mainly containing of thinner) is produced as pollutant. Figure 1 represents “the life cycle of the thinner” in traditional auto industries.

From the above explanation it is obvious that the recovery of thinner from waste paint in auto manufacturing plants is imperative, since thinner is composed of a range of hydrocarbons, which are flammable and toxic. Therefore, they have potential environmental impacts (*PEIs*) as well as risks to the safety of automotive plants and operation staffs. Besides, thinner is a valuable solvent.

In order to isolate thinner from thinner waste, thermal separation techniques may be employed. The integration of such a chemical process into automotive factories (hybrid processes) will result in Cradle-to-Cradle design, which decreases the *PEIs* and the risks to the process safety and increases the company’s profits. Figure 2 represents a hybrid process where thinner is delivered to “Blending” unit of an automotive plant to be mixed up with paint. The diluted paint is sent to “Painting” unit where the manufactured cars are painted. A significant amount of waste paint generated due to flushing out of the “Painting” facility by thinner solvent is delivered to “Solvent Recovery” unit to bear thermal treatment and to isolate thinner from the waste paint. Then, the recovered thinner is returned to “Thinner Storage” tank.

The loop in Figure 2 demonstrates the concept of Cradle-to-Cradle design with respect to thinner, where the thinner is recovered from waste paints and returned to the beginning of the process for further usage. The Cradle-to-Cradle loop continues to work perfectly for goods, provided that make-up fresh thinner is fed to the “Thinner Storage” tank when required.

4.2. *Standalone (conventional) process design*

Figure 3 illustrates standalone painting unit operated by majority of auto industries. Fresh thinner is received in a receiving tank and then, it is sent to the painting unit for coating of manufactured cars. The flushing of the painting unit for cleaning purposes prior to using different colors for produced autos requires consumption of considerable amounts of thinner. The resulted effluent from the flushing of the painting facility is considered as waste paint mostly consisting of thinner. The waste paint is undesirable and regulated by government, since it is toxic and flammable. Therefore, the waste paint must bear cost-effective end-of-pipe treatments otherwise, the government will penalize the auto industry based on the waste volume and the concentration of generated pollution (i.e. waste paint).

In the conventional design (Figure 3), the "Used Thinner" stream denotes the production line where the thinner is applied to painting of cars. This production line is out of scope of this paper. The "Waste Thinner" stream with the average flow rate of 5,270 lb/h represents the effluent thinner, which is used for the cleaning and flushing of the painting facility. This process inflicts several metrics such as material and energy impacts on environment as well as safety risks. In this paper, these metrics are:

- The risk to the process safety was calculated in "Number of Affected People per Year" using the *ISD* (Inherent Safer Design) index presented by Ordouei et al. (2014b).
- The material impacts on the environment was estimated based on the existing *WAR* (WAste Reduction) algorithm (Cabezas et al., 1999; Young and Cabezas, 1999; Young et al., 2000). EPA has developed WAR GUI (2008) software in order to calculate the environmental impacts of a material in Potential Environmental Impacts per hour (PEIs/hr).
- The estimation of the energy impacts on the environment was carried out on the basis of the energy index introduced by Ordouei et al. (2014a). Given the characteristics of a fossil fuel, the energy index (Eq. 4) quantifies CO_2, SO_2 and NO_2 emissions to the environment.

Table 1 reveals a typical composition and a typical characteristics of heavy oil (Mobin Sarmayeh Company, 2014). The impacts of energy consumption on the environment associated with the process shown in Figure 3 are calculated on the basis of the data provided in Table 1.

4.3. *Hybrid (Cradle-to-Cradle) process design and description*

As stated in preceding section, the environmental impacts of materials in the standalone process are significant. Such impacts can be reduced by minimization of waste thinner in a hybrid process; i.e. a combination of separation and painting plants in a car manufacturing company (Figure 4).

The waste thinner (paint) contains up to 10 wt% sludge on average. Therefore, the objectives of the hybrid process design are to remove the sludge from the waste paint and then, to purify the thinner from dissolved paint by thermal separation technique. The waste thinner from the painting unit is received in W/T Separator, a three phase separator, in order to remove the sludge through W/T separator's boot. "Crude Thinner" stream is waste thinner from other auto industries. The crude thinner on the upper phase of the W/T Separator is then pumped to the fourth tray of a distillation tower called "Thinner Tower", which is equipped with totally six trays, after passing through a heat exchanger in order to increase the temperature of crude thinner up to 150 ^{o}F. In order to decrease utility (steam) consumption, Recovered Thinner stream (the product of the Thinner Tower) at 230 ^{o}F is used as heating medium. The Recovered Thinner is then received in Thinner Control Tank in order to control the quality of recovered thinner and when needed to add fresh thinner through MakeUp Thinner line. When the quality of the recovered thinner is approved by quality control department, the thinner is pumped to Painting Unit by Thinner Pump. The temperature of thinner is controlled by a cooler, which may be used intermittently. The waste thinner from the Painting Unit is recycled to the beginning of the hybrid plant (W/T Separator).

The flow rate through "ATM" stream (to atmosphere) from condenser is negligible. The bottom outlet from Thinner Tower (To Incinerator stream) contains hydrocarbons as well as remaining paint and has a flow rate of about 53 lb/hr and a heating value of about 1.74×10^6 Btu/lbmole. Therefore, it is a good idea to use its energy content in a boiler or in an incinerator.

The flow rates of "Sludge" and "To Incinerator" streams in the hybrid process are totally about 152 lb/h, which are not economic for recovery purposes. However, the flow rate of "Waste Thinner" stream (5,284 lb/h) is close to that in standalone design (5,270 lb/h) and therefore, it is worthwhile to recover thinner from the waste stream by employing separation techniques. It goes without saying that fresh thinner should be always supplied to "Thinner Control Tank" as make-up. The streams "Vent1", "Vent2" and "ATM" have nil flow rates at steady state operation and have no contribution in waste generation.

It is essential to note that in the both designs, the "Used Thinner" streams designate the thinner used for coating of manufactured cars in automotive plants and as stated before these streams are out of scope of this paper.

5. Results and discussion

Table 2 summarizes all necessary data for decision making such as waste thinner generation, total capital investment (*TCI*) including cost of utility consumptions within the recovery process, cost of fresh thinner, the impacts of material and energy on the environment, as well as the risks to process safety. The economic analysis of each design plays a decisive role in identifying sustainable process as well as contentment of investors. It can be observed from Table 2 that the recovery of such a large amount of thinner from waste paint saves a great deals of money (about US$ 38 million in this case study).

The summary of sustainability performance analyses of both standalone and hybrid processes follow (Table 2):

- *Standalone design (base process):*
  ISD Index = 26.97 (number of affected people/year)
  Material impacts on the environment = 2,710 *PEI*/h
  Energy impacts on the environment = 0.1 kg/h (0.22 lb/h) gases (CO_2, SO_2, NO_2)

- *Hybrid design (alternative process):*
  ISD Index = 0.47 (Number of affected people/year)
  Material Impacts on the Environment = 58.8 *PEI*/h
  Energy Impacts on the Environment = 231.6 kg/h (510.6 lb/h) gases (CO_2, SO_2, NO_2)

The production rate of the automotive factory is almost the same in both designs, which means that the rate of thinner consumption is the same. *ISD* Index represents the risk to a chemical process; the lower the ISD value implies that the lower risks to process safety do exist. Hence, a quick look at risk index reveals that the Hybrid design (*ISD* = 0.47) is much safer than Standalone design (*ISD* = 27). The same result was observed when compared the material impacts on the environment for both processes. In this regard, the Hybrid design (59 *PEI/h*) is environmentally friendlier than Standalone design (2,710 *PEI*/h) by a factor of 46. In other words, the standalone design accounts for much more emissions to the environment. Unlike *ISD* and Potential Environmental Impacts (*PEIs*) of material on the environment, the impacts of energy on the environment in Standalone design (0.1 kg/h) is much lower than that in Hybrid design (232 kg/h). Table 3 summarizes the information about the rate of emissions released to atmosphere due to heat and power consumptions. The emission rates of NO_2 and SO_2 in the both designs are negligible. So is the emission rate of CO_2 in standalone design. However, the rate of the CO_2 emission in hybrid design is relatively high. This amount of CO_2 emission accounts for energy (in the forms of heat and power) required for thinner recovery by using distillation tower, heat exchangers and pumps.

Now, it is easy to select the sustainable and profitable process. As stated above, the hybrid process is an inherently safer design when compared with the standalone process. However, in the hybrid process (Figure 4), more energy is used when compared with the standalone process (Figure 3) resulting in more emissions as listed in Table 3. The extra energy usage is due to material (thinner) recovery. The streams “Feed Thinner” in Figure 3 and “Make-Up Thinner” in Figure 4 represent fresh thinner supply streams to the standalone and the hybrid processes at the rates of 13,180 lb/h and 1,683 lb/h, respectively. The price of fresh thinner is C$ 825 per tonne (37.5 ₡/lb) on average; therefore, the fresh thinner costs for the standalone and the hybrid designs are C$ 4,930/h and C$ 630/h, respectively. The hybrid design demands to allocate annual financial resource for about C$ 5,529,000 as revolving investments for purchasing fresh thinner only, while the standalone process requires more than C$ 43,296,000 a year for the same purpose. Therefore, the hybrid design saves about C$ 38 million which accounts for thinner recovery.

Based on the above results, the hybrid process is environmentally friendlier, inherently safer, and also reimburses the capital cost within one year after completion of the retrofitting project (Table 2). Thus, the hybrid process satisfies the sustainability and profitable definitions.

By applying the *CSI* methodology to the presented cases study, it turns out that the hybrid process satisfies the concept of Cradle-to-Cradle design. The hybrid process also meets all characteristics of a sustainable company (Sneirson, 2009) as elaborated in “Section 1; Introduction”. For instance, the present Cradle-to-Cradle design helps to recover thinner from waste thinner, to reuse the recovered thinner in painting unit, to decrease in thinner consumption, to minimize the impacts of the waste on environment, to mitigate the risks to the process safety and society, to switch from end-of-pipe treatment (e.g. burning the waste thinner in an incinerator) to on site waste recovery, and finally to augment the plant profitability by allocating lower budget for purchasing thinner.

Hence, the concept of Cradle-to-Cradle design should be extensively employed by all manufacturing companies including auto industries in order to create “sustainable corporations”.

The *CSI* methodology has an outstanding potential to be incorporated into the *LCA* methodology, since the *LCA* consists of several steps, including Raw Material Acquisition, Process Manufacturing, Product Distribution, etc. The *CSI* can be effectively employed in the “Process Manufacturing” step when a chemical process is concerned. As such, *AlChE* Sustainability Index (Cobb et al., 2007) can take advantage of the *CSI* methodology, which requires minimum available data.

Likewise, the *CSI* can be effectively treated in evaluation of environmental impacts, operating condition, risk assessment and reduction (Sugiyama et al., 2009; Torres et al., 2011 and Rathnayaka et al., 2014). On the other hand, the *CSI* methodology is a great competitor for existing sustainability methodologies involving chemical processes (Section 2; Literature Review). Study of Li’s methodology (2009) indicates that the method of evaluation of environmental impact potential of material is very similar to potential environmental impact calculation method proposed by *WAR* algorithm (Section 3.1.1). Besides, the *WAR* is well recognized and integrated into a software package by the *EPA*. Therefore, the *CSI* has adopted the *WAR* algorithm as one of its three main advocates.

Unlike the *CSI*, proposed methodologies by Hossain and *LInX* require large amount of information. Hossain’s methodology (2011) is not applicable at the early stage of a process design, since it requires data acquisition from a pilot plant or an operating plant. Like *LCA, LInX* (Khan et al., 2004) demands numerous data, which is unavailable at the initial stage of a process design.

It is crucial to note that in this case study all of the three metrics employed by the *CSI* methodology are inseparable. This clearly necessitates that the evaluation of the impacts of material and energy of a process as well as the risk assessment have to be carried out simultaneously to get an insight to the process as it has been done it this paper otherwise, the result may be misleading. For example, in absence of the *WAR* algorithm (Young and Cobezas, 1999 and WAR GUI, 2008) and *ISD* (Ordouei et al., 2014b) the evaluation of the processes under investigation in this study based on energy efficiency index (Eq. 4) would not be reliable, since the conventional design would be considered as a sustainable process.

6. Conclusions

The objective was to provide a lucrative methodology to forestall emissions from chemical processes at all stages from design to manufacturing of products and to diminish the risks associated with the processes. A composite sustainability index (*CSI*) methodology was presented and discussed in this paper as a response to this genuine demand. In the present research, the *CSI* was successfully applied to a case study comprising a conventional painting unit in a car manufacturing plant and a hybrid process with the aim of waste thinner recovery within the painting unit. Further analysis by the *CSI* methodology revealed that sustainability is knotted with process profitability.

We have learned from chemical engineering that waste recycling processes encompass more equipment, higher energy consumption and therefore, it needs more capital investments. This paper divulges that the larger capital investment accounts for the lower potential impacts of materials on environment, higher return on investment, and more benign products generation. From the case study and the application of the *CSI*, it can be concluded that the hybrid process is economically feasible, minimizes waste generation, mitigates environmental impacts and safety risks. In addition, the *CSI* verified that the hybrid process meets the concept of Cradle-to-Cradle design.

Consequently, the *CSI* methodology endows a constructive tool to measure the sustainability enactment of an operating plant and also to design a sustainable process without compromising profitability. The *CSI* has numerous pros as follow: It is a quantitative and a user friendly tool and is based on reliable information provided by *EPA*. The *CSI* presents simple mathematical models for evaluation of risks, energy and environmental impacts associated with a chemical process. The *CSI* requires minimum available data, such as the composition and the conditions of products and waste streams within a process. The applicability of the *CSI* methodology can be extended to fossil fuel, biofuel, syngas, mineable oil sand, and product designs. Subsequently, the *CSI* is a robust indicator for process engineers, product designers, decision makers as well as regulators.

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Figures:

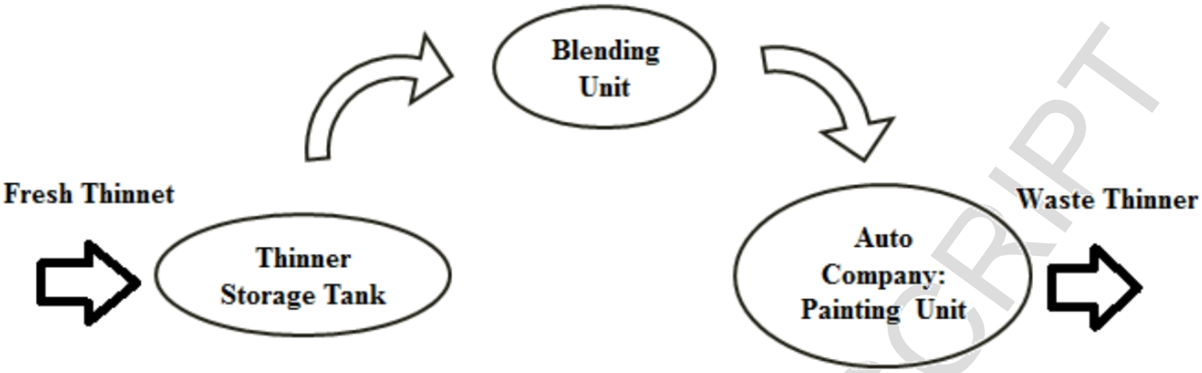


Figure 1: The life cycle of thinner solvent in a conventional auto industry.

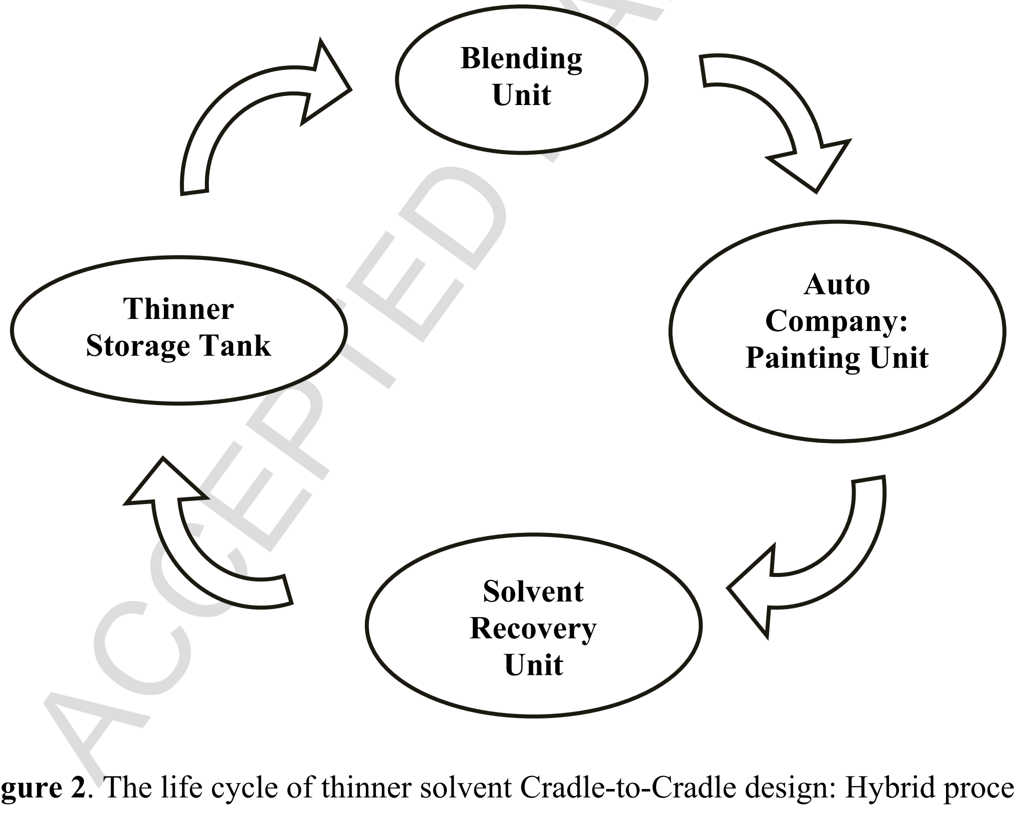


Figure 2. The life cycle of thinner solvent Cradle-to-Cradle design: Hybrid process.

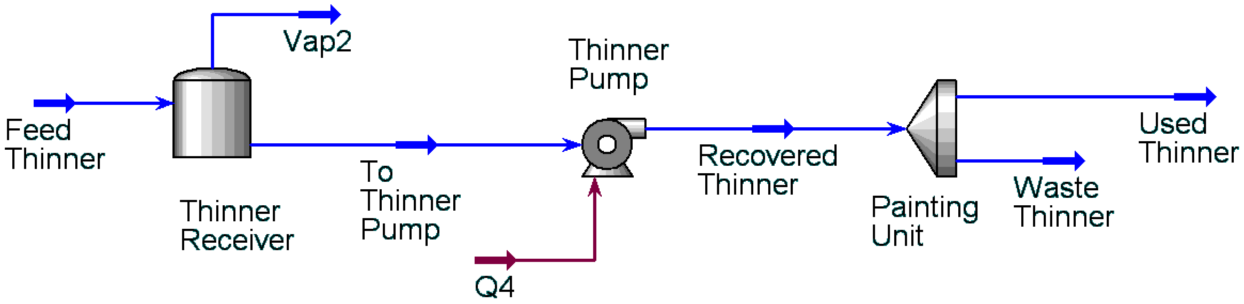


Figure 3. A standalone painting unit in a traditional auto plant.

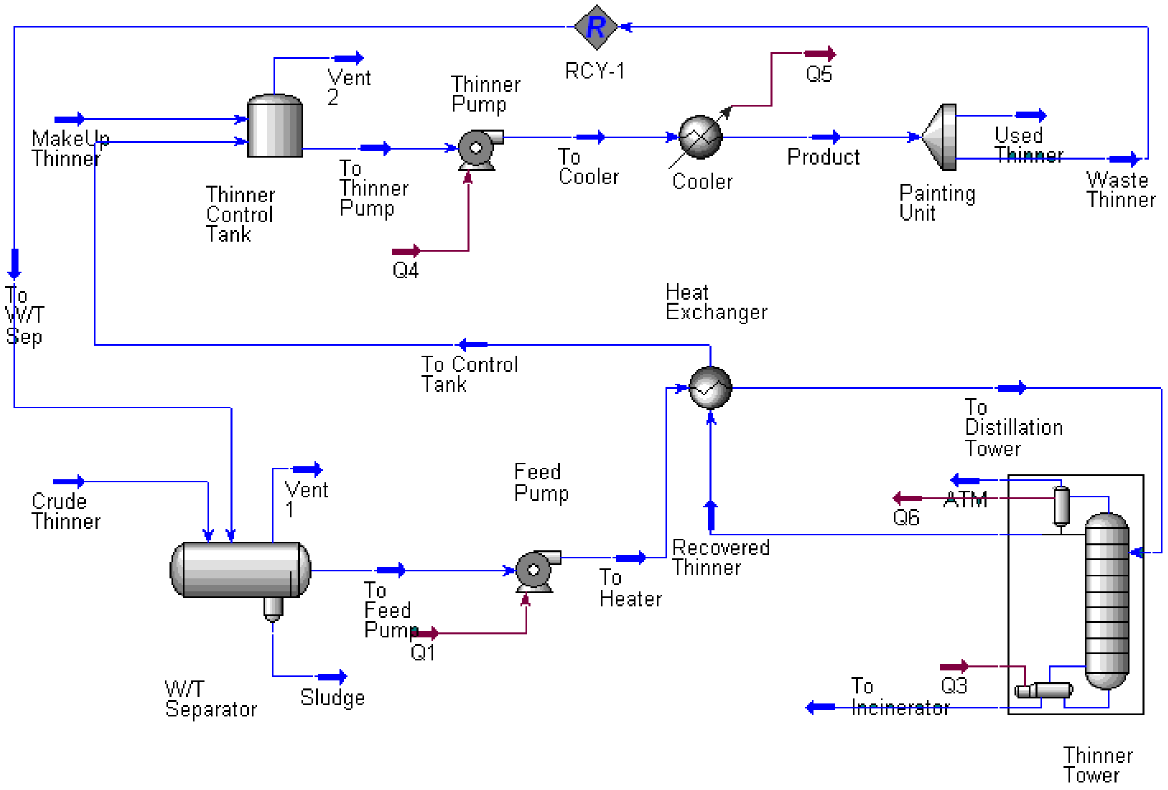
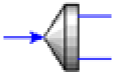
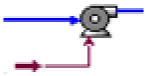


Figure 4. Thinner recovery in a hybrid processes plant: A separation unit and a painting unit.

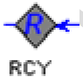
Symbols:



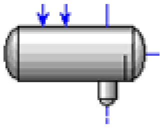
Stream Splitter



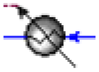
Pump



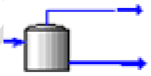
Recycling Stream



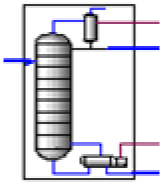
Three Phase Separator



Heat Exchanger



Storage Tank



Distillation Tower + Condenser + Re-boiler

Tables

Table 1. The characteristics of heavy fuel oil and the breakdown of HHV and heat flow.

Fuel Characteristics	Value
Sp. Gr.	0.941
HHV, kJ/kg ((Btu/lb)	42,330 (18,200)
S (wt%)	2.7
C (wt%)	84.8
N (wt%)	0.5
H (wt%)	11.93

Table 2. The summary of the metrics of both designs.

Metrics	Standalone Design	Hybrid Design
Waste Generation (Lb/Hr)	5,270	152
Total Capital Investment (TCI)*, C$	1,901,054	3,090,266
Required Fresh Thinner Price, C$ / Year	41,029,124	3,286,191
Environmental Impacts, PEI/Hr	2,710	58.8
Safety Risk Index, No. of Affected People/Year	26.97	0.47
Energy Impacts, lb gases (CO_2+SO_2+NO_2) /Hr	< 0.22	510.8

* Total Investment or TCI consists of the costs of equipment, erection, piping, instrument and control, electrical, civil, structure, lagging and paint, working capital and utility expenses

Table 3. Comparison of heat & power energies, and total emissions from both designs.

Stream	Standalone Design	Hybrid Design
Energy (Heat), kJ/h (Btu/h)	0	2.8×10^6 (2.6×10^6)
Energy (Power), kJ/h (Btu/h)	880.3 (834.4)	2,592.2 (2,456.9)
Waste Production, kg/h (lb/h)	2,390.5 (5,270)	69 (152)
CO_2 emissions, kg/h (lb/h)	0.07 (0.15)	231.6 (510.6)
SO_2 emissions, kg/h (lb/h)	4.0×10^{-5} (8.8×10^{-5})	0.1 (0.22)
NO_2 emissions, kg/h (lb/h)	2.2×10^{-6} (4.9×10^{-6})	0.007 (0.015)
Total emissions, kg/h (lb/h) gases	<0.1 (<0.22)	231.7 (510.8)

Highlight:

- A new methodology was introduced which uses new sustainability quantification indices
- The indices were used to design and analyse a Cradle-to-Cradle sustainable process
- The above methodology ascertains sustainable processes without compromising economy
- The methodology can be extended to biofuels/energy, product & process at design stage
- The new methodology ranks processes based on safety, environmental & energy impacts