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DOI
10.1016/B978-0-443-28824-1.50253-2

Publication date
2024

Document Version
Final published version

Published in
Proceedings of the 34th European Symposium on Computer Aided Process Engineering

Citation (APA)
Conceição, S., Mousazadeh, F., Posada, J. A., Gutierrez, J., Swinkels, P. L. J., & de Haan, A. (2024). Sustainability-driven conceptual process design at the cooperative Cosun. In F. Manenti, & G. V. Reklaitis (Eds.), *Proceedings of the 34th European Symposium on Computer Aided Process Engineering: 15th International Symposium on Process Systems Engineering (ESCAPE34/PSE24)* (pp. 1513-1518). (Computer Aided Chemical Engineering; Vol. 53). Elsevier. https://doi.org/10.1016/B978-0-443-28824-1.50253-2

Flavio Manenti, Gintaras V. Reklaitis (Eds.), Proceedings of the 34th European Symposium on Computer Aided Process Engineering / 15th International Symposium on Process Systems Engineering (ESCAPE34/PSE24), June 2-6, 2024, Florence, Italy
 http://dx.doi.org/10.1016/B978-0-443-28824-1.50253-2

Sustainability-driven conceptual process design at the cooperative Cosun

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Abstract

The aim of this study is to introduce and showcase the applicability of the 'Green-by-Design method', a tool created by the cooperative Cosun that integrates different indicators involving economic, environmental, inherent safety and health aspects for comparative analysis at an early design stage. Two case studies are presented to exemplify the evaluation principles and steps considered along the 'Green-by-Design method': ethylene glycol production and fava bean protein isolate extraction. The results indicate that the 'Green-by-Design method' provides a comprehensive comparison of different design concepts, by combining various indicators into a single score, enabling sustainability to be an integral aspect in the decision-making during an early design phase.

Keywords: green-by-design; sustainability assessment; early-stage conceptual design; single score sustainability index.

1. Introduction

Cosun is a leading agricultural cooperative producing high-quality plant-based products. As part of the company's strategy, Cosun has set ambitious goals to contribute to a sustainable world for current and future generations. In alignment with these objectives, Cosun is introducing an early-stage sustainability assessment tool named the 'Green-by-Design method'. This tool is designed to support decision-making in the early-stage conceptual design by facilitating both comparison of multiple design options and identification of process hotspots in relation to their sustainability potential. This methodology can be used in any process design innovation project when multiple design options need to be compared.

Various qualitative and quantitative methods fulfill similar purposes (Patel et al., 2015). Nevertheless, the literature review revealed a gap for approaches with easy and swift implementation in industry, tailored to support decision making in early stages of innovation projects.

2. Methodology description

The Green-by-Design method includes 13 indicators grouped into three main categories: Economic, Environment and Inherent Safety & Health. The rating is based on the summation of the score of these three groups, considering specific weight factors (see

Eq.(1)). The used weight of each category – *Economic* 40 % ($I^j_{Economic}$), *Environment* 30 % ($I^j_{Environment}$) and *Inherent Safety and Health* 30 % (I^j_{ISH}) - follows the idea that all three categories are similarly important to create green (sustainable) design concepts. The category *Economic* has a slightly higher weight because it is the primary requirement to implement a new design on industrial scale.

$$Final\ score = 0.40 \cdot I^j_{Economic} + 0.30 \cdot I^j_{Environment} + 0.30 \cdot I^j_{ISH} \quad (1)$$

Since each indicator has a specific unit of measure, the obtained values cannot be added directly. Therefore, the results are normalized by the maximum value (see Eq.(2)).

$$I^j_{i,norm.} = \frac{I^j_i}{\max(I_i)} \quad (2)$$

In Eq.(2), $I^j_{i,norm.}$ and I^j_i represent the normalized and non-normalized indicator i of the process option j, respectively and $\max(I_i)$ represents the highest value obtained for the indicator i among the results from the different process options.
The final score can vary between 0 and 1 and the higher the final score, the higher is the potential of the design concept under evaluation to be 'Green-by-Design'.

2.1. Economic category

The Economic category represents the economic viability of the process. It is composed of four indicators: *Economic Potential*, *Utility Costs*, *Process Complexity* and *Potential of Energy Recovery*.
Economic Potential (see Eq.(3)) has the highest weight since. As a general consensus from literature, it's the most important criterion to evaluate the potential of a process at an early stage. In addition, *Utility Costs* and *Process Complexity* have a higher chance to be the major cost contributions to capital expenditures and operational expenses while also being susceptible of changing when more details become available during process design.

Table 1: Green-by-Design indicators and weight factors of the Economic Category. a) In the 'Green-by-Design' method, a higher score represents a higher sustainability potential. As the variable represents a negative impacts/process parameters, the indicator is estimated as 1 divided by the variable; b) For endothermic/ exothermic reactions under 200 ˚C the given score is equal to zero (adapted from (Patel et al., 2015)). m: mass flow rate; P: commercial price; N: number of process steps.

Category: Economic (40%)			
Economic Potential (40 %)		**Utility Costs (20 %) a)**	
$I^j_{EP} = \Sigma^P_{i=1} m^{Prod.}_i P^{Prod.}_i - \Sigma^{RM}_{i=1} m^{RM}_i P^{RM}_i$	(3)	$I^j_{UC} = \frac{1}{\sum^u_{i=1} m^u_i P^u_i}$	(4)
Process Complexity (20 %)		**Potential of Energy Recovery (20 %) b)**	
		Heat of reaction (KJ/mol)	**Score**
$I^j_{PC} = \frac{1}{(N_{up/downstream} + N_{reaction\ section})}$	(5)	>-100 kJ/mol →	1
		-100 – -300 kJ/mol →	2
		< -300 kJ/mol →	3
$I^j_{Economic} = 0.4 \cdot I_{EP,\ norm.} + 0.2 \cdot I_{UC,\ norm.} + 0.2 \cdot I_{PC,norm.} + 0.2 \cdot I_{ER,norm.}$			(6)

The fourth indicator, *Potential of Energy Recovery*, is used as a proxy to quantify the possibility to recover useful process energy which can be achieved when, exothermic reactions occur above 200˚C (Patel et al., 2015). Hence, heat integration might reduce the amount of utilities required, and consequently the utility costs. Table 1 shows the equations and weighting factors used to calculate the Economic category.

2.2. Environmental category

The *Environmental* category intends to identify and compare different environmental impacts on Earth's natural systems: water resources, land and atmosphere. For this reason, one impact indicator per natural system is included in the tool – *Global Warming Potential*, *Wastewater* and *Land Use*. A fourth impact indicator, *Process Circularity*, is additionally accounted for in this category to evaluate the side-streams of each process option.

To categorize the side streams of each process, an inhouse framework is used – Cosun's pyramid for circular economy (Figure 1). 'Cosun's Pyramid for Circular Economy' was created drawing inspiration from the 'Waste Framework Directive' designed by the EU, also known as 'Waste Management Hierarchy' (European Commission, n.d.). It comprises a ranking system which identifies four different types of side-streams and an ideal scenario where side-streams are prevented. The side-streams are therefore scored between 1 to 4 according to their destinations. Table 2 summarizes the indicators included in the *Environment* category.

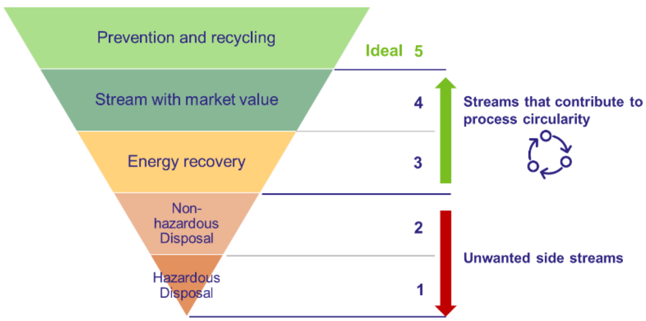

Figure 1: Cosun's Pyramid for Circular Economy. Adapted from (European Commission, n.d.)

Table 2: Green-by-design indicators and weight factors of the *Environmental* category. a) In the 'Green-by-Design' method, a higher score represents a higher sustainability potential. As the variable represents a negative impacts/process parameters, the indicator is estimated as 1 divided by the variable; b) Includes CO_2 footprint of the raw materials, process utilities and direct CO_2 emissions of the process; GHG: green-house gas emissions; a_i: score based on 'Cosun's Pyramid for Circular Economy'.

Category: Environmental Category (30%)	
Global warming potential (25%) [a), b)]	**Wastewater (25%)** [a)]
$I^j_{GWP} = \frac{1}{GHG_{Cradle-to-gate}}$ (7)	$I^j_{water} = \frac{1}{m_{wastewater}}$ (8)
Land use (25%) [a)]	**Process Circularity (25%)**
$I^j_{Land} = \frac{1}{Land\ use}$ (9)	$I^j_{P.Circularity} = \frac{1}{n}\sum_{i=1}^{n} a_i\ ;\ 1 < a_i < 4$ (10)
$I^j_{Environment} = 0.25 \cdot I_{GWP,\ norm.} + 0.25 \cdot I_{water,\ norm.} + 0.25 \cdot I_{land,norm.} + 0.25 \cdot I_{P.Circ.,norm.}$ (11)	

2.3. Inherent Safety and Health category

Inherent Safety and Health aims to compare the potential of health hazards to the employees and communities close to the production locations.

Index-based methods have been widely used since they are simple and user friendly and require information that is available at an early design stage. To select inherent safety and health indicators for the present tool, methods such as "Prototype of Inherent Safety"(Edwards & Lawrence, 1993), "Inherent Safety Index" (Heikkilä, 1999) and "Inherent Occupational Health Index" (Hassim & Hurme, 2010) were reviewed. The selection of indicators was based on three main requirements: the indicators are easily estimated with the input data available at an early design stage; double counting should be avoided; and the indicators should have a significant impact on safety and health hazards.

Inherent Safety and Health is divided into two subcategories: *Process Safety* (see Table 3), focusing on the evaluation of the process conditions and operation mode, and *Health Hazards* (refer to Table 4), which evaluates chemical properties of the components present in the process. Eq.(12) illustrates that indicators based on operational conditions carry a greater weight than operating mode, since critical operating conditions can pose a higher hazard compared to batch processes (Hassim & Hurme, 2010).

Table 3: Green-by-design indicators and weight factors of the *Inherent Safety and Health* category, *Process Safety* subcategory. Adapted from (Hassim & Hurme, 2010; Heikkilä, 1999).

Category: Inherent Safety & Health (40%) - Subcategory: Process Safety

Process Safety (50%)

$$I_{PS}^{j} = 0.2 \cdot I_{OP,\ norm.} + 0.4 \cdot I_{RS,\ norm.} + 0.4 \cdot I_{U/DS,\ norm.} \quad (12)$$

<u>Overall Process (OP)</u>

- Index-based indicator.

Operation mode		**Score**
Batch (100 %)	→	1
Semi-batch (50 % - 100 %)	→	2
Semi-batch (1 % - 50 %)	→	3
Continuous	→	4

<u>Reaction Section (RS)</u>

- Sum of index-based indicators (Heikkilä, 1999).
- Accounts for operating pressure/temperature of the reaction section and heat of reaction.

<u>Up/Downstream Section (U/DS)</u>

- Sum of index-based indicators (Heikkilä, 1999).
- Accounts for operating pressure/temperature of different units in upstream and downstream sections.
- The process step with most critical conditions is the one accounted for in the final score.

Pressure (bara)	**Temperature (°C)**	**Heat of reaction (kJ/kg)**		**Score**
>200	>600	≤ - 3000	→	1
50 – 200	300 – 600	> -3000	→	2
25 – 50	150 – 300	> -1200	→	3
5 – 25	70 – 150	< -600	→	4
0.5 – 5	0 – 70	≤ -200	→	5
0.2 – 0.5	< 0	-	→	4
0 – 0.2	-	-	→	3

Table 4: Green-by-Design indicators and weight factors of the *Inherent Safety and Health* category, *Health Hazards* subcategory. FP: flash point; BP: boiling point; LD_{50}: lethal dose. Adapted from (Erhirhie et al., 2018; Heikkilä, 1999)

Category: Inherent Safety & Health (40%) - Subcategory: Health Hazards

Health Hazards (50%)

$$I_{HH}^{j} = 0.5 \cdot I_{Toxicity,\ norm.} + 0.5 \cdot I_{Flammability,\ norm.} \quad (13)$$

Flammability

- Index-based indicator (dependent on the flash point values)(Heikkilä, 1999).
- The most flammable compound is the one accounted for in the final score.

Toxicity

- Index-based indicator (dependent on the LD_{50} values)(Erhirhie et al., 2018).
- The most toxic compound is the one accounted for in the final score.

Flammability	Toxicity		Score
Very flammable (FP< 0˚C and BP ≤ 35 ˚C)	Extremely toxic (LD_{50} (mg/g) ≤ 5)	→	1
Easily flammable (FP < 21 ˚C)	Highly toxic (5 < LD_{50} < 50)	→	2
Flammable (FP ≤ 55 ˚C)	Moderately toxic (50 < LD_{50} < 500)	→	3
Combustible (FP > 55 ˚C)	Slightly toxic (500 < LD_{50} < 5000)	→	4
Nonflammable	Practically toxic (5000 < LD_{50} < 15000)	→	5
-	Non-toxic (15000 ≤ LD_{50})	→	6

$$I_{ISH}^{j} = 0.5 \cdot I_{PS,\ norm.} + 0.5 \cdot I_{HH,\ norm.} \quad (14)$$

3. Results and discussion

Applicability of the 'Green-by-Design method' is demonstrated in two case studies: ethylene glycol production and fava bean protein isolate extraction process. To generate the results depicted in Figure 2, data for each process option were collected, and the indicators outlined in the previous section were estimated using Microsoft Excel.

Three process options for ethylene glycol production are compared: the conventional process of ethylene (fossil-based) to glycols, sucrose hydrogenolysis and fermentation of thick juice to produce first ethylene and then glycols. The results obtained from the 'Green-by-Design method' are shown in Figure 2 a).

It can be concluded that the process with the highest economic potential is sucrose hydrogenation. The raw material is cheaper compared to the conventional process of producing ethylene glycol from ethylene and during the hydrogenation of sugars, other valuable products are obtained, such as glycerol and propylene glycol.

When comparing the three processes in terms of environmental impacts, the fossil-based process appears to have a better score than the other two processes. Despite the 'ethylene to glycols' process having a higher CO_2 footprint, the plant-based processes have larger wastewater streams and greater land use to produce the required raw materials. Regarding Inherent Safety and Health, the three processes have very similar scores.

In the second case study, two options are compared for the production of fava bean protein isolate production from fava flour: protein extraction using pH precipitation and ultrafiltration. Since there are no reaction sections in these processes, the ones related to the reaction section were left out of the evaluation for estimating the indicators with the 'Green-by-Design method'. This shows some flexibility on the application of the method.

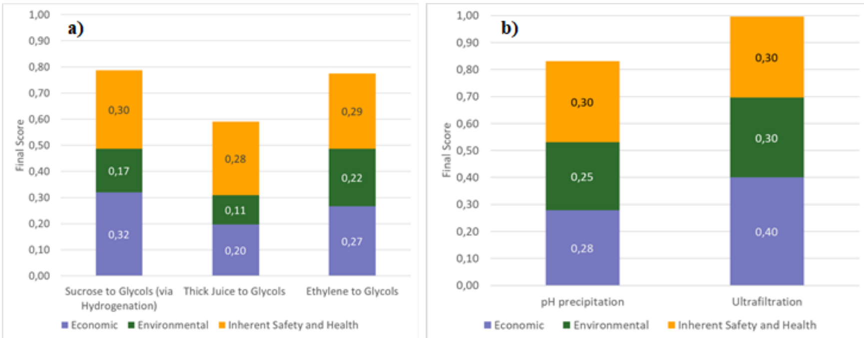

Figure 2: Comparative Results of the 'Green-by-Design method' of the two case studies: a) ethylene glycol production; b) fava bean protein isolate production. The final score can vary between 0 and 1 and the higher the final score, the higher is the sustainability potential of the design concept under evaluation.

As it can be seen in Figure 2 b), the process route using ultrafiltration has higher scores (meaning better performance) in two of the categories of the 'Green-by-Design method': Economic and Environmental. Ultrafiltration enhances the product functionalities, resulting in a higher selling price for the protein isolate. This makes ultrafiltration a more economically attractive choice. Regarding the environmental impacts, pH precipitation requires additional steps after the extraction step to neutralize the pH, and it produces larger wastewater streams. Therefore, the score for the Environmental category is considerably lower (meaning worse performance) compared to ultrafiltration.

4. Conclusions

The 'Green-by-Design method' developed at Cosun showed to be useful for comparing different design concepts and identifying hotspots in aspects related to three main sustainability related categories–Economic, Environmental and Inherent Safety & Health – to support decision making in an early design stage. In addition, the method is user friendly and flexible, by combining index-based indicators and indicators estimated by means of simple equations.

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