Escola Politécnica da Universidade de São Paulo

# PQI 3535: Avaliação de Ciclo de Vida (ACV)

Gil Anderi da Silva
Luiz Kulay

# EXERCÍCIO DE FIXAÇÃO n.6
comentários

## Informações do enunciado

Tabela 1 – Inventário de aspectos ambientais referentes ao ciclo de vida do produto.

| Aspecto Ambiental | Quantidade (kg/UF) |
|---|---|
| Consumo de gás natural | 9,74 |
| Consumo de diesel | 7,05 |
| Emissão de formaldeído | 0,15 |
| Emissão de dióxido de nitrogênio ($NO_2$) | 2,02 |
| Emissão de dióxido de enxofre ($SO_2$) | 19,0 |
| Emissão de dióxido de carbono ($CO_2$) | 580,5 |
| Emissão de metano ($CH_4$) | 0,86 |
| Emissão de propileno ($C_3H_6$) | 0,18 |
| Emissão de óxido nitroso ($N_2O$) | 0,21 |
| Emissão de amônia ($NH_3$) | 0,16 |
| Emissão de CFC-113 | 0,008 |
| Emissão de benzeno | 0,36 |
| Emissão de ácido clorídrico (HCl) | 0,43 |
| Descarte de mercúrio (Hg) como efluente líquido | 0,02 |
| Descarte de cromo hexavalente ($Cr^{6+}$) como efluente líquido | 0,06 |
| Demanda Química de Oxigênio (DQO) dos efluentes líquidos | 186 |

## Informações do enunciado

### Depleção de Recursos Energéticos

| Composto | Fator de Caracterização kg petróleo-eq / kg |
|---|---|
| Carvão mineral | 0,455 |
| Óleo combustível | 1,07 |
| Diesel | 1,1 |
| Gás Natural | 0,912 |

### Eutrofização

| Composto | Fator de Caracterização (kg $PO_4^{3-}$-eq / kg de composto) |
|---|---|
| $PO_4^{3-}$ | 1,00 |
| $NO_3^-$ | 0,10 |
| $NO_2$ | 0,13 |
| $N_2O$ | 0,27 |
| $NH_3$ | 0,35 |
| $NH_4^+$ | 0,33 |
| N | 0,42 |
| P | 3,06 |
| DQO | 0,022 |

(Fonte: BAUMANN & TILLMAN, 2004)

### Toxicidade Humana

| SUBSTÂNCIA | Fator de Caracterização (kg de 1,4-DB-eq / kg substância) |
|---|---|
| Arsênio | 355.000 |
| Cádmio (ar) | 150.000 |
| Cobre (ar) | 4.300 |
| Cobre (água) | 1,3 |
| Cromo hexavalente (água) | 3,4 |
| Cromo hexavalente (solo) | 500 |
| Mercúrio (água) | 1.400 |
| Mercúrio (solo) | 5.900 |
| Níquel (água) | 330 |
| Níquel (ar) | 35000 |
| Formaldeído | 0,831 |
| PAH (ar) | 575.000 |
| $NH_3$ (ar) | 0,1 |
| benzeno (ar) | 1.900 |
| Hexaclorobenzeno | 3.260.000 |
| Fenol (ar) | 0,52 |
| Glifosato (solo) | 0,02 |
| HCl (ar) | 0,5 |
| $H_2S$ (ar) | 0,22 |
| $SO_2$ (ar) | 0,096 |
| $NO_2$ (ar) | 1,2 |
| Material Particulado (PM10) | 0,821 |

(Fonte: CML, 2001)

### Mudança Climática

| Composto | Fator de Caracterização (kg $CO_2$ eq / kg composto) |
|---|---|
| $CO_2$ | 1 |
| $CH_4$ | 25 |
| $N_2O$ | 298 |
| $SF_6$ | 22.800 |
| CFC-11 | 4.750 |
| CFC-12 | 10.900 |
| CFC-113 | 6.130 |
| HCFC-22 | 1.810 |
| HCFC-123 | 77 |
| HFC-23 | 14.800 |
| HFC-143a | 4.470 |
| $CCl_4$ | 1.300 |
| $CH_3CCl_3$ | 146 |
| $CF_3Br$ | 7.140 |

(Fonte: IPCC, 2007)

### Formação de Foto-Oxidantes

| Composto | Fator de Caracterização (kg $C_2H_4$ / kg composto) |
|---|---|
| CO | 0,027 |
| $NO_2$ | 0,028 |
| $SO_2$ | 0,048 |
| metano | 0,006 |
| etano | 0,123 |
| propano | 0,176 |
| Propileno | 1,120 |
| Hidrocarbonetos (média) | 0,377 |
| benzeno | 0,218 |
| tolueno | 0,637 |
| acetona | 0,094 |
| formaldeído | 0,519 |

(Fonte: DERWENT & JENKINS, 1990; BAUMANN & TILLMAN, 2004)

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| Níquel (ar) | 35000 |
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(Fonte: DERWENT & JENKINS, 1990; BAUMANN & TILLMAN, 2004)

## Classificação

| Aspecto Ambiental | DRN | CC | EUT | POF | HT |
|---|---|---|---|---|---|
| Gás natural | X | | | | |
| Diesel | X | | | | |
| $CH_2O$ | | | | X | X |
| $NO_2$ | | | X | X | X |
| $SO_2$ | | | | X | X |
| $CO_2$ | | X | | | |
| $CH_4$ | | X | | X | |
| $C_3H_6$ | | | | X | |
| $N_2O$ | | X | X | | |
| $NH_3$ | | | X | | X |
| CFC-113 | | X | | | |
| $C_6H_6$ | | | | X | X |
| HCl | | | | | X |
| Hg | | | | | X |
| $Cr^{6+}$ | | | | | X |
| DQO | | | X | | |

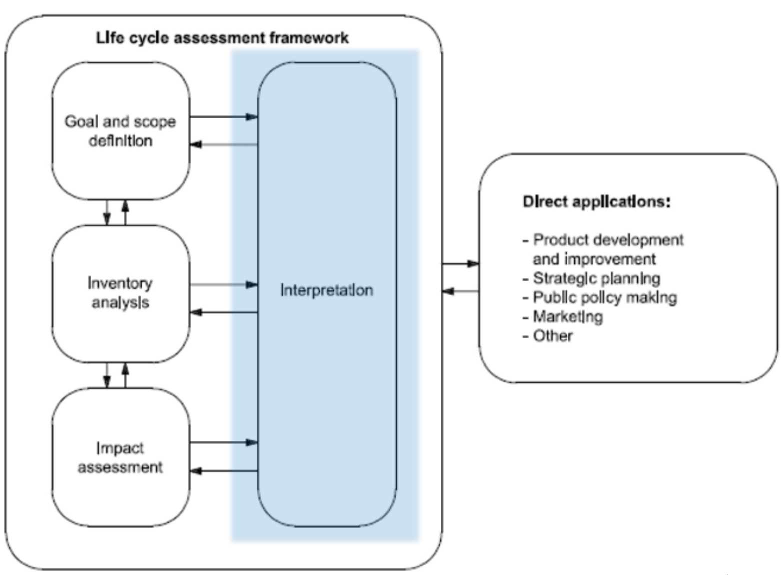
## Caracterização

| Aspecto Ambiental | DRN | CC | EUT | POF | HT |
|---|---|---|---|---|---|
| Gás natural | 0,912 x 9,74 = **8,8829** | | | | |
| Diesel | 1,1 x 7,05 = **7,755** | | | | |
| $CH_2O$ | | | | 0,519 x 0,15 = **0,0779** | 0,831 x 0,15= **0,1247** |
| $NO_2$ | | | 0,13 x 2,02 = **0,2626** | 0,028 x 2,02 = **0,0566** | 1,2 x 2,02 = **2,424** |
| $SO_2$ | | | | 0,048 x 19 = **0,912** | 0,096 x 19 = **1,824** |
| $CO_2$ | | 1 x 580,5 = 580,5 | | | |
| $CH_4$ | | 25 x 0,86 = 21,5 | | 0,006 x 0,86 = **0,00516** | |
| $C_3H_6$ | | | | 1,12 x 0,18 = **0,2016** | |
| $N_2O$ | | 298 x 0,21 = 62,58 | 0,27 x 0,21 = **0,0567** | | |
| $NH_3$ | | | 0,35 x 0,16 = **0,056** | | 0,1 x 0,16 = **0,016** |
| CFC-113 | | 6130x0,008= 49,04 | | | |
| $C_6H_6$ | | | | 0,218 x 0,36 = **0,0785** | 1900 x 0,36 = **684** |
| HCl | | | | | 0,5 x 0,43 = **0,215** |
| Hg | | | | | 1400 x 0,02 = **28** |
| $Cr^{6+}$ | | | | | 3,4 x 0,06 = **0,204** |
| DQO | | | 0,022 x 186 = **4,092** | | |

## Perfil Ambiental

| Categoria de Impacto | Unidade | Resultado do indicador da categoria |
|---|---|---|
| DRN | kg eq. petróleo / FR | 16,6 |
| CC | kg eq. $CO_2$ / FR | 713 |
| EUT | kg eq. $PO_4^{-3}$ / FR | 4,47 |
| POF | kg eq. $C_2H_4$ / FR | 1,33 |
| HT | kg eq. 1,4-DB / FR | 716 |

## Estrutura do Método de ACV




(ISO 14040:2006)

## Conceito e Objetivo

Conceito

Fase da ACV na qual as constatações do estudo são combinadas de maneira consistente com o objetivo e o escopo visando obter a partir destas conclusões e recomendações

Objetivos

- Analisar os resultados
- Obter conclusões
- Explicitar as limitações
- Oferecer recomendações com base nas constatações
- Relatar os resultados de forma transparente

## Elementos

- Identificação de Questões Significativas
- Avaliação
- Conclusões, Recomendações e Relatório

## Identificação de Questões Significativas

Objetivo

estruturar resultados para determinar questões significativas de acordo com a definição da objetivo e escopo

A partir das definições de objetivos e escopo de um estudo de ACV, a estruturação/forma de comunicação dos resultados obtidos pode ocorrer de diferentes maneiras. São elas:

- por estágios do ciclo de vida
- por grupos de processos (transporte, energia, ...)
- por graus de influência da gestão (gestão própria, ou responsabilidade externa)

## Estruturação das Entradas e Saídas do ICV por Estágio do Ciclo de Vida

| Entradas/saídas do ICV | Produção de materiais (kg) | Processos produtivos (kg) | Fases do uso (kg) | Outros (kg) | Total (kg) |
|---|---|---|---|---|---|
| Carvão | 1200 | 25 | 500 | - | 1725 |
| $CO_2$ | 4500 | 100 | 2000 | 150 | 6750 |
| $NO_x$ | 40 | 10 | 20 | 20 | 90 |
| Fosfato | 2,5 | 25 | 0,5 | - | 28 |
| AOX | 0,05 | 0,5 | 0,01 | 0,05 | 0,61 |
| Resíduos urbanos | 15 | 150 | 2,0 | 5,0 | 172 |
| Aparas | 1500 | - | - | 250 | 1750 |

Estruturação das Entradas e Saídas do ICV por Grupos de Processos

| Entradas/saídas do ICV | Fornecimento de energia (kg) | Transporte (kg) | Outros (kg) | Total (kg) |
|---|---|---|---|---|
| Carvão | 1500 | 75 | 150 | 1725 |
| $CO_2$ | 5500 | 1000 | 250 | 6750 |
| $NO_x$ | 65 | 20 | 5,0 | 90 |
| Fosfato | 5,0 | 10 | 13 | 28 |
| AOX | 0,01 | - | 0,6 | 0,61 |
| Resíduos urbanos | 10 | 120 | 42 | 172 |
| Aparas | 1000 | 250 | 500 | 1750 |

Avaliação

Estudo de ACV

elevado número de dados e de hipóteses → necessidade de avaliar a qualidade dos resultados e conclusões.

Objetivos

estabelecer e elevar os graus de certeza e de confiabilidade dos resultados do estudo de ACV ou ICV

Avaliação deve considerar o uso das técnicas:

- verificação de completeza
- verificação de sensibilidade
- verificação de consistência

## Conclusões e Recomendações

Objetivo

obter as conclusões e fazer as recomendações para o público alvo a quem o estudo se destina

As conclusões deve ser obtidas de maneira interativa com os outros elementos do estudo de ACV. Para tanto, é fundamental obedecer à sequência indicada abaixo:

- identificação das questões relevantes
- avaliar a completeza, sensibilidade e consistência dos resultados e da metodologia
- obtenção das conclusões preliminares
- verificação de sua consistência com aspectos definidos nas etapas de objetivo e o escopo: p.e. requisitos de dados, hipóteses, decisões subjetivas, ...

## Verificação de Completeza

Objetivo

assegurar que todas as informações relevantes estejam disponíveis e completas

Informação não disponível ou incompleta

Caso ocorra uma situação dessa natureza, deve-se avaliar a necessidade desse dado (ou parâmetro) para que as orientações estabelecidas nas etapas de definição de objetivo e escopo fossem atendidas:

- se a informação for considerada necessária, deve-se rever às fases executivas da ACV (ICV e/ou AICV), ou mesmo, à definição de objetivos e de escopo;
- caso a informação seja considerada desnecessária, deve-se registrar a justificativa para tal conclusão

## Verificação de Consistência

Objetivo

verificar se as hipóteses, métodos e dados são consistentes com os objetivo e (condicionantes de) escopo estabelecidos para o estudo

Devem ser verificadas as seguintes questões:

- se as diferenças na qualidade dos dados ao longo do ciclo de vida de um SP e entre diferentes SP's são consistentes com objetivo e escopo
- consistência na definição das fronteiras do sistema
- consistência na aplicação dos critérios de alocação
- (...)

## Verificação de Sensibilidade

Objetivo

avaliar a confiabilidade dos resultados e das conclusões atingidos

Verificação quanto incertezas associadas a dados e a hipóteses podem afetar a confiabilidade dos resultados e conclusões

# ESTUDOS DE CASO

## Estudo de Caso n.1

Int J Life Cycle Assess (2017) 22:644–655
DOI 10.1007/s11367-016-1108-7

LIFE CYCLE ASSESSMENT: A TOOL FOR INNOVATION IN LATIN AMERICA

**Verifying the effectiveness of environmental performance improvement actions in the chain of production of an agrochemical produced in Brazil**

Luiz Kulay[1] · Victor Sette Gripp[1] · Alex Rodrigues Nogueira[1] · Gil Anderi Silva[1]

Received: 4 December 2015 / Accepted: 4 April 2016 / Published online: 13 April 2016


**Abstract**
*Purpose* A Brazilian agrochemical company agreed to conduct an initiative to further evaluate the environmental impact caused by its product SC50. This agrochemical is obtained from thiophanate-methyl, an active ingredient produced in Brazil as well as in Japan, where another industrial plant of the same corporation is located. The initiative evaluated the environmental performance of the SC50 life cycle so as to provide the company's private management with information to influence stakeholders in the sector.
*Methods* The working method comprised five steps. Step 1 established the impact profile associated to the SC50 life cycle. The diagnosis was obtained by LCA from a 'cradle-to-grave' approach. Step 2 identified the stages causing significant environmental impacts throughout the entire life cycle. In Step 3, improvement actions were proposed in order to mitigate, reduce, or even minimize the effects detected. Step 4 comprised the modeling, in which specific scenarios and their environmental impacts were analyzed. The synergistic effect was checked by successive additions of improvement actions, characterizing each scenario. Step 5 analyzed the results, comparing impact profiles of each scenario with the original diagnosis (as a baseline scenario) and verifying the individual effect of each action.
*Results and discussion* The results indicate relevant contributions of the dispersion from the SC50 life cycle in terms of global warming, terrestrial ecotoxicity, human toxicity, and eutrophication. Regarding to the manufacture, the use of diesel has great influence in the impacts of SC50, and its performance as eutrophication is conditioned to the low efficiency of the wastewater treatment. While the company decided not to implement improvements in the dispersion stage fearing market losses, five alternatives based on cleaner production principles were proposed to improve performance: to review the instrumentation systems in the plant, to adjust wastewater treatment, to stop importing thiophanate-methyl from Japan, to install an energy cogeneration system, and to substitute renewable glycerin with a fossil counterpart. All scenarios led to improvements from baseline.
*Conclusions* The use of LCA determined the impact profile associated to SC50 in soybean pest control. Because of strategic reasons, the company decided not to propose improvements in the most significant stage of this life cycle. Among the improvements, we highlight the replacement of imported thiophanate-methyl by a Brazilian equivalent and the installation of a combined cycle for energy recovery. For both these cases, however, the appropriate organizational measures must be taken before implementation.

**Keywords** Agribusiness · Agrochemicals · Cleaner production · Performance analysis · Thiophanate-methyl

### 1 Introduction

Chemical compounds classified as pesticides are seen as serious threats by various sectors of contemporary society. In general, these agents are no longer considered a necessary evil used to improve agricultural productivity. Furthermore, the scientific literature on the topic has noted significant damage caused by these products in areas where they are used, given their medium- and long-term impact on humans and the environment (Levitan 2000; Reus et al. 2002; Garthwaite and

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Kulay et al. (2017)
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https://doi.org/10.1007/s11367-016-1108-7

## Objectives & Motivation

Pesticides: for society it is “**necessary evil**" to increase agricultural productivity in order to meet the food needs of modern society

IHARA:
Assessing the environmental performance of its products
Identification of opportunities to improve environmental performance

Selected Product:
Methyl thiophanate (SC 50).

Why SC 50?
Regular use in cultivation of soybeans, cotton, beans, rice, tomato, citrus, etc.
2009-2010: soybean cultivation in the Cerrado - Brazil: **70.4%** of IHARA's sales were due to SC 50

Company’s expectations:
Supporting decision-making processes: **environmental variable**
Guide agricultural products (consumer of the product)

## Scope Definition

Conceptual framework: NBR ISO 14044 (2006)

General approach: cradle-to-grave

Product: Methyl thiophanate (SC 50)(sol.) – diluted solution (1:1)w/w = SC 50%

Function: Control the growth **of fungi** in soybean planting in the Brazilian Cerrado

Reference flow: adding 100L (= **116.2 kg**) of SC 50 to control the growth of fungi in the planting of **100 ha** of **soybean** in the Brazilian Cerrado

System boundaries:
Processing stages of SC50
Transports;
Manufacture of intermediates;
Use of SC 50 in soybean cultivation;
Production of process utilities (water and effluent treatment, generation and transport of electricity)

## Scope Definition

Data quality:
1ary data: SC 50 fabrication; transports; and industrial utilities
2ary data: other unit processes

Exclusion criteria:
Cumulative contributions in terms of mass or energy < 2.0%

Data quality - Coverage:
Temporary: 2009-2010

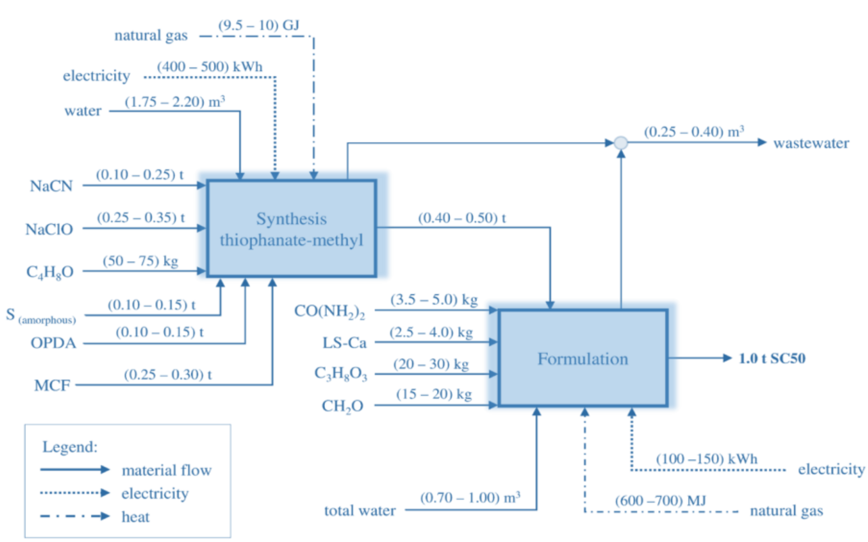
Geographical: SP (production SC 50 + raw materials); MT, GO, BA (use SC 50); JP (production of Methyl thiophanate)

Technological: current

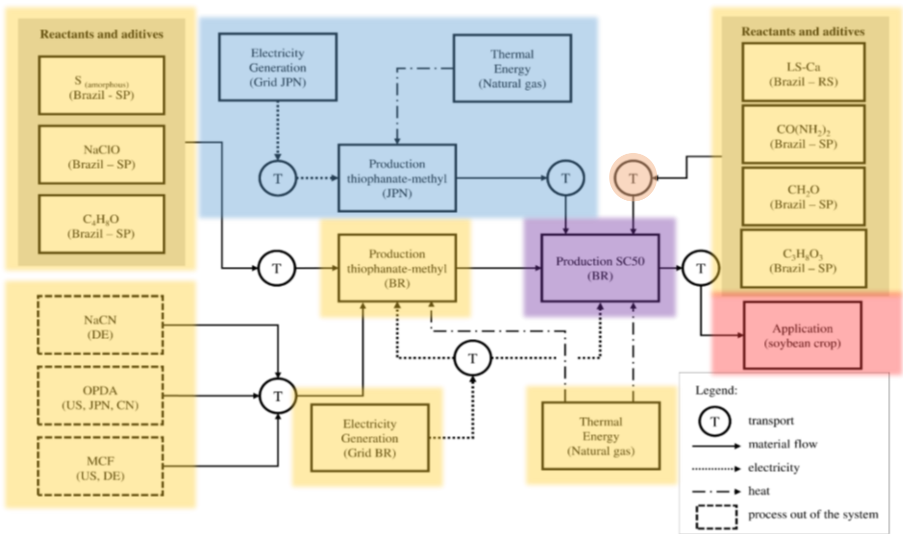
Multifunctionality situation: product system doesn't present multifunctional processes

Impact Assessment categories: AD, AC, EUT, GWP, PHO, $HT_c$, $HT_{nc}$, ECT

## Technological approach



## Product System




## Results

Environmental impact for fungal growth control in soybean crops using SC 50

| Impact category | Unit | Total | Final disposal | Use | Transport | Manufacture |
|---|---|---|---|---|---|---|
| AD | kg Sb eq | 6.85 | 0.00 | 5.22 | 2.99E-01 | 1.34 |
| AC | kg $SO_2$ eq | 7.06 | 0.00 | 6.16 | 2.06E-01 | 6.92E-01 |
| EUT | kg $PO_4^{3-}$ eq | 2.60 | 0.00 | 1.44 | 5.35E-02 | 1.11 |
| GWP | kg $CO_2$ eq | 951 | 0.00 | 813 | 42.7 | 95.5 |
| PHO | kg $C_2H_4$ eq | 1.63E-01 | 0.00 | 1.08E-01 | 6.44E-03 | 4.89E-02 |
| HTc | CTUh | 1.45E-08 | 0.00 | 5.68E-09 | 8.66E-10 | 7.99E-09 |
| HTnc | CTUh | 1.20E-09 | 0.00 | 7.27E-10 | 1.21E-10 | 3.49E-10 |
| ECT | CTUe | 1900 | 1839 | 1.05 | 7.15E-02 | 59.5 |

dispersion of the agrochemical on soybean crops (by plane)

## Analysis based on corporate strategy

- LCA results depicted that the method of dispersion should be the focus of collective environmental impact improvement actions
- The company, however, discouraged projects that addressed that aspect, fearing that if the impact reduction were associated to a procedure managed by farmers, they would feel required to take part in a process. This could, in its turn, lead to considerable market losses
- Proposals aimed to reducing SC 50 final disposal impact were also disregarded. In the company's view, the best way to deal with the issue would be to develop a new molecule based on concepts of DfE, which is an expensive procedure, with only long-term results
- Conversely, the company identified situations throughout the production chain of SC 50 in which Cleaner Production actions could be taken and result in potential decreased impact.

## Scenarios for potential improvement of environmental performance

After applying a selection criteria based in management and technical-operational requirements, five improvement actions have been selected by the company

| Action | Description | Scenario | Arrangement |
|---|---|---|---|
| A | Review of in-plant instrumentation and control systems | S1 | A |
| B | Closing of process water/effluent circuit + redesign of effluent treatment plant | S2 | A + B |
| C | Discontinuation of imported thiophanate-methyl from Japan + replacement of the OPDA supplier | S3 | A + B + C |
| D | Implementation of a steam cogeneration system | S4 | A + B + C + D |
| E | Replacing renewable glycerin for fossil glycerin | S5 | A + B + C + D + E |

## Results

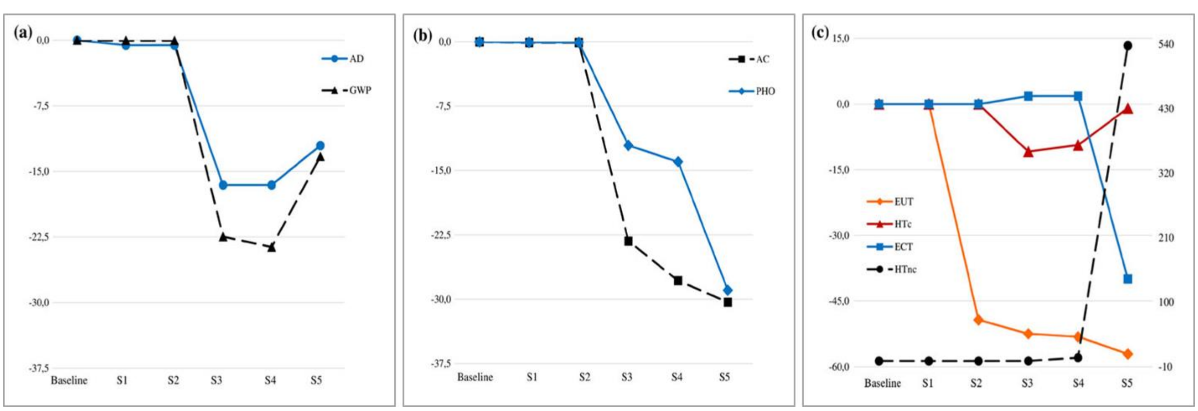
Distinct effects of each improvement action on the environmental impact profile of SC 50 production

| Impact category | Baseline scenario | Relative contribution (%) per improvement action | | | | | |
|---|---|---|---|---|---|---|---|
| | Unit | Total | A | B | C | D | E |
| AD | kg Sb eq | 1.34 | (−) 0.59 | 0.00 | (−) 15.4 | 0.57 | 4.51 |
| AC | kg $SO_2$ eq | 6.92E-01 | (−) 0.09 | 0.00 | (−) 23.0 | (−) 2.23 | (−) 2.51 |
| EUT | kg $PO_4^{3-}$ eq | 1.11 | 0.00 | (−) 49.3 | 0.27 | (−) 0.35 | (−) 3.92 |
| GWP | kg $CO_2$ eq | 95.5 | (−) 0.03 | 0.00 | (−) 22.4 | (−) 0.57 | 10.4 |
| PHO | kg $C_2H_4$ | 4.89E-02 | (−) 0.06 | 0.00 | (−) 12.0 | (−) 0.89 | (−) 15.0 |
| HTc | CTUh | 7.99E-09 | 0.00 | 0.00 | (−) 10.8 | 0.74 | 8.42 |
| HTnc | CTUh | 3.49E-10 | (−) 0.05 | 0.00 | 0.10 | 2.84 | 532 |
| ECT | CTUe | 59.5 | 0.00 | 0.00 | 1.83 | 0.00 | (−) 41.8 |

Discontinuation of imported thiophanate-methyl from Japan + replacement of the OPDA supplier

## Results

Effect of successive deployment of improvement actions on the Environmental Profile of SC50 production.
Results regarding: **(a)** GWP and AD; **(b)** AC and PHO; **(c)** EUT, HTc, HTnc and ECT



## Conclusions

- Discontinuing the use of thiophanate-methyl imported from Japan, while in disagreement with a corporate directive, was found to be an effective action. The implementation of this measure is, however, conditioned to cultural changes within the company itself

- Installation of an energy cogeneration unit in order to decouple it from the Brazilian power grid. Despite the slight environmental gains of this action, such an undertaking needs to consider an economic analysis

- The use of fossil-sourced glycerin instead of its renewable counterpart is controversial. This leads to gains in terms of EUT, ECT and PHO, but also disadvantages in AD, GWP and specially, in $HT_{nc}$

- This study met its original expectations, to support the organization's management in decision-making process that could incorporate the environmental variable as a prerogative for this kind of action

## Estudo de Caso n.3

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*Article*

**Using the Life Cycle Approach for Multiobjective Optimization in the Context of the Green Supply Chain: A Case Study of Brazilian Coffee**

**Hugo Sakamoto [1,2,*], Larissa Thais Bruschi [3], Luiz Kulay [3] and Akebo Yamakami [1]**

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**Abstract:** This study proposes a multiobjective optimization model (MOO) based on a green supply chain so that coffee produced in Brazil could supply the North American market with lower environmental impacts and costs. Production and distribution arrangements were established considering four coffee-producing regions, three ports of origin in Brazil, four destination ports, seven roasting plants, and fifteen consumption centers, all distributed throughout the American territory. Environmental and economic performances regarding global warming potential (GWP) and costs were determined for a life cycle approach. The results indicate that coffee cultivation has the most significant contributions to the GWP of the arrangements. The transport of the product by road also plays an essential role, especially if extensive distances are covered during the port–roaster–consumer center journey in the United States. The analysis showed differences of 2.0 kg $CO_{2eq}$ and US$8.00 per ton of coffee between the best and worst arrangements, which can be considered significant when projected to the Brazilian annual coffee export scale. In the environmental limit condition, the optimization can lead to non-trivial results compared to the real market. The model conceived for the MOO can be improved to reproduce more realistic conditions by incorporating producer and consumer markets, inserting uncertainties.

**Keywords:** life cycle assessment; multiobjective optimization; Brazilian coffee; green supply chain

**Citation:** Sakamoto, H.; Bruschi, L.T.; Kulay, L.; Yamakami, A. Using the Life Cycle Approach for Multiobjective Optimization in the Context of the Green Supply Chain: A Case Study of Brazilian Coffee. Sustainability **2023**, 15, 13987. https://doi.org/10.3390/su151813987

Academic Editor: Riccardo Testa

Received: 15 August 2023
Revised: 14 September 2023
Accepted: 18 September 2023
Published: 20 September 2023



**1. Introduction**

As one of the most consumed beverages worldwide, coffee has become a commodity of great economic significance [1]. This is so true that in 2023 alone, the global coffee industry is expected to process just over 167 million 60 kg bags of the product, which at current prices projects a revenue of US$496 billion [2]. In recent years, the coffee supply–demand binomial has become quite polarized: on the one hand, only six countries have the largest share of green bean production, i.e., Brazil (37%), Vietnam (17%), Colombia (8.4%), Indonesia (7.0%), and Ethiopia (4.3%) [3], while on the other hand, the European Union (63%) and the United States, its leading consumer on a global scale (~18%), are frequent destinations for roasting and subsequent consumption [4].

As with other world-class products, coffee production and distribution chains are susceptible to limitations. Examples are (i) the low financial return for the rural producer [5], which was significantly affected by the pandemic of COVID-19 [6]; (ii) the vulnerability of supply in extreme weather scenarios [7]; (iii) the economic disparity between producing and consuming countries, characterized by exchange rate differences [5]; and (iv)

Sustainability **2023**, 15, 13987. https://doi.org/10.3390/su151813987 www.mdpi.com/journal/sustainability

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Sakamoto et al. (2023)
Sustainability – MDPI
(2023) 15, 13987
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# Using the Life-Cycle Approach for Multi-Objective Optimization in the context of the green supply chain: a case study of Brazilian coffee

Hugo Sakamoto[1,2], Larissa T. Bruschi[3], Luiz Kulay[3], Akebo Yamakami[1]

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# Agenda

Context

Literature gap

Life Cycle Modeling

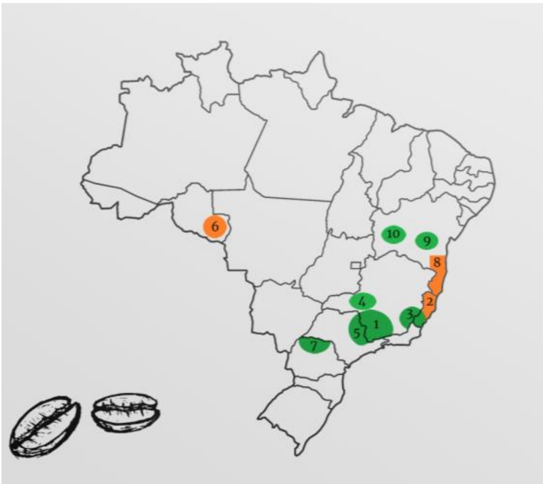
Optimization Modeling

LCA results

Optimization results

Conclusions and future works

# Context – World coffee market




Projected revenue 2023: US$ 496 bi

Market share:
1. Brazil – 37%
2. Vietnam – 17%
3. Colombia – 8.4%
4. Indonesia – 7.0%
5. Ethiopia – 4.3% (73.7%)

Main destinations:
EU (63%) and USA (18%)

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# Context – Supply chain problem?

Supply Chain Management (SCM): economic and performance improvement;

Environmental + SCM = Green Supply Chain Management (GSCM);

Social + Environmental + SCM = Sustainable Supply Chain Management (SSCM).

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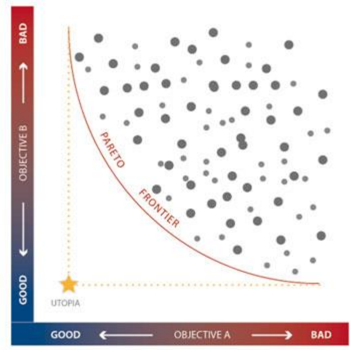
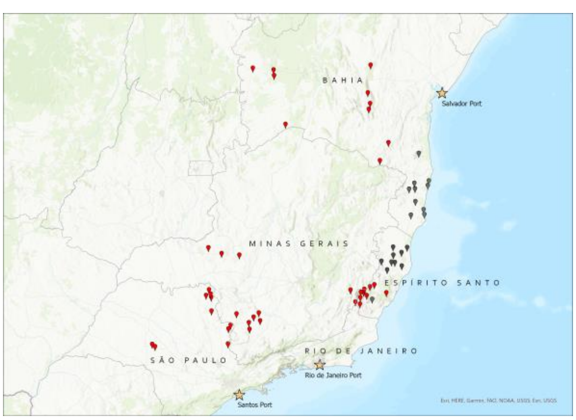
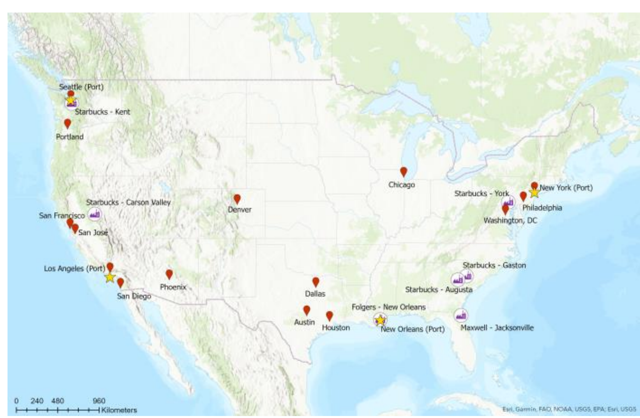
# Literature gap

- GSCM = Multi-objective optimization (environmental x economic);
- Environmental: Life Cycle Assessment (LCA) (novelty);
- Economic: cost to export Brazilian coffee to US market. Life Cycle thinking.




# Brazilian coffee to the US




- Coffee production: 4 main states;
- Exportation by 3 ports;
- Transportation: truck.

- 4 ports (US divided into four quadrants);
- Transportation to 7 coffee roasting units (3 brands);
- 15 consumer cities;
- Transportation: truck.

# Life Cycle Modeling

- Reference flow: 'making available 1.0 kg of roasted and ground Brazilian coffee at the distribution point (i.e., coffee shop, supermarket, store) of a large North American consumer center';
- Life Cycle Inventory: secondary data from Ecoinvent database adapted by including information from scientific articles and technical reports;
  - Brazilian coffee production: Coltro et al. (2006) adjusted to 2018 – 2021 period;
  - Brazilian electricity matrix: National Energy Balance 2021;
  - Ratio green coffee/roasted coffee: Giraldi-Díaz et al. (2018);
  - Sea and road transportation distances: Google Maps and searates.com;
- LCA prospective study: 9 categories;
- Optimization study: Global Warming Potential (GWP).

# Optimization Modeling

- Main equation, based on the Weighting Sum Method:

$$\min(1-w)\left(\frac{EI}{f_{EI}^{0}}\right)+w\left(\frac{\$I}{f_{\$I}^{0}}\right)$$

- EI = environmental indicator; $I = cost indicator;
- Normalized by respective utopia points;
- 0 ≤ w ≤ 1: degree of preference.

# Optimization Modeling

- Environmental indicator:

$$EI = \sum_{i}^{6}\sum_{j}^{3} EIPROD_{ij}y_{ij} + \sum_{i}^{6}\sum_{j}^{3} EIFBR_{ij}x_{ij}y_{ij} + + \sum_{j}^{3}\sum_{m}^{4} EIFRE_{jm}z_{jm} + \sum_{m}^{4}\sum_{n}^{7} EIRST_{mn}w_{mn} + \sum_{n}^{7}\sum_{p}^{15} EIDIST_{np}k_{np}$$

- $(EIPROD)$: environmental impact (kg $CO_{2,\ eq}$/kg coffee) generated during the agricultural processing of coffee in each producing region of Brazil;
- $(EIFBR)$: environmental contribution due to road transport from the farm to the port of origin (kg $CO_{2,\ eq}$/(kg coffee.km));
- $(EIFRE)$: impact of sea freight between Brazilian and US ports (kg $CO_{2,\ eq}$/kg coffee.km);
- $(EIRST)$: impact caused by the road transfer between the American port of destination and the roaster (kg $CO_{2,\ eq}$/kg coffee);
- $(EIDIST)$: portion referring to the road transport that takes place on American territory between each roaster and the consumption centers supplied by it (kg $CO_{2,\ eq}$/kg coffee).

# Optimization Modeling

- Cost indicator:

$$\$I = \sum_{i}^{6}\sum_{j}^{3} CPROD_{ij}y_{ij} + \sum_{i}^{6}\sum_{j}^{3}\left[\frac{(CDCx_{ij} + LUC + WTC)y_{ij}}{(R\$ \rightarrow US\$\ exchange) \times (450\ \times 60)}\right] + \sum_{j}^{3}\sum_{m}^{4} CFRE_{jm}z_{jm} + \sum_{m}^{4}\sum_{n}^{7} CRST_{mn}w_{mn} + \sum_{n}^{7}\sum_{p}^{15} CDIST_{np}k_{np}$$

- $(CPROD)$: is the cost of coffee production (in US$/kg coffee) in each place in Brazil where this occurs (CEPEA-USP);
- $(CFRE)$: is the cost of maritime freight between the Brazilian and American ports (in US$/kg coffee);
- $(CRST)$: corresponds to the cost of shipment from the docks to the roasters (in US$/kg coffee);
- $(CDIST)$: refers to the freight to be paid to transport the coffee from the roasting plant to the cities where the product will be consumed (in US$/kg coffee) (ANTT).

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# Optimization Modeling

- 48 restrictions and 174 variables;
- Google Colab + Pyomo optimization package

# LCA results

| Consumption center | GWP (kg $CO_{2eq}$) | $O_3F$, HH (g $NO_{xeq}$) | FPMF (g $PM2.5_{eq}$) | $O_3F$, TE (g $NO_{xeq}$) | TEcoT (kg 1,4-DB) | MEcoT (g 1,4-DB) | HCTox (g 1,4-DB) | MRS (g $Cu_{eq}$) | FRS (kg $oil_{eq}$) |
|---|---|---|---|---|---|---|---|---|---|
| Austin | 6.19 | 26.3 | 17.0 | 27.1 | 20.8 | 535 | 424 | 29.1 | 0.89 |
| Chicago | 6.25 | 26.5 | 17.1 | 27.3 | 21.7 | 538 | 428 | 29.2 | 0.91 |
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| San Jose | 6.54 | 27.5 | 17.4 | 28.4 | 25.6 | 548 | 447 | 29.8 | 1.01 |
| Seattle | 6.56 | 27.7 | 17.5 | 28.6 | 25.9 | 549 | 449 | 29.9 | 1.02 |
| Washington DC | 6.13 | 26.1 | 16.9 | 26.9 | 19.9 | 533 | 420 | 29.0 | 0.87 |


Roasted coffee logistics was determinant: Texas and Northeast with favorable results.

*GWP – Global Warming; $O_3F$, HH – Ozone Formation, Human Health; FPMF – Fine Particulate Matter Formation; $O_3F$, TE – Ozone Formation, Terrestrial Ecosystems; TEcoT – Terrestrial Ecotoxicity; MEcoT – Marine Ecotoxicity; HCTox – Human Carcinogenic Toxicity; MRS – Mineral Resource Scarcity; FRS – Fossil Resource Scarcity.*

# LCA results

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Roasted coffee logistics was determinant: in California and Northwest, higher impacts (Folgers and Maxwell coffee have to cross the country).

# LCA results

| Consumption center | GWP (kg $CO_{2eq}$) | $O_3F$, HH (g $NO_{xeq}$) | FPMF (g $PM2.5_{eq}$) | $O_3F$, TE (g $NO_{xeq}$) | TEcoT (kg 1,4-DB) | MEcoT (g 1,4-DB) | HCTox (g 1,4-DB) | MRS (g $Cu_{eq}$) | FRS (kg $oil_{eq}$) |
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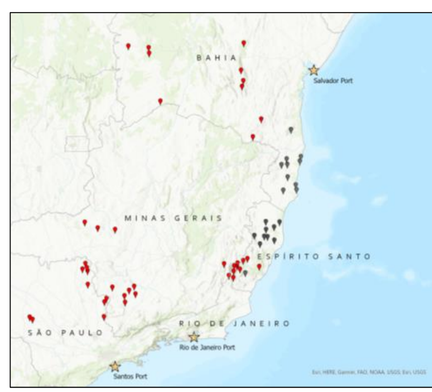
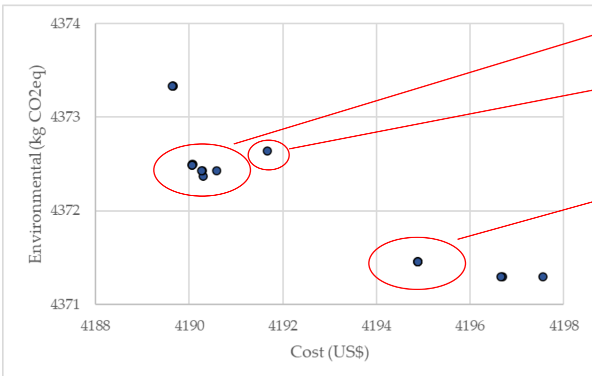



GWP: Brazilian coffee cultivation resulted in 5.31 $CO_{2,eq}$/kg green coffee (81 – 87% of total), confirming the results of Giraldi-Díaz et al. (2018), Usva et al. (2020), Tavares and Mourad (2020).

# Optimization results




w = 0.17, 0.18, 0.19, 0.20, 0.30, 0.40, 0.50, 0.60

w = 0.15

w = 0.12, 0.13, 0.14, 0.16

Variation: US$ 8.00 and 2.0 kg $CO_{2,\,eq}$ per ton.
Considering Brazilian exportations: US$ 24 mi and 6.0 kt $CO_{2,\,eq}$

Multi-objective optimization results for exporting 1.0 ton of Brazilian coffee to the United States.

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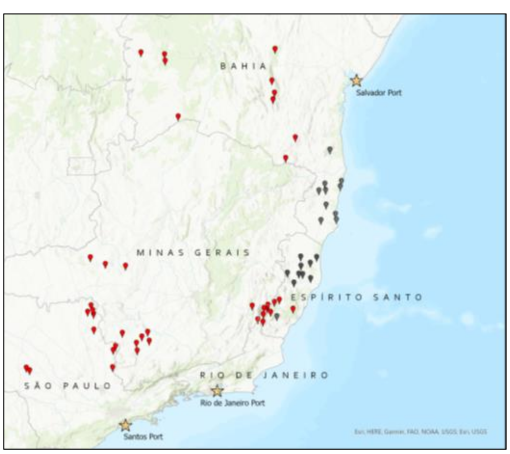
# Optimization results




When $w \to 0$ (environmental prevails over economic):

- Minas Gerais coffee should be shipped by Rio, no longer through Santos (16.35 kg);
- Espírito Santo coffee should be shipped by Santos, not through Rio (323.52 kg).

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# Optimization results

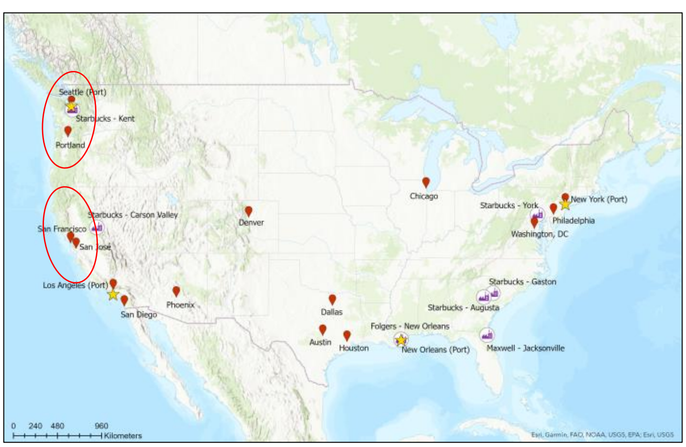
When $w \to 1$ (economic prevails over environmental):

- New Orleans: 730.4 kg from Rio and 11.6 kg from Salvador;
- Los Angeles: 107.8 kg from Santos;
- New York: 57.7 kg from Salvador;
- Seattle: 82.3 kg from Rio and 10.0 kg from Salvador.

When $w \to 0$ (environmental prevails over economic):

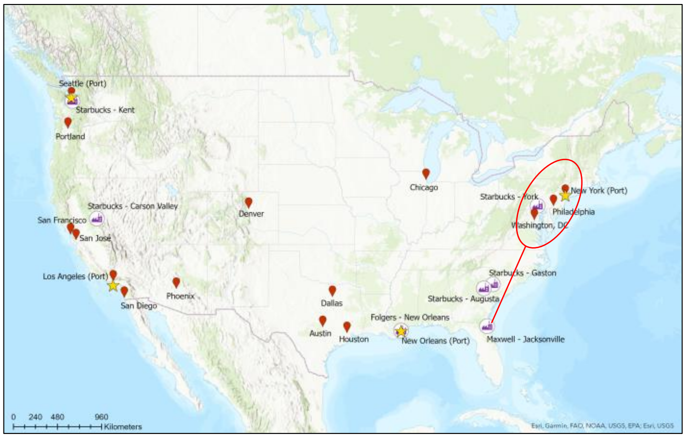
- New Orleans: 400.5 kg from Rio, 310.3 kg from Santos and 31.2 kg from Salvador;
- Los Angeles: 43.6 kg from Santos, 45.2 kg from Rio and 19.2 kg from Salvador;
- New York: 13.5 kg from Salvador, 22.3 kg from Rio and 21.9 kg from Santos;
- Seattle: 37.8 kg from Rio, 17.8 kg from Salvador and 36.7 kg from Santos.

# Optimization results




There are cities no longer supplied by Folgers (the main coffee brand in US).

# Optimization results




Maxwell House supplies only Northeastern cities.

# Optimization results


Starbucks: local supply.
Gaston and Augusta do not contribute to coffee distribution.

# Conclusions

- LCA confirms literature results pointing out the main contributions from coffee cultivation.
  - Road Transportation in US plays an important role.
- 2.0 kg $CO_{2eq}$ and 8.00 US$ between the best and worst arrangements for the environmental and economic domains: it can be significant projecting the Brazilian annual coffee exportation.
- Considering environmental aspects for supply chain management can bring non-trivial results. Environmental and economic variables are really competing.

# Future works

- Modelling uncertainties (maybe Fuzzy);
- Other markets (producers and consumers), excess demand or supply, etc.;
- Effect of installing a coffee roasting facility in Brazil;
- Carbon tax, credit, etc.
- Sustainable supply chain management (+ social).

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# Using the Life-Cycle Approach for Multi-Objective Optimization in the context of the green supply chain: a case study of Brazilian coffee

Thank you!