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MINIMISING EMISSION FOOTPRINTS IN CIRCULAR ECONOMY BY PROCESS INTEGRATION

MINIMALIZACE EMISNÍCH STOP V OBĚHOVÉ EKONOMICE METODOU INTEGRACE PROCESŮ

SHORT VERSION OF DOCTORAL THESIS

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Abstract

This thesis presents methodologies that have been developed to reduce emission footprints in the context of a transition to a Circular Economy through the application of a Process Integration approach to analysis and design, while also addressing challenges which have previously prevented practical implementation. Environmental sustainability, which is frequently indicated by low emissions and waste footprints, plays a critical role in facilitating the transition towards a Circular Economy. Three methodologies which are based on the breakeven concept and the extension of Pinch Analysis and P-Graph frameworks are proposed. The applicability of these methodologies is demonstrated by six case studies focused on transportation and waste management. My contributions to the field include:

(i) A novel breakeven based decision-making tool, with parallels to the classical phase diagram that aids rapid decision-making on the processes (e.g. selection of transport mode for a given distance and load) with the lowest environmental burden.

(ii) An emissions accounting system which aggregates GHG, SO_x, PM and NO_2 as a Total Environmental Burden through a scientific-based environmental-impact price.

(iii) An extended waste management Pinch Analysis system for regional planning, accounting for both burdening and unburdening footprints, to determine the waste treatments and allocation design with low emission footprints.

(iv) An assessment model underpinned by the P-graph tool to identify optimal and near-optimal integrated waste treatment systems for different waste compositions, which includes the identification of sustainable pre-and post-treatment processes.

Abstrakt

Tato práce prezentuje metodologii snižování emisních stop v souvislosti s přechodem na oběhovou ekonomiku aplikováním integrace procesů při analýze a projektování při zohlednění výzev, které ztěžují praktické aplikace. Udržitelnost životního prostředí se vyznačuje snahou o snižování emisí a zlepšení hospodaření s odpady a hraje rozhodující roli při přechodu na oběhovou ekonomiku. Byly navrženy tři metodiky založené na bezztrátovém konceptu a rozšiřujících metodiky Pinch Analysis a P-Grafů. Aplikovatelnost je demonstrována šesti případovými studiemi transportu a nakládání s odpady. Mé příspěvky v této oblasti jsou následující:

(i) Nový bezztrátový rozhodovací nástroj paralelní s klasickým fázovým diagramem, který napomáhá rychlému rozhodování o procesech (např. výběr druhu dopravy pro danou vzdálenost a náklad) při nejnižší možné environmentální zátěži.

(ii) Systém kvantitativního vyhodnocování emisí, který agreguje a vyhodnocuje celkové environmentální zatížení způsobené sklemíkovými plyny, SO_x, PM a NO_2.

(iii) Rozšířená analýza nakládání s odpady pro regionální plánování s přihlédnutím k zatěžování i odstranění zatěžování emisní stopou, dále rozhodování o způsobu hospodaření s odpady a výběru způsobu zpracování odpadu s cílem nejnižší možné emisní stopy.

(iv) Model posuzování pomocí nástroje P-grafu pro identifikaci optimálních integrovaných systémů zpracování odpadu různého složení, který identifikuje a vyhodnocuje stav udržitelnosti procesů před a po zpracování.

Contributing Publications

This thesis is developed based on the author's publication, a total of 30 articles, in several highly recognised international journals. The developed methodology in Chapter 2 is published in Renewable and Sustainable Energy Reviews (IF: 10.566) [1] and Chemical Engineering Transactions [4]. Two publications closely related to the work in Chapter 3 are published in Chemical Engineering Transactions [5,6]. The results in Chapter 4 is based on the works accepted in Science of Total Environment (IF: 5.589) [2] and published in Journal of Environmental Management (IF: 4.865) [3]. The other articles that make up the full PhD thesis are published in Frontiers of Chemical Science and Engineering (IF: 2.643), Clean Technologies and Environmental Policy (IF: 2.277), Journal of Cleaner Production (IF: 6.396), Energy Conversion and Management (IF: 6.377), Journal of Environmental Management (IF: 4.865), Chemical Engineering Transactions and conference proceedings such as IEEE (Scopus Index). I have presented the research underpinning this thesis at 17 international conferences in Kentucky (USA), Stavanger (Norway), Adelaide (Australia), Delft (Netherland), Brač Island (Croatia), Bologna (Italy), Singapore, Tomsk (Russia Federation), Johor (Malaysia), Palermo (Italy), Prague (Czech Republic), Gangwon (South Korea), Krakow (Poland), Bangkok (Thailand), Dubrovnik (Croatia), Tianjin (China), Milan (Italy). The work in Chapter 4 was awarded best young scientist presenter (Session 1) in Sustainable and Efficient Use of Energy, Water and Natural Resources conference, Tomsk, Russia Federation, 14 - 16 November 2018. I am also a co-author of several plenary and invited lectures, where the works have been presented by my supervisor at 24 international conferences worldwide.

1. **Fan Y.V.,** Klemeš,JJ., Walmsley T.G., Perry, S. 2019. Minimising the Energy Consumption and Environmental Burden of Freight Transport using a Novel Graphical Decision-Making Tool. Renewable and Sustainable Energy Reviews, 114, 109335 **[IF: 10.566]**
2. **Fan Y.V.,** Klemeš, J.J., Walmsley T.G., Bertok, B., 2019. Implementing circular economy in municipal solid waste treatment system using p-graph, Science of Total Environment **[IF: 5.589] (Accepted)**
3. **Fan Y.V.,** Perry S.J., Klemeš J.J., Lee C.T., 2019, Anaerobic Digestion of Lignocellulosic Waste: Environmental Impact and Economic Assessment, Journal of Environmental Management.231, 352-363. **[IF: 4.865] (5 citations)**
4. **Fan Y.V.,** Klemeš, J.J., Chin, H.H., 2019 Extended waste management pinch analysis (E-WAMPA) minimising emission of waste management: EU-28. Chemical Engineering Transactions, 74, 283-288. **(Scopus Index)**
5. **Fan Y.V.,** Klemeš J.J., Tan R.R., Vabarnov P.S., 2019. Graphical Breakeven based Decision-Making (BBDM) Tool to Minimise GHG Footprint of Biomass Utilisation: Biochar by Pyrolysis. Chemical Engineering Transactions. **(Scopus Index) (Accepted)**
6. **Fan, Y.V.,** Klemeš, J.J., 2019. Biomass supply and inventory management for energy conversion. Chemical Engineering Transactions. **(Scopus Index) (Accepted)**

Complete Publication List is provided in the full-length thesis

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CHAPTER 1 INTRODUCTION

1.1 General Introduction

Circular Economy (CE) serves as a framework of system designs in recent various municipality and government strategy plan, especially in the European Union (EU). The current measuring of the circular economy is based on material flow accounting system. Environmental concerns about maintaining the circularity deserve more attention. Robust engineering design and comprehensive assessment framework in facilitating the planning to achieve a sustainable circular economy transition is still lacking. GHG footprint receives significant research attention due to the climate change issue. GHG emissions have been generally decreased in all sectors except for transport which has increased by 223 Mt (26 %) (Eurostat, 2018). Transport is also the main contributor of most of the anthropogenic such as CO, Pb and NO_x emissions (Fan et al., 2018). The degree of circularity (both material and ecological loops) still has a vast room for improvement (Haas et al., 2015) by enhancing waste management. In this thesis, the selected case studies to demonstrate the developed methodologies for low emissions planning are focus on waste treatment/ management and transportation activities with the consideration of its roles in CE and as one of the biggest emitters (GHG and non-GHG).

It is commonly noticed that environmental sustainability has been simply represented by CO_2 emission/GHG footprint in most of the optimisation assessment and performance analysis (Fan et al., 2018). A network or process design with low GHG emission might not be an optimised solution when air pollutants are considered. A methodology to measure GHG and air pollutants simultaneously by considering the synergistic effect is needed. It is crucial for minimising the potential of footprint shifting and poor decision-making. Process Integration (PI) is an idea of taking a holistic approach to process design and optimisation that looks at how a collection of processes or system are best integrated (Linnhoff, 1994). This concept can form a foundation from which to embed sustainability (emission reduction) and CE into system design. Pinch analysis (Linnhoff et al., 1982) is among the standard approach/technique of PI. This targeting approach with graphical representation is suitable for practical purpose, easier to understand by the practitioner and serve as an excellent platform in minimising the problem size for the following detail planning. Another possible tool for low emission process design in a circular economy is P-Graph. The advantages of choosing P-graph over other mathematical programming tools are the use of a graphical user interface for inputting maximal structures and displaying results, the emphasis on structural optimisation leading to optimal and near-optimal solutions and software is open-source (Walmsley et al., 2018). The consideration of the near-optimal solutions is an important feature for low emission planning as it is difficult to capture in a mathematical model a high-fidelity representation of the real situation because of uncertainties, subjective parameters and weightings, and many practical constraints.

Research studies that applied these tools/methods (e.g. Pinch Analysis, P-graph or graphical approaches) to minimise the emission footprints in waste management and transportation activities is still underdeveloped. Mathematical optimisation is the common approach, but the models are still having a limited concern on non-GHG emission and integrated design. It is also comparatively difficult to understand the reason for obtaining the optimal solutions and communicate the results to decision-makers as specific mathematical modelling knowledge is needed. This study proposed three novel methodologies (i. Novel graphical tools based on a breakeven concept, ii. Extension of Pinch Analysis, iii. P-graph based model), considering integrated solutions and non-GHG emissions in identifying a low emission footprints design for waste management and transporting activities.

1.2 Thesis Aim and Scope

The overall aim of the research is to investigate and develop methods to minimise the emission footprints in the Circular Economy by Process Integration.. Robust engineering design and comprehensive assessment framework in facilitating the planning to achieve emission reduction are proposed. Waste management and transportation are the targeted sectors, where the case study based on, to demonstrate the developed methodologies. Three novel methodologies are proposed and applied to six case studies. The scope of the study is divided into the following main focuses:

i) Breakeven based decision-making tool for low emission planning

To develop a novel graphical tool based on the breakeven concept in facilitating the selection of processes with the lowest emission possible. GHG, NO_x, SO_2, and PM are aggregated by environmental price as Total Environmental Burden (TEB).

<u>Case Study 1: Transportation</u>

Identification of low emission transporting solution under different circumstance (e.g. load and travelled route/distance) for different scenarios (e.g. EU-28, Latvia, Sweden; transports powered by electricity, diesel, biodiesel, compressed natural gas and liquefied natural gas).

Case Study 2: Pyrolysis of Biomass

Identification of optimal biomass utilisation (to burn or to bury the biochar) where the lowest GHG emissions and the highest possible profit indicate the optimal choice. Different type of biomass, GHG pricing and carbon intensity of a country are assessed.

ii) Pinch Methodology to minimise the emissions of waste management system through integrated regional planning

To extend the methodology of Waste Management Pinch Analysis for integrated regional planning, consider both burdening and unburdening life cycle emission.

Case Study 1: Integrated Regional Municipal Solid Waste Management

Determination of the waste management system to achieve a defined emission reduction target. The net emission per capita considering the waste amount, population and waste treatment practices (both burdening and unburdening footprints) is accessed and compared.

Case Study 2: Integrated Regional Biomass Inventory and Sourcing Management

Identification of optimal production rate, inventory, storage and biomass network flow with the lowest possible cost incurred. The seasonal availability of supply and demand market of biomass (surplus and deficit) is overcome through integration planning.

iii) P-graph structure to assess the waste treatment design with minimal emission.

To develop a maximal structure by using P-graph in identifying an integrated design (integrated waste treatment system, pre-and post-treatment) with minimal emission footprints and maximum profit. The optimising approach can capture both optimal and near-optimal solutions.

Case Study 1: Waste Treatment System

Identification of suitable treatment system for municipal solid waste (MSW) by considering the economic balance between the main operating cost, type, yield, quality of products as well as GHG emission. Four types of MSW composition by country income level are investigated.

Case Study 2: Pre-and Post-Treatment

Identification of optimal pre-and post-treatment by considering the cost and environmental performance. 16 treatments and 7 environmental impacts have been assessed.

CHAPTER 2 BREAKEVEN BASED DECISION-MAKING TOOL FOR LOW EMISSION PLANNING

2.1 Application to Transport Case Study

2.1.1 Introduction

Various decision models have been proposed to facilitate transport mode selection. Studies include non-GHG emissions and/or consider more than two transportation modes in a single study is relatively few. The transport mode with the lowest GHG emission is not necessarily the best solution when considering other air pollutants. Most of the proposed decision models use mathematical optimisation. This study aims to propose a novel graphical approach to facilitates the transportation selection by suggesting the mode with lower emissions and total environmental burden (TEB) for a given transportation distance and load. The novel contributions of this work include:

(i) A new graphical tool where the ratio of the compared travelled distance (R) and load (L) is introduced to determine the selection with a lower environmental burden.

(ii) A set of equations that forms the basis for the graphical tool, considering the transport load capacity and body weight of an empty vehicle.

(iii) The determination of a TEB that considers GHG emission and air pollutants contributing to smog/haze formation through environmental prices, which aids the selection of the transport mode.

These contributions are demonstrated in a case study with an expanded scope of included transportation modes. Two scenarios of transporting goods from Rotterdam to Antwerp and Rotterdam to Genova help illustrate the application of the proposed tool in identifying the freight transportation mode with the lowest emissions. The mass goods to be transported are set in categories as 50 t, extended to 1,000 t for further discussion. The specification of transportation modes, distance between the two destinations by different modes as well as the environmental price that applied in this case study reported in Fan et a1. (2019a).

2.1.2 Method

The total emissions released (E_{tot}) is determined using Eq(1). It is formulated based on the idea that emissions from a vehicle are linearly proportional to its total weight (body weight of vehicle + load). Most transport emissions factors are reported for a fully-loaded vehicle on a per t of transport freight. As a result, the first term ($n\ e_{empty}\ D$) in Eq(1) relates to the emissions due to the bodyweight, and $L\ e_{load}\ D$ determines the emissions due to the weight of the load.

$$E_{tot} = \left(n \cdot e_{empty} + L \cdot e_{load}\right)D, \quad \text{where} \quad n = \text{Roundup}\left(\frac{L}{w_{l,max}}\right) \quad \text{and} \quad n \in Z^{+} \tag{1}$$

Where e_{empty} is the specific emission of an empty transport vehicle fleet (MJ/km or t/km); e_{load} is the marginal specific emission of a transport vehicle fleet per t of transport load (MJ/tkm or g/tkm); n is the required number of transport vehicles; D is the total transport distance that each vehicle has to travel (km), and L is the total transport load across all vehicles (t). e_{load} are independent of L and D and can be related to standard full-load emission factors, EF_{full}, which have the units of MJ/t·km (or g/t·km), noting t (in the denominator) is a ton of transport load (excludes the empty vehicle weight) and a transport distance in km.

$$e_{empty} = EF_{full}\left(w_{l,max}\frac{w_{empty}}{w_{full}}\right) \tag{2}$$

$$e_{load} = EF_{full}\left(\frac{w_{l,max}}{w_{full}}\right) \tag{3}$$

Where $w_{l,max}$ is the maximum load that one vehicle can transport (t), w_{empty} is the weight of an empty vehicle (t), and w_{full} is the weight of a full vehicle (t).

To identify the point where the generating emission of two transportation modes (i and j) are the same, i.e. $E_{tot(i)} = E_{tot(j)}$, the following equation has been obtained for the ratio R, which is D_i/D_j, for a constant L.

$$R = \frac{D_i}{D_j} = \frac{n_j \cdot e_{empty,j} + L \cdot e_{load,j}}{n_i \cdot e_{empty,i} + L \cdot e_{load,i}} \tag{4}$$

In the developed graphical tool, R is plotted on the y-axis, and L serves as the x-axis. To construct a breakeven line on the graphical tool, L is varied from 1 to 100,000 t. A log scale is applied to the axis. The identified border divides the space and suggests that under a given amount of load (L) to be transported and the known distance ratio of two routes (R), which transportation mode would have lower emission. The plot $E_{tot,i} = E_{tot,j}$ can only capture and compares a single dimension, e.g. one type of emission. TEB, T_{env} (€), as in Eq(5), is introduced to account for the emissions of both GHG and air pollutants by summing the cost/price contribution of each emission/pollutant, k.

$$T_{env} = \sum_{k}\left(E_{tot}(k)c_{env}(k)\right) \tag{5}$$

Where c_{env} is the cost coefficient (e.g. carbon tax, environmental prices) of the emission type (e.g. CO_2eq, SO_2, NO_x and PM) in €/t. In this study, environmental prices are applied.

To identify the border where the environmental price is the same, $T_{env,i} = T_{env,j}$, the following equation is obtained. The R ratio is determined under a constant load L.

$$R = \frac{D_i}{D_j} = \frac{\sum_k \left(\left(n_j \cdot e_{empty,j}(k) + L \cdot e_{load,j}(k) \right) c_{env}(k) \right)}{\sum_k \left(\left(n_i \cdot e_{empty,i}(k) + L \cdot e_{load,i}(k) \right) c_{env}(k) \right)} \tag{6}$$

The generic algorithm/steps in constructing the graphical tool and interpretation are discussed in Fan et al. (2019a). The graphical tool consists of R as the y-axis, L as the x-axis where the lines represent $E_{tot,i} = E_{tot,j}$ or $T_{env,i} = T_{env,j}$. The graphical tool can be interpreted in a similar way as a phase diagram (Chemguide, 2014). The boundary line represents the situation where both transportation modes have the same level of emissions. The distinct phase (area) represents the situation (R and L) where the listed transport mode has the lowest emissions in transporting the goods.

2.1.3 Results and Discussion

Figures 1(a) - (e) show the graphical tool results based on GHG, NO_x, PM, SO_2 and TEB. Electric trains are the most environmentally friendly option in most cases, as observed by the larger area, especially when R=1. A lorry is a better option than the train only if the distance to travel by train (D_{kj}) is considerably longer, i.e. small R-value (D_{ki}/D_{kj}), and the load (L) is small as well. The train options are preferable with the increase of the load. When the train option is available, a ship (either container or cargo) would not be the preferred choice unless the route distance of the train is notably longer and/or the required load is very high. This trend is apparent particularly for air pollutants emission. The train is a better option under most of the circumstances (covered a larger area) in term of NO_x, PM and SO_2 emissions.

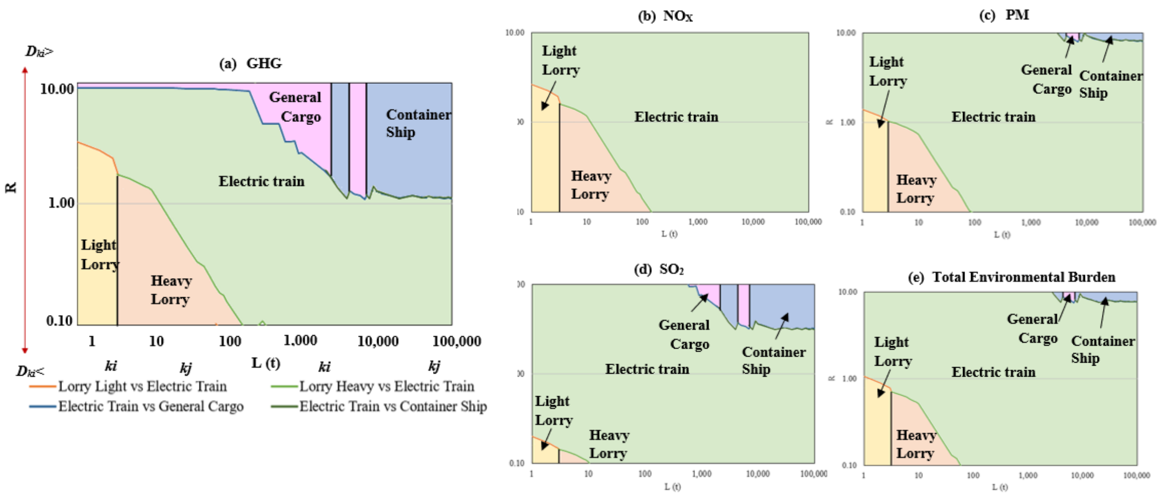
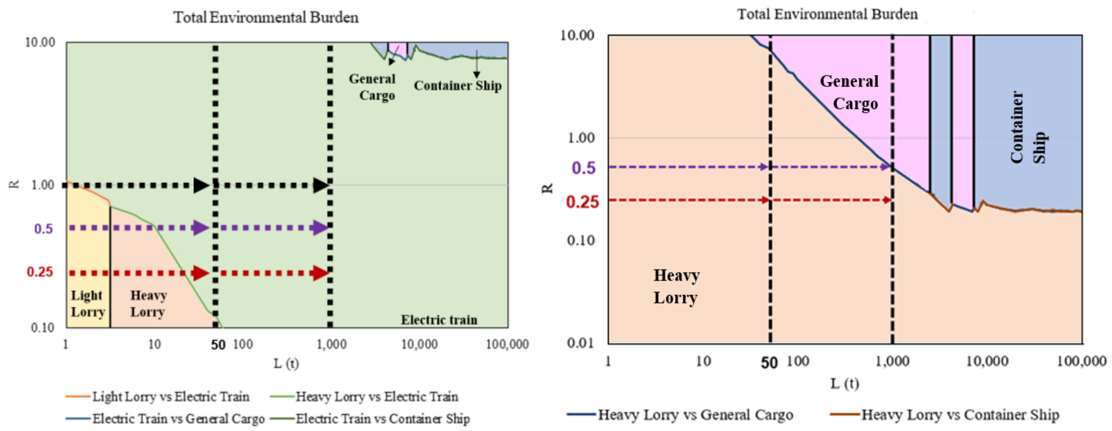


Figure 1: Graphical tool based on (a) GHG, (b) NOx, (c) PM, (d) SO_2, (e) TEB

According to the distance and route stated reported in Fan et al. (2019a), the R-values are identified as approximately:

- R-values of Rotterdam to Antwerp: D_{road}/D_{sea} = 0.5; D_{road}/D_{rail} = 1; and D_{rail}/D_{sea} = 0.5
- R-values of Rotterdam to Genova: D_{road}/D_{sea} = 0.25; D_{road}/D_{rail} = 1; c) D_{rail}/D_{sea} = 0.25

Figure 2a shows that the electric train is the transport mode with the lowest TEB in transporting 50 t and 1,000 t of goods from Rotterdam to Antwerp and Genova by implementing the identified R-value. The R values at the load of 50 t lie in the area of an electric train. The solutions presented are based on the full availability of all transport modes. There is the possibility that an electric train may not be an option. In this case, the graphical tool may be adapted based on the proposed method.



(a) (b)

Figure 2: Graphical tool based on the TEB (a) case study (b) what if there is no train option

Figures 2b shows that result from the situation without train availability. When considering TEB (Figure 2b), the second-best options when there is no train possibility, the ship (general cargo nor container ship) is not chosen for loads under 50 t and 1,000 t. In term of GHG only, when the load to be transported is 50 t, the lorry is the preferred option for both transport scenarios. The ship (general cargo) emits less GHG pollution than a lorry when transporting a 1,000 t load. The result suggests that air pollutants from shipping are high, having a significant bearing on overall selection. The result highlights that the transport selection with the lowest GHG emissions might not be the selection with lower air pollutants. The impact of energy source (fuels type and electric mix - Fan et al., 2019a) are also assessed. The energy sources considered for lorry are electricity, diesel, biodiesel, compressed natural gas (CNG) and liquefied natural gas (LNG). The emissions (GHG and TEB) of the lorry are compared to that of the electric train. Three scenarios are illustrated to show the impact of the electricity grid mix (Moro and Lonza, 2018), considering: (i) Latvia, 1,168 g CO_2eq/kWh (ii)

Sweden, 47 g CO_2eq/kWh (iii) The EU 28 average, 447 g CO_2eq/kWh. In the case of Latvia, at R=1 (distance to travel by lorry and train is equivalent), biodiesel lorry is the best from the view of GHG and CNG lorry by TEB under all assessed loads (1-100,000 t). In Sweden, lorry run by electricity is the best from both GHG and TEB perspective. The electric train is the preferable option in Sweden with the increasing load. This is not in the case of Latvia, which dominated by biodiesel and CNG at R=1. At R=1, biodiesel is the option with the lowest GHG emission in EU-28. However, CNG is the best option when considering the TEB. This again emphasises the possible bias of considering only GHG emission in decision making. Electrification generally leads to a lower TEB in EU for a country which has a carbon intensity of below average (447 g CO_2eq/kWh).

2.1.4 Conclusion

The proposed tool which has been developed graphically is expected to ease the selection process compared to mathematical optimisation. The graphical tool is feasible for comparison of more than two transportation modes, and R is established as a way to prevent the model from being restricted to the origin-destination pairs considered. Environmental price is applied as a medium to consider both GHG and air pollutants (TEB), without which, it is inherently difficult to combine. Throughout the case study, two issues have been highlighted. (i) Bodyweight of transportation has a significant effect on the overall emissions. (ii) SO_2 and NO_x play a key role in the environmental sustainability of transportation. Low GHG selection is not equal to low air emission selection. The proposed tool based on breakeven concept can be applied to other processes for the selection of low emission, low energy consumption, and high profit (or all three objective functions) design.

2.2 Application to Pyrolysis of Biomass

2.2.1 Introduction

This study aims to propose a graphical decision-making tool based on the BBDM concept (see Section 2.1) in facilitating the selection of biomass treatment or utilisation. The novel contributions of this work include:

(i) A set of generic equations that form the basis for the decision-making tool, considering both the economic and life-cycle environmental footprint (GHG).

(ii) An extended graphical Break-even Based Decision-Making (BBDM) tool, where the environmental price (GHG) and the GHG intensity of energy are chosen to determine the suitable biomass utilisation.

(iii) A pyrolysis case study of biomass, where energy crop and agricultural residue for energy and biochar production, are assessed to demonstrate the applicability of BBDM. BBDM is designed to be feasible in capturing the optimal utilisation under the dynamic change of GHG price and GHG intensity of energy.

The type of biomass assessed in this study is energy crops and agricultural residues. The selected treatment option is pyrolysis, specifically slow pyrolysis system. The applied data are reported in Fan et al. (2019b). The assessed scenarios are (1) Switchgrass + Pyrolysis optimised for energy (burn), (2) Switchgrass + Pyrolysis optimised for biochar (bury), (3) Wheat straw + Pyrolysis optimised for energy (burn), (4) Wheat straw + Pyrolysis optimised for biochar (bury).

2.2.2 Method

The break-even point in this context defines when two pyrolysis treatment processes (*i and j*) would generate equivalent profit, see Eq(7). GHG price is applied to reduce the multi-objective problem into a single objective. The total profit is defined as in Eq(8), $Profit_{economic}$ considers the earning from the selling of recovered products (energy and biochar) deducted by the operating cost of the entire life cycle, Eq(9). $Profit_{environment}$, defined in Eq(10), considers the GHG credit from recovering the energy and applying the biochar to the soil (sequestration) deducted by the emission released along with the processes which incur a penalty cost of GHG. Eqs(11) - Eq(13) show the estimation of GHG credit and GHG penalty incurred by the process. The independent variable is the “break-even” GHG price. Eq(14) shows the estimation of GHG price when the total profit of two pyrolysis processes are equal.

$$Profit_{total\,(i)} = Profit_{total\,(j)} \tag{7}$$

$$Profit_{total} = Profit_{economic} + Profit_{environment} \tag{8}$$

$$Profit_{economic} = Eenergy + Ebiochar - OC \tag{9}$$

$$Profit_{environment} = Cenergy + Cbiochar - P_{op} \tag{10}$$

$$Cenergy = AmountRE \times CI \times GHG_{price} \tag{11}$$

$$Cbiochar = AmountB \times SF \times GHG_{price} \tag{12}$$

$$P_{op} = A_s \times O_{ef} \times GHG_{price} \tag{13}$$

Where $Eenergy$ are the earnings from recovered energy, $Ebiochar$ are the earnings from biochar, and OC is the operating cost. Where $Cenergy$ is the GHG credit from the recovered energy, $Cbiochar$ is the GHG credit from the application of biochar, P_{op} is the GHG penalty by the operating process, $AmountRE$ is the amount of recovered or generated energy (syngas, bio-oil and or biochar) by the pyrolysis process of agricultural waste or energy crops, CI is the GHG intensity of energy (e.g. electricity power) where the emission is associated with electricity generation from identified regions based on the energy mix, GHG_{price} = is the cost coefficient (e.g. carbon emission tax, environmental price), $AmountB$ is the amount of biochar produced, SF is the carbon emission sequestration factor of biochar, A_s is the amount of substrate, O_{ef} is the emission factor of pyrolysis processes. Eq(14) is applied to identify the break-even point/ boundary, where $Profit_{total\,(i)} = Profit_{total\,(j)}$. GHG_{price} is identified by varying the CI. The steps to construct the graphical decision tool are described as in Fan et al. (2019b).

$$GHG_{price} = \frac{Eenergy_j + Ebiochar_j - OC_j - Eenergy_i - Ebiochar_i + OC_i}{AmountRE_i \times CI - P_{op,i} + AmountB_i \times SF - AmountRE_j \times CI - P_{op,j} + AmountB_j \times SF} \quad (14)$$

2.2.3 Results and Discussion

Figure 3 shows the developed BBDM tool to compare (a) Scenario 1 and 2 as well as (b) Scenario 3 and 4. When there is no GHG charge, all the circumstances (energy crop or agricultural residue; small or large GHG intensity) suggest pyrolysis optimised for energy production. Burning the recovered products for energy provides a higher profit. The selection shift to pyrolysis optimised for biochar production with the increase of GHG price (> 0.03 USD/kg CO_2eq for switchgrass, >0.01 USD/kg CO_2eq for wheat straw), where the biochar is applied to the soil (bury). The GHG price is essential to encourage the application of biochar for GHG footprint reduction. However, burning is preferable with increasing GHG intensity. This is due to the higher footprints offset by displacing the dirty electricity grid mix (higher GHG intensity) with energy generated from pyrolysis. The applicability of the developed tool for decision-making can be demonstrated by using Country A (200 g CO_2eq/kWh) and Country B (1,000 g CO_2eq/kWh) as an example, at GHG price of 0.025 USD/kg (Plumper and Popovich, 2019). Figure 3a suggests the switchgrass in Country A and B is more suitable for energy production (burn) in order to have a higher total profit (earnings from selling the energy and the GHG credit). Figure 3b suggests the wheat straw in Country A should be utilised for biochar production but energy generation for Country B. To encourage the production of biochar (bury) in Country B, as illustrated in Figure 3b, the GHG price have to be increased, e.g. to 0.04 USD/kg. Figure 4 shows the impact of substrate types to the break-even based decision-making tool. At 200 g CO_2eq/kWh (Country A), wheat straw is a better substrate for pyrolysis unless the GHG price is set to be higher than 0.02 USD/kg CO_2eq, see Figure 4a.

Switchgrass, the dedicated biomass, has a higher net GHG footprint compared to wheat straw (agricultural residue) due to the burdening effect of field production in growing the switchgrass. However, switchgrass has a higher net GHG footprint with increasing GHG intensity, as reflected in Figure 4a (preferable options than wheat straw), due to the higher amount of energy from pyrolysis to displace the high GHG intensity energy mix.

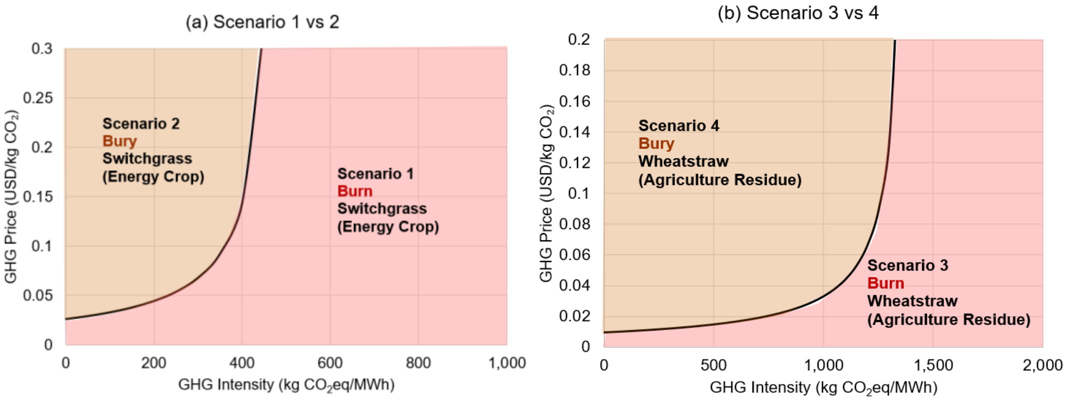


Figure 3: BBDM tool (burn or bury) (a) Scenario 1 vs 2 (b) Scenario 3 vs 4

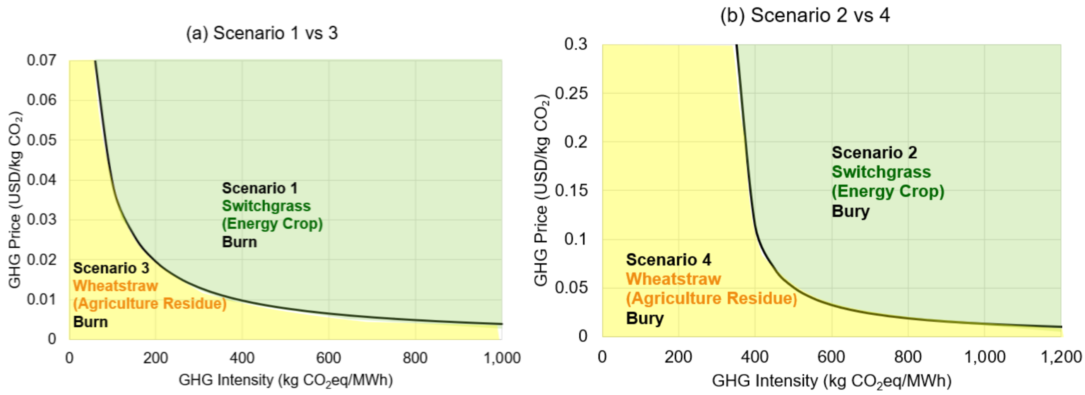


Figure 4: BBDM tool (types of substrate) (a) Scenario 1 vs 3 (b) Scenario 2 vs 4

2.2.4 Conclusion

The BBDM tool has been proposed as a means to determine the suitable biomass utilisation with highest possible profit and lowest GHG emission for a particular context with known GHG intensity and a defined GHG price. The tool provides rapid and effective decision support capability via an intuitive graphical display. It is feasible for the comparison of different treatment options (e.g. gasification, pyrolysis and other waste to energy), technologies (pyrolysis in different setting e.g. temperature), utilisation (energy, soil amendment, activated carbon), types of substrate and useful to capture the impacts contributed by the changes of GHG intensity and GHG price. The results of the pyrolysis case study show that energy generation is generally a preferable decision, especially with the increase of GHG intensity, for both switchgrass and wheat straw, then biochar for carbon emission sequestration.

CHAPTER 3 PINCH ANALYSIS TO MINIMISE THE EMISSIONS OF WASTE MANAGEMENT SYSTEM

3.1 Application to Municipal Solid Waste Management

3.1.1 Introduction

This study aims to propose a graphical approach in identifying the WMS (a set of waste treatments) with lower emissions. The proposed graphical approach is an extension of the existing WAMPA (Ho et al., 2017). In this study, the approach is referred to as E-WAMPA, representing Extended-WAMPA. It facilitates the waste treatment selection by suggesting the strategies based on defined targets (e.g. recycling rate, waste amount, landfill reduction). The novel contributions of this work include:

(i) The intensity of the WMS (Net GHG emission per capita) is introduced as an indicator of the potential reduction of a country. The net GHG emission is accounted by the amount of emission emitted from the treatment processes and the emission mitigated from material reprocessing and avoided primary production

(ii) The step by step algorithm of WAMPA is improved by considering the limitation in developing WAMPA. For example, the assumptions of 3R activities have no emission, WtE is given priority over 3R, which are not truly reflecting the real-life condition.

(iii) The applicability is demonstrated by EU-28 case study rather than a hypothetical case study.

The data of the EU-28 case study and the required input data to estimate net GHG emissions are available at Fan et al. (2019d). The target/Pinch Point of this case study is to reduce the net GHG emission of EU WMS by 10 %, and the waste to the landfill has to be reduced by 50 %.

3.1.2 Method

The emission intensity of the WMS is determined by using Eq(15). Emission intensity including carbon emissions intensity has been commonly used as an indicator to evaluate the environmental performance of energy source in the unit of CO_2eq/GDP (Dong et al., 2018), where a lower value is representing a greener energy source (e.g. higher share in renewable energy). Eq(15) is based on a similar idea, but the emissions are divided by per population. It is determined by summing the net emission contribution of each waste treatment alternatives divided by population (p, capita). This study considers GHG (CO_2, CH_4, N_2O).

$$T_{\mathrm{netEwaste/cap}} = \frac{\sum_t (E_{\mathrm{emitted}} - E_{\mathrm{avoided}})}{p} \tag{15}$$

Where t is representing the waste treatment alternatives, E_{emitted} is the emission release by the waste treatment processes, E_{avoided} is the emission mitigated by primary production and material reprocessing (Fan et al., 2019c). The lower value of WMS emission intensity ($T_{\text{netEwaste/cap}}$) represents the environmental performance better. In some cases, the value is in negative and suggests the waste treatment practices achieve emission saving (Turner et al., 2015). It may be through recycling as it can replace the primary production of virgin products. It does not represent the achievement of sequestration. E-WAMPA is presented as a 2D-graph where the x-axis is the cumulative waste amount, and the y-axis is the cumulative net emissions. The step by step algorithm of E-WAMPA has been published in Fan et al. (2019d).

3.1.3 Results and Discussion

Figure 5 shows the cumulative emission and waste amount of the assessed EU countries in 2017 (yellow line) and 2030 (red line), arranged in increasing emission intensity. The average emission intensity of the EU is -0.05 tCO_2eq/cap. Germany, Slovenia, Netherlands, Estonia, Denmark and Belgium are well above the average. Germany is one of the top ten countries with the high absolute amount of waste, but in tCO_2eq/cap it has the best performance, contributed by the WMS which capable in mitigating the footprint of waste and lower waste generation per capita. Malta, Greece, Cyprus and Romania, which located at the end of the red line are the selected countries for improvement. The demonstrated case study focuses on only one strategy- treatment transition (switch to treatment options with lower emission). The other possible strategies are waste trading (import and export activities based on treatment capacity) and enhancing treatment efficiency.

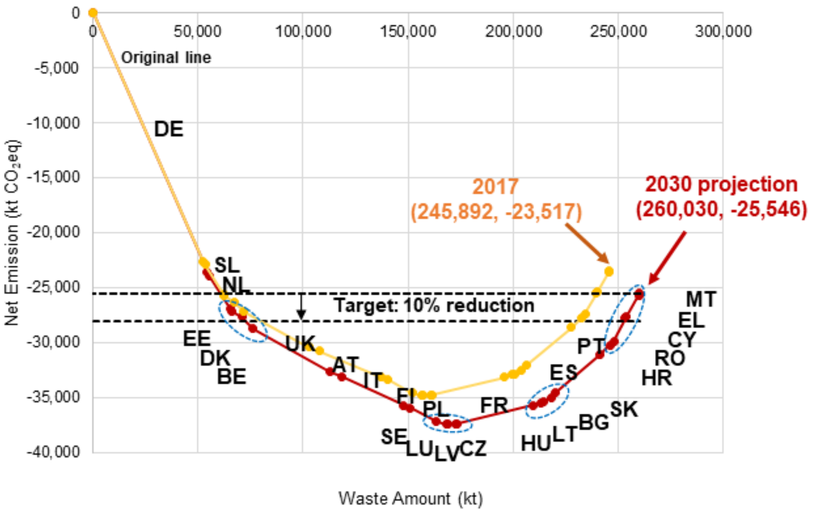


Figure 5: E-WAMPA for the waste management system of EU counties (in abbreviation) - Supply Curve.

Figure 6 shows the shifts (treatment transition) in Malta, Greece, Cyprus and Romania contribute to the reduction of EU emission of WMS (-25,546 to -28,114 kt CO_2eq). Following the E-WAMPA methodology, one of the possible solutions is: In Malta (MT): send 50 % waste for landfill to D10; In Greece (EL): send 50 % waste for the landfill to D10, R1, C&A; In Cyprus (CY): send 50 % waste for the landfill to C&A; In Romania (RO): send 50 % waste for the landfill to R1 and D10. The shifting contributed to the decrease (10%) in the overall WMS emission of EU and met the Pinch point (Figure 7). The zoomed view shows the shift where waste emissions are reduced despite handling the same amount of waste (260,030 kt). Data availability on the waste treatment capacity could further improve the feasibility of the allocation and waste trading.

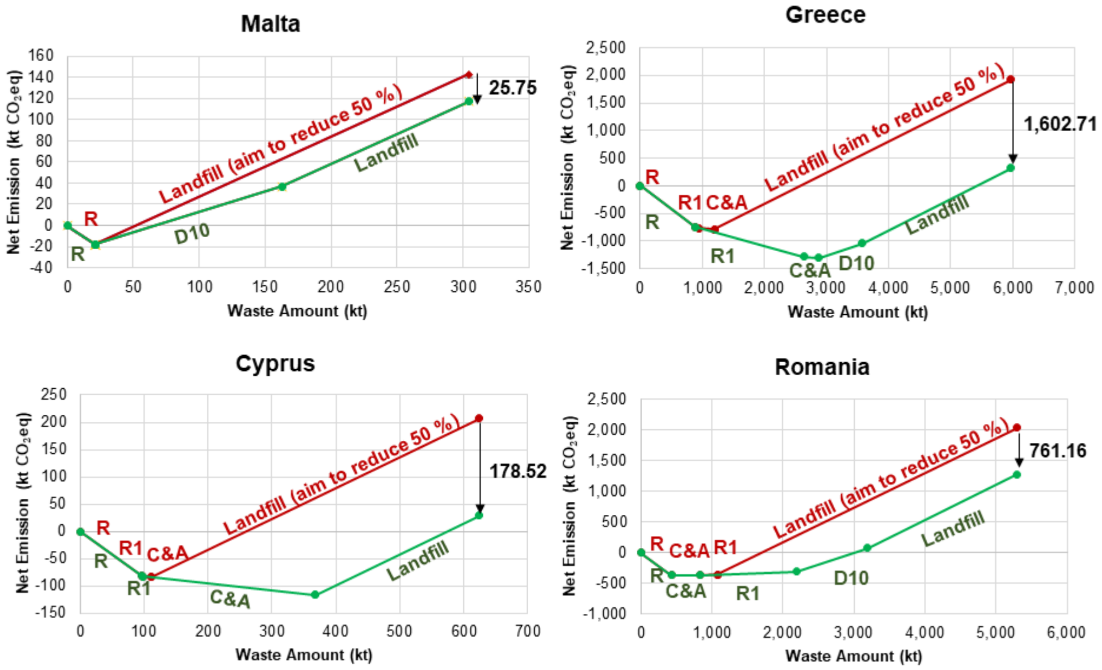


Figure 6: Treatment transition of Malta, Greece, Cyprus and Romania. R = Recycling, D10 = Incineration without energy recovery, C&A = Composting and Anaerobic Digestion, R1 = Incineration with energy recovery

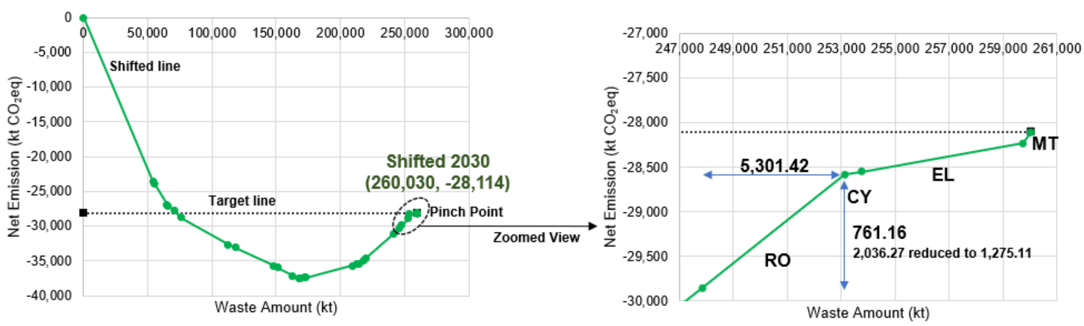


Figure 7: E-WAMPA for the waste management system of EU countries- Shifted Curve and its zoomed view

In line with the EU priority to circular economy policies (EuroStat, 2018), the proposed methodology (E-WAMPA) is designed in a way that the common EU emission reduction can be achieved by improving the treatment transition of any of the EU members based on the potential. The potential can be referred to as treatment capacity, financial, waste handling technologies, the demand for recovered product or utilities. Building new facilities or infrastructure to manage the waste is in contradiction to the waste prevention action plan. The cost of building a new treatment plant and social acceptance is also the challenges of waste treatment transition. Waste trading (import and export activities based on available treatment capacity) on the other hand, offers the sharing of resources and facilities to achieve a mutually beneficial design. The targeting tool by Ooi et al. (2013) based on Pinch Analysis can be adapted and integrated with BBDM to facilitate waste trading planning.

3.1.4 Conclusion

This work proposed E-WAMPA to facilitate the waste allocation in WMS towards emission mitigation graphically. The applicability of E-WAMPA is demonstrated through treatment transition. Malta, Greece and Cyprus and Romania are chosen as the demonstrated countries as the net GHG emission from the waste treatments per capita are high. The presented results are focused on waste treatment transition. Waste trading is an alternative strategy which could potentially further reducing the emissions. It could be a more promising strategy than treatment transition in the sense that current system design is in the transition towards a circular economy or zero waste target.

3.2 Application to Biomass Management

3.2.1 Introduction

The main challenge of the biomass supply chain is the source which is disseminated over a large area and influenced by a strong seasonality. Zandi et al. (2018) highlighted that the studies integrate decisions such as plant localisation and dimensioning in biomass supply design is scarce. Pinch Analysis (Linnhoff et al., 1982) is one of the potential methods. This targeting approach with graphical representation serve as an excellent platform in minimising the problem size for the following detail planning. A total of 6 Pinch production strategies have been later summarised by Ludwig et al. (2009). However, the proposed approach has not been well demonstrated through biomass supply chains case study. This study aims to integrate Pinch Analysis for targeting and mathematical model for the follow-up optimisation of the production rate, product inventory (e.g. bio-oil), biomass storage and biomass network flow (allocation). The biomass to energy demand is satisfied in a way that maximises the profit through minimising the inventory. The biomass network flow is optimised by reducing the cost incurred in transporting and carbon tax (environmental price). This method is demonstrated through a case study where 6 locations with different type and amount of biomass as well as energy demand (bio-oil) are considered. The detailed description of the case study as well as the input data such as efficiency of pyrolysis, GHG price, transporting cost and emission factors are reported in Fan et al. (2019e).

3.2.2 Method

Pinch Analysis for aggregated planning by Singhvi and Shenoy (2002) is adapted to estimate the possible production rate and inventory level of biomass to energy conversion. Y-axis is replaced with energy to fit the purpose of the case study. The profit is maximised by minimising the inventory (product accumulation). Insufficient inventory to fulfil the demand leads to a loss in sales and profits while a surplus of inventory results in unnecessary costs. Figure 8a shows the composite curves example and its interpretation. The Composite Curves are Demand Curve and Production Curve. Demand Curve is plotted by cumulative demand at different time. Production Curve is identified by rotating the horizontal axis from the starting inventory as the pivot until it touches the Demand Curve as described by. Grand Composite Curve is plotted by minus the Production Curve by Demand Curve. The supply of biomass is subjected to seasonality and availability. Biomass storage is needed to fulfil the demand and production rate at each time interval. It can be determined by further extending the Pinch Analysis (see Figure 8b), where a grand composite curve is plotted by minus Supply Availability Curve by Production Curve for excessive availability of supply. The required supply (and hence the biomass storage for low supply period) at a various time can be identified for further biomass flow (from which source and its amount) optimisation.

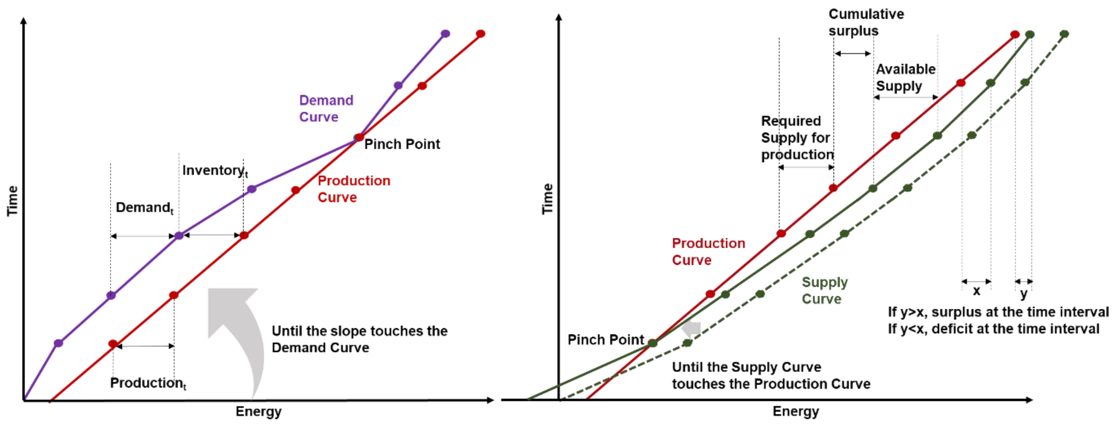


Figure 8: Composite Curves of aggregate planning in supply chain (a) Demand (Purple) and Production (Red) Curve; (b) Production (Red) and Supply (Green) Curve

The biomass flow (sources - location and amount) is identified by Eq(16) and Eq(17) with the consideration of energy content (GJ/ t) of biomass, transporting distance, load (required supply) and the number of the trip. The identified required supply at a various time by Pinch Analysis has to be fulfilled. The objective function is minimising the cost, includes both transportation and GHG emission.

$$Min_{cost} = \sum_k (n \cdot e_{empty} + L \cdot e_{load}) D_k \times GHG_{cost} + (L_k \times D_k \times T_{cost}) \quad (16)$$

$$n = Roundup \left(\frac{L}{W_{max}}\right) \; and \; n \in Z^+ \quad (17)$$

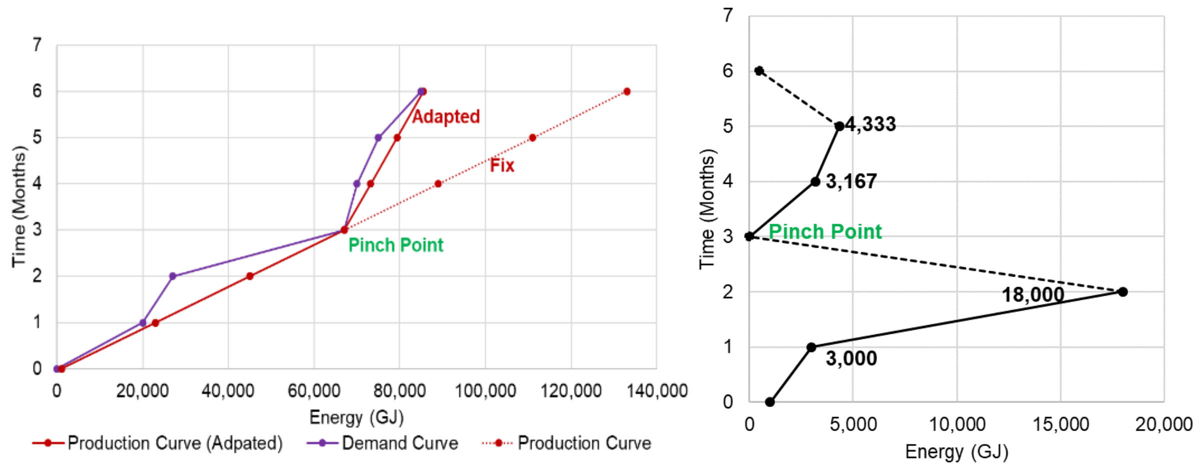
Where e_{empty} is the specific emission of an empty transport vehicle fleet (g/km); e_{load} is the marginal specific emission of a transport vehicle fleet per t of transport load (g/tkm); n is the required number of transport vehicles; D is the transport distance that each vehicle has to travel (km), and L is the total transport load across all vehicles (t). GHG_{cost} is the GHG pricing (e.g. carbon tax), T_{cost} is the transporting cost; k is the source of biomass, in this study labelled as S1-S6. $W_{max}$is the maximum capacity of the transport mode. Eq(16) is accompanied by two constraints listed in Eq(18) and Eq(19). The total supply amount ($S_{k)}$) multiply by energy content per t of biomass (EC_k) and energy conversion efficiency (CE) has to equal to the identified necessary supply (IRS) at each time intervals. The amount of supply at each source point (S_k) cannot exceed its available supply.

$$IRS = \sum_k (S_k \times EC_k \times CE) \quad (18)$$

$$S_k \leq Available \; supply \quad (19)$$

3.2.3 Results and Discussion

Figure 9 shows the identified production rate and inventory by Pinch Analysis with the consideration of the supply and demand availability. The fixed production rate is identified as 22,000 GJ/month. It can be decreased (adapted) to 6,167 GJ/month after the Pinch Point to minimise the bio-oil inventory. The workforce and number of hired are reduced accordingly. Another option of production rate after Pinch Point is 9,067 GJ/month (with the surplus product/utility), where all the available biomass supply would be processed (Figure 10) if there is a possible additional demand (e.g. non bio-oil to energy purpose). By referring to the Supply Availability Curve (Figure 10), the biomass supply is generally higher than the production rate.



(a) (b)

Figure 9: (a) Composite Curves of demand and production rate and (b) the Grand Composite Curve showing product (bio-oil) inventory

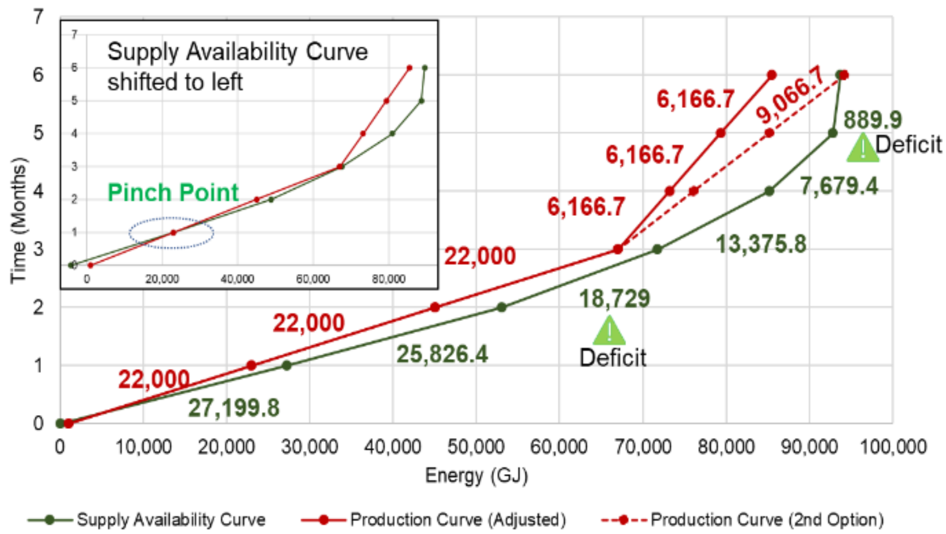
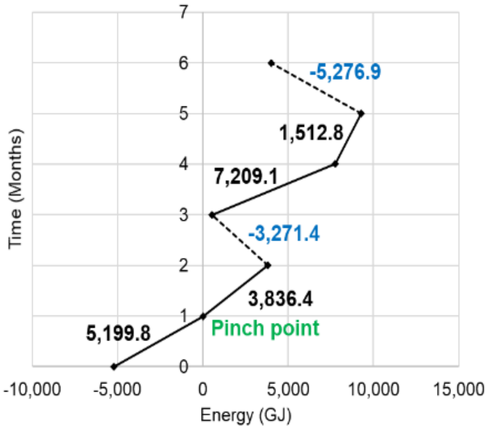


Figure 10: Composite Curves of production and available supply.

However, there is a surplus or deficit at each time interval, as shown in the Grand Composite Curve in Figure 11. Biomass storage is required to overcome the deficit on Month 3 and 6. The identified values are 3,271.4 GJ (302 t) on Month 2, 3,764.1 GJ (301 t) on Month 4 and 1,512.8 GJ (138 t) on Month 5. Different network flow and source can be chosen to obtain the required biomass supply for energy conversion. Eq(15) is applied to obtain the flow with the lowest emission and transporting cost, as illustrated in Figure 12. For example: 3 biomass sources (S4 = 100 t, S5 = 500 t, S6 = 500 t) are available in Month 4; the selected sources are S5 = 500 t, S6 = 295 t (Figure 12) with the optimised cost of 3,581 € (0.36 €/t, Month 4). The average cost for 6 months is 0.51 €/t (43,253 €).



Month	Available Supply (GJ)	Required Supply (GJ) based on Production Curve	Storage (GJ)
1	27,199.8	23,000.0	0
2	25,826.4	23,000.0	3,271.4
3	18,729.0	23,000.0	Deficit
4	13,375.8	6,166.7	3,764.1
5	7,679.4	6,166.7	1,512.8
6	889.9	6,166.7	Deficit
Storage required to overcome the deficit on Month 3 and 6			

Figure 11: The Grand Composite Curve showing excessive and deficit biomass availability and the identified required supply. Value in blue font indicates the deficit at that time interval.

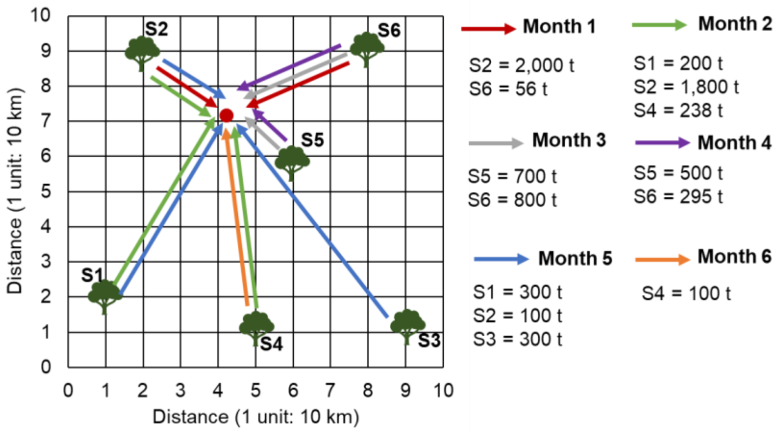


Figure 12: The biomass flow in each time intervals (Month) to fulfil the demand

3.2.4 Conclusion

The applicability of extended Pinch Analysis in production, inventory and storage planning has been demonstrated. Results of the case study suggest a production rate of 22,000 GJ/month (Month 1 - 3) and 6,167 GJ/month (Month 4 - 6). To fulfil a total energy demand of 85,000 GJ, which does not distribute evenly across the month, inventory (Month 1 = 3,000 GJ; Month 2 = 18,000 GJ; Month 4 = 3,167 GJ; Month 5 = 4,333 GJ) is needed. Biomass storage of 302 t on Month 2, 301 t on Month 4 and 138 t on Month 5 are required to overcome the deficit on Month 3 and 6. The biomass flow (sourcing/allocation) is optimised for the lowest emission and transporting cost solution (0.51 €/t). Pinch Analysis can be even further extended as it offers the room for the inclusion of social preferences to the planning. An optimum target is identified for the following analysis with the mathematical model. Uncertainty of supply, degradation during the holding time, pre-treatment, inclusion of a wider range of transportation mode, the transfer station and scheduling are going to be developed in a future study.

CHAPTER 4 P-GRAPH TO ASSESS THE WASTE MANAGEMENT SYSTEM

4.1 Application to Waste Treatment System

4.1.1 Introduction

A comprehensive assessment framework, supported by appropriate engineering tools, can assist the integrated design and selection of MSW treatment operations. One such process engineering tool is P-graph (Friedler et al., 1996). The aim of this study is to develop and demonstrate the applicability of P-graph for an integrated design of waste management systems in support of a Circular Economy (CE). The novel contributions of the presented study are (i) The demonstration and application of P-graph as a potential optimisation tool in proposing a suitable waste management system that progresses the CE concept. (ii) An optimisation procedure that can scale to consider the integration of multiple treatment solutions (iii) The identification of both optimal and near-optimal solutions for MSW systems to develop a set of options that can be further analysed for practicality, safety, and other factors that are difficult to embed into a mathematical model. (iv) The analysis of linking income level to waste composition and optimal waste utilisation structure as demonstrated through a case study.

4.1.2 Method

A waste treatment structure is developed in P-graph to assess the following sets of analysis (i) To investigate a set of optimal treatment pathways/waste management system from the economic and environmental (GHGs expressed in externality cost) perspectives of four different MSW composition, (ii) To analyse the differences in the optimal system structure with and without the consideration of GHG credits, and, (iii) To examine the sensitivity of the optimal structure under different product and utility prices. The objective function of the optimisation is to maximise profit (P) as defined in Eq(20):

$$\max P, \text{ where } P = A_{ghg}C + MV_{pu} - OC - E_{ghg}C \tag{20}$$

where $A_{ghg}C$ is the credit of avoided GHG emission from the recovered product/utility. MV_{pu} is the market value of the product/utility recover from the treatments, OC is the operating cost of waste treatments, $E_{ghg}C$ is the penalty of GHG emission during the treatment process. The reported unit is in € (Euros).

Four assessed scenarios are based on different compositions, as described in Fan et al. (2019f). The composition is divided based on the income level. The focus is on the synthesis and integration of waste treatment and utilisation operations that produce the highest profit (or minimum cost) by considering the economic balance between the main operating cost, type, yield, quality of products, as well as the GHG emission (as an externality cost). Figure 13 shows the developed waste treatment structure for this case study.

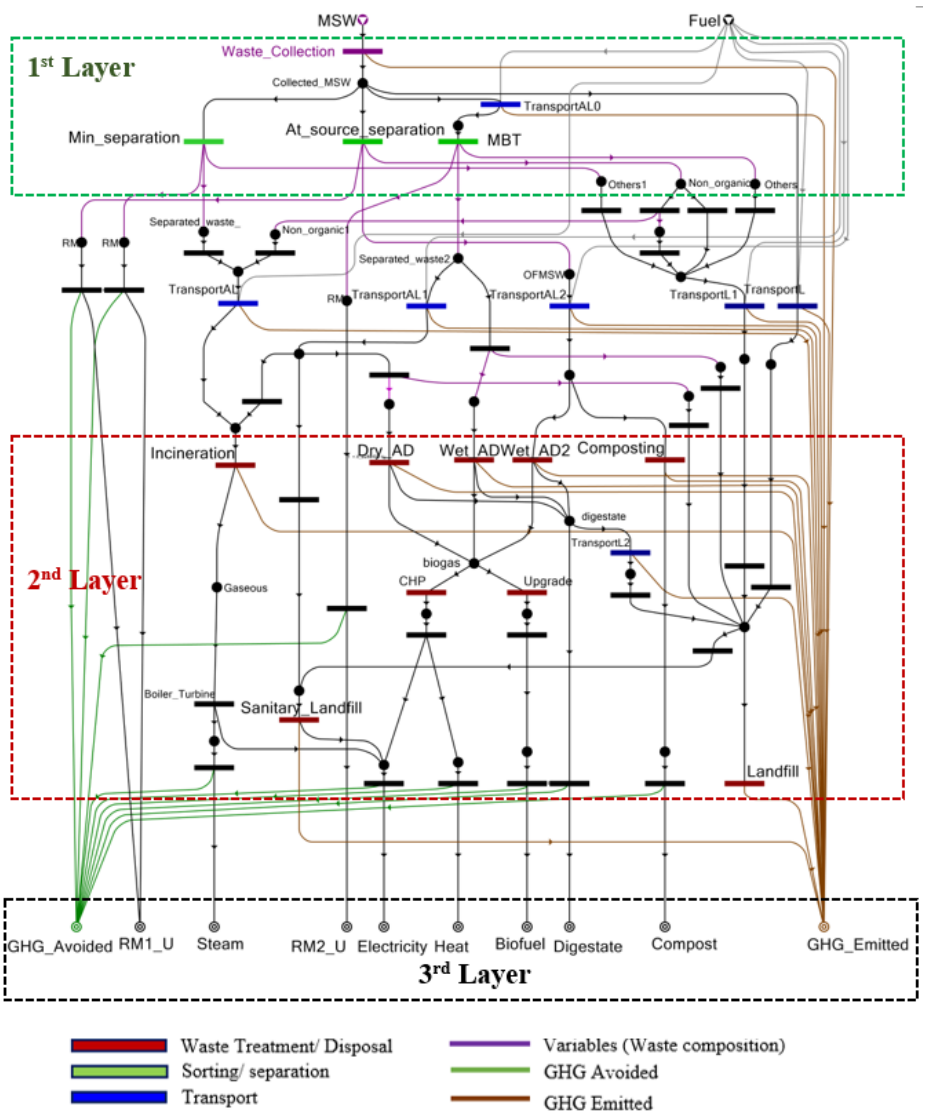


Figure 13: The complete waste treatment structure used in the case study

The MSW pre-treatment and separation processes (Layer 1) include minimum separation, at source separation and mechanical biological treatment (MBT). The waste amount of all scenarios is set at 500,000 t/y (Chefdebien 2016). The second layer is different treatment and disposal methods (incineration, anaerobic digestion (AD), composting, sanitary landfill, landfill and recycling). The third layer consists of electricity, heat, recycle materials, biofuel, digestate, compost, as well as the GHG emitted and avoided. The detailed data input of the treatment approaches, utility, product, emission and the interface of P-Graph software are reported in Fan et al. (2019f). To assess the impacts of altering the price of products/utility (Sensitivity analysis), the price of the biofuel, digestate, compost and GHG is modified by applying 100 % reduction to + 100 % increment (20 % interval).

4.1.3 Results and Discussion

The suggested optimal waste treatment structure for Composition 1 (low-income country) by the developed P-graph structure consists of Layer 1 – at source separation, Layer 2 – recycling, incineration, wet AD, landfill, with Layer 3 – heat, electricity, biofuel, digestate, recycle material. The total GHG emitted is 166,210 tCO_{2eq} and the total GHG avoided is 87,493 tCO_{2eq}. This gives a net increase of 78,717 t GHG emitted. By comparison to the baseline scenario with all MSW sent to landfill, the suggested optimal solution avoided 284,000 tCO_{2eq} from landfill and 125 tCO_{2eq} from transporting the waste to the landfill. This result suggests the emission from transportation is comparatively insignificant. The net GHG mitigated is equal to 205,408 tCO_{2eq} (411 $kgCO_{2eq}$ /t of processed MSW). The breakdown of overall profit is extracted from the P-graph, as illustrated in Figure 14. The potential profit of the suggested optimal waste treatment structure for Composition 1 is 15,860,100 € (32 €/t). Based on Figure 14, the GHG externality cost of the optimal solution is -1,369,680 €. The negative value indicated the need for paying the GHG emission. The GHG avoided from the generated products and utility did not compensate for the GHG emission during the treatment process. However, the net GHG emission remains significantly lower than the base case of using a landfill. Compared to the baseline of all MSW sent to landfill, the suggested optimal solution offers an additional 4,943,780 € (10 €/t) profit from the GHG eternality cost. The profit with the inclusion of the avoided emission from the landfill is approximately 20,803,880 € (42 €/t of processed MSW).

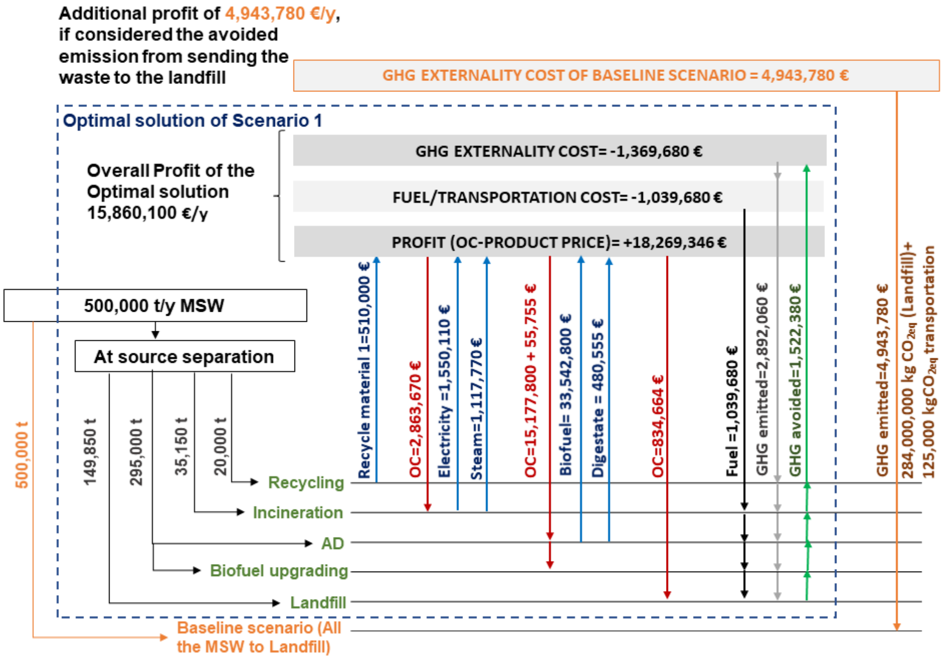


Figure 14: Optimal structure of Composition 1 (cost breakdown). OC = Operating cost.

The other near-optimal structures and the potential profit of Composition 1 are shown in Table 1. In contrast to Composition 2 (low-middle income country), MBT is not the first selection for Composition 1. The integrated solution for Composition 2 consists of MBT, recycling, AD (biofuel, digestate) and landfill offers a potential profit of 18,476,300 €/y (37 €/t). Compositions 3 (24,130,700 €/y or 48 €/t) and 4 (22,364,300 €/y or 45 €/t) have the same optimal pathway. However, the potential profit is different due to the differences in the waste composition and hence the processing amount of the different waste treatment approach. An increase in the income level of the country increases the preference for implementing MBT. Composting is not selected in any of the cases. The underlying reason for this non-selection is the product quality, and economic value is low (compost, assumed to contain 3 % of N). The current utilisation and the confidence level of composts for agricultural land remain low.

Table 1: The optimal and near-optimal solution of Composition 1. Add 4,943,780 €/y (included the avoided emission from the baseline) for the overall profit

Composition 1 (Low)- The pathway	**€/y**	**€/t**
At source separation, recycling, incineration (heat, electric), wet AD (biofuel, digestate), landfill	15,860,100 (Optimal)	32
At source separation, recycling, wet AD (biofuel, digestate), landfill	15,618,900	31
At source separation, recycling, incineration (heat, electric), wet AD (biofuel, digestate), sanitary landfill	13,036,000	26
MBT, recycling, wet AD (biofuel, digestate), landfill	12,812,400	26
At source separation, recycling, wet AD (biofuel, digestate), sanitary landfill	12,132,500	24

Figure 15 shows the changes in structure and profit after altering the cost of biofuel, digestate, compost, GHG, as well as electricity and heat by using Composition 1 as an example. Based on Figure 15, the potential profit (blue line/arc) increase with the increase of the biofuel price. The optimal structure remains the same as at source separation, recycling, incineration, AD (biofuel, digestate) and landfill. There is no profitable solution when the price of biofuel is reduced by 60 % (2.8 x 10^6 €/y). The structure with minimum loss is suggested. AD treatment with electricity and heat production is preferable. However, by considering the avoided GHG from landfill, offers a gain of 2.1 x 10^6 €/y. The impact of varying the price of compost and digestate on the potential profit is minimal. Composting is not selected even if the price of compost increases by 100 % (original price=3.81 €/t). The change in optimal waste treatment structure only occurs when the prices of electricity and heat are fluctuated over 20 %. When there is a 100 % decrease in the price of GHG (i.e. zero cost), the amount of waste that was originally used incineration is now sent to the landfill.

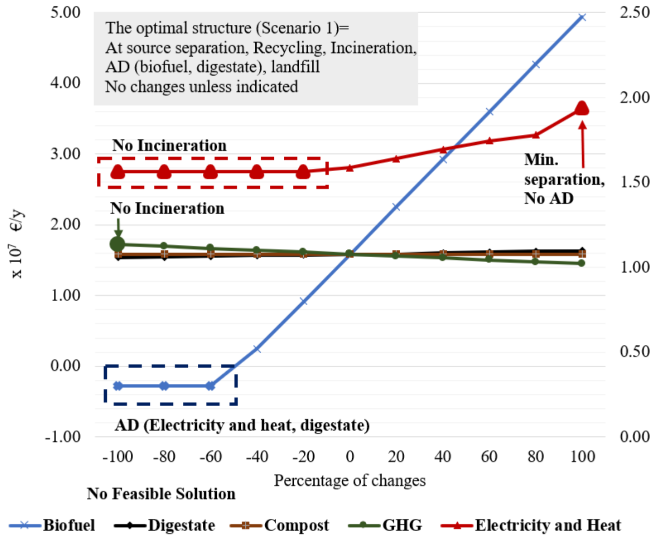


Figure 15: The impact of the products and utility cost on the potential profit and the suggested optimal solution. The right y-axis (x 10^7 €/y) is for electricity and heat (the red line).

4.1.4 Conclusion

The developed waste treatment structure can be implemented to specific case studies for localised solutions by inputting the relevant data of waste composition, expenditure, capital depreciation, transport distance, emission policy, and product market prices at the targeted area. Near-optimal solutions obtained in P-graph offer a guideline for the stakeholders with conflicting priorities that share the liabilities of MSW and can help achieve mutual agreement on a compromise option. The treatment solutions suggested for the low-income economy is at source separation, recycling, incineration (heat, electric), wet AD (biofuel, digestate) and landfill. The potential profit of the demonstration case study (Scenario 1) is 32 €/t. The estimated profit, including the additional profit from the credit of GHG, avoided from landfill is 42 €/t. GHG mitigated is up to 411 kg CO_{2eq}/t of processed MSW. The potential profit of Scenarios 2, 3, 4 is 37 €/t, 48 €/t and 45 €/t. The other outcomes include: (1) MBT is suggested with the increase in income level. (2) Changes in the prices of electric and heat by >20 % shifts the optimal solution to select AD instead of incineration. (3) Contribution of transportation emission to the total system emissions is low.

4.2 Application to Pre-and Post-Treatment in Waste Management

4.2.1 Introduction

Pre-treatments play an important role in improving the process of economics by maximising the accessibility of lignocellulosic waste (LW) to achieve high biogas yield. Post-treatments determine the quality and utilisation value of biogas. Li et al. (2017) perform the environmental and economic life cycle assessment of different anaerobic digestion pathways (includes different pre-treatment and post-treatment). However, the study focusses on physical treatments and is for sewage sludge. This presented study simultaneously assesses the pre-treatment and post-treatments of LW for AD from both perspectives (cost and the environmental performances).

4.2.2 Method

LW is assumed to have the potential biogas yield of 400 m^3 biogas/t. The amount of biogas without pre-treatment is 50 % of the potential biogas yield. The sustainable options in term of economics were identified using the developed structure by P-graph studio version: 5.2.1.4 (P-graph studio, 2015). The environmental impacts which include global warming potential (GWP), human toxicity, ozone depletion potential (ODP), particulate matter (PM), photochemical oxidant creation (POCP), acidification (AP) and eutrophication potential (EP) were evaluated by using GaBi Software ts version 2017 (Thinkstep AG, 2017). The trade-off between cost and environmental options are discussed. A total of assess eight different types of pre-treatment (No treatment - P0, Grinding - P1, Steam explosion - P2, Water Vapor - P3, CaO - P4, NaOH - P5, H_2SO_4 - P6, Enzyme - P7, Microbial Consortium - P8) and post-treatment (H_2S removal + pressure water scrubbing, HSR PWS; H_2S removal + organic physical scrubbing, HSR OPS; H_2S removal + amine scrubbing, HSR AS; H_2S removal + pressure swing adsorption, HSR PSA; H_2S removal + membrane separation, HSR MS; Biofuel, BF; Combined Heat and Power, CHP; Fuel Cell, FC; sterilisation and composting) are assessed. The detailed information and conversion factors for the case study are as in Fan et al. (2019g). The input of LW is assumed to be 100 t/y. The identified value serves as an indicator for the cost optimised pre-treatment and post-treatment pathway, where a higher value reflects higher feasibility. The cost-optimal and near-optimal solutions identified by P-graph were further discussed by considering the environmental impacts. The gross compensated or avoided environmental impacts were identified by considering the avoided impacts from the conventional production (electricity, gasoline, heat) Fan et al. (2019g). The impact factors are generated by GaBi software (GaBi ts, AG ThinkStep, Germany). The overall environmental impacts of post-treatments were estimated by divide the environmental impacts in performing post-treatment by gross avoided impacts. Sensitivity analysis is conducted to curtail the uncertainty of the input data. The effect of changing the cost on the optimal solution is identified.

4.2.3 Results and Discussion

P4 pre-treatment and HSR MS post-treatment are identified as the best cost option by P-graph, with heat, electricity and digestate as the product materials. P4 requires a higher operating cost than physical approaches such as P1 and P2. However, it is offering a higher enhancement of the yield of biogas (59 %, from 200 m^3/t to 310 m^3/t). HSR MS post-treatment was identified as the most suitable pathway in the economic perspective. Although the main operating cost of HSR MS is higher than HSR PSA and HSR OPS, the value of products (heat and electricity) are higher, where the estimated profit is higher (20,653.0 €/y). The other near-optimised solutions by P-graph are P4, HSR MS, without composting (20,653.0 €/y); P4, HSR MS, with composting (20,523.0 €/y); P4, HSR OPS, without composting (20,307.1 €/y); P4, HSR OPS, with composting (20,189.6 €/y); P4, HSR AS, without composting (19,856.8 €/y). P4 remains as the suggested pre-treatment option. The near-optimal post-treatments for biogas treatment are HSR OPS (20,307.1 €/y) and HSR AS (19,856.8 €/y). The environmental impacts of P4, which represents the low-cost approach, is presented in Table 2. The environmental impacts are not as low as the biological treatment (P7 and P8) and water P3. However, it is an option with higher cost feasibility. P5 has the worst environmental performance in GWP, ODP, human toxicity, POCP and EP. P6 has the worst environmental performance in AP and PM. In general, P7, P8, P3 have relatively low environmental impacts. P1, P2 and P4 are in the medium range. P5 and P6 are in the higher range.

Table 2: The environmental impacts of the identified cost-optimal solution

	CaO pre-treatment (P4)	The worst
GWP (excluded biogenic CO_2), kg $CO_{2\ eq}$	72.6	99.0 (P5)
ODP, kg R11eq	4.58×10^{-11}	3.08×10^{-9} (P5)
Human toxicity (cancer), CTUh	6.57×10^{-8}	1.36×10^{-7}(P5)
PM, $PM_{2.5eq}$	1.76×10^{-3}	3.29×10^{-2} (P6)
POCP, kg $NMVOC_{eq}$	2.55×10^{-2}	2.46×10^{-1} (P5)
AP, mole of H^{+}_{eq}	2.50×10^{-2}	6.88×10^{-1} (P6)
EP, mole of N_{eq}	9.31×10^{-2}	1 (P5)

Post-treatment of CHP shows the best environmental performance in all the assessed environmental impacts. HSR PWS has the highest impact (worst environmental performance) in term of human toxicity, PM, POCP, AP and EP. HSR MS, HSR AS and HSR OPS are the cost-optimal and near-optimal solutions. However, by referring to the environmental impacts, HSR AS has the worst performance in term of GWP (1.01×10^{-1} kg $CO_{2\ eq}$/t of LW) and ODP (4.47×10^{-11} kg R11 $_{eq}$/t of LW). This suggests HSR OPS and HSR MS are the post-treatment which are comparatively feasible in term of both cost and environmental impacts. Table 3 shows the overall environmental impacts of different post-treatments. HSR MS and HSR AS are having better overall environmental impacts performances than HSR OPS. HSR MS has the lowest OD, Human Toxicity, and PM. HSR AS has the lowest GWP, POCP, AP, and EP.

This study identifies a wider range of options (optimal and near optimal). This enables better decision making based on the constraints and environmental concern at a place.

Table 3: Overall environmental impacts

	HSR OPS	HSR AS	HSR MS
GWP (excluded biogenic CO_2), kg CO_{2eq}	-2.70	**-2.82**	-2.73
ODP, kg $R11_{eq}$	-7.00×10^{-11}	-3.25×10^{-11}	**-7.24×10^{-11}**
Human Toxicity (cancer), CTUh	-1.53×10^{-9}	-1.27×10^{-9}	**-1.58×10^{-9}**
PM, $PM2.5_{eq}$	-2.93×10^{-4}	-1.72×10^{-4}	**-3.01×10^{-4}**
POCP, kg $NMVOC_{eq}$	-3.20×10^{-3}	**-3.31×10^{-3}**	-3.27×10^{-3}
AP, mole of H^{+}_{eq}	-5.54×10^{-3}	**-5.77×10^{-3}**	-5.71×10^{-3}
EP, mole of N_{eq}	-1.13×10^{-2}	**-1.17×10^{-2}**	-1.16×10^{-2}

Sensitivity analysis has been performed. Under most of the changes, P4 + HSR MS remains as the best solution. The near cost-optimal solution P4 + HSR OPS is a better option when the operating cost of P4 and HSR MS have a more than 10 % increment. The best combination from the perspective of environment impacts is biological treatments + CHP. The biological (P7, P8) and physical (P1, P2, P3) pre-treatments alternatives have lower environmental impacts than chemical pre-treatments (P4, P5, P6) however they are not part of the near cost-optimal solutions. CHP is the post-treatment with the lowest environmental impacts. Among the near cost-optimal alternatives, post-treatment HSR AS has a better performance in the overall environmental impacts followed by HSR MS and HSR OPS. Although the identified best solutions in term of environmental and cost-optimal are different, there is no significant contradiction.

5.2.4 Conclusion

This study suggests the sustainable pre-treatment and post-treatments of LW for AD, in term of cost and environmental performances. P-graph provides wider rational decision options by considering the near-optimal solutions. The trade-offs between cost and environment performances can be compromised by referring to near-optimal solutions. Biological pre-treatments (P7 and P8) are having lower environmental impacts than P4. However, they are not within the near cost-optimal solution. Among the cost-optimal/near-optimal post-treatment alternatives, based on the number of the impact of categories, HSR AS has the lower overall environmental impacts follows by HSR MS and HSR OPS. The suggested cost-optimal solution (CaO pre-treatment (P4), H_2S removal with membrane separation post-treatment (HSR MS) and without the composting of digestate) has considerately low environmental impacts and cost-effective.

CHAPTER 5 OVERALL CONCLUSION AND RECOMMENDATION

Embedding Process Integration into Circular Economy is essential to ensure that the transition of the circular system is sustainable. The developed methodologies in this thesis inculcate Process Integration in process design and optimisation. The shared feature is that they consider a system as a whole, which exploits the interactions between different units, to minimise emissions footprints (which includes employing resources effectively) and cost. Their effectiveness in solving the problems was demonstrated through the case studies. My main contributions are highlighted in the abstract. The graphical basis, which is easier for adaption and application, as well as the other discussed advantageous features, offer a wide potential for practical implementation. The specific insights identified in each cases study include: (i) BBDM identified the electric train as a better option (at Load = 2,000; Distance ratio=1) than the electric lorry in Sweden, offering a 30% reduction in TEB (GHG, NO_x, SO_2, PM). A lorry powered by compressed natural gas was shown to be a better option than an electric lorry in Latvia (49 % TEB reduction). (ii) In the second cases study, adapted BBDM suggests burning of biochar for electricity is generally a preferable option. Biochar application as a form of carbon sequestration is suggested at low GHG intensity and becomes preferable when the GHG price is higher than 0.03 USD/kg CO_2eq for switchgrass and 0.01 USD/kg CO_2eq for wheat straw. (iii) The analysis run by the novel approach using E-WAMPA suggests an overall 10 % emission reduction (2,568 kt CO_2eq) can be achieved by performing waste transition in Malta (-25.75 kt CO_2eq), Greece (-1,602.71 kt CO_2eq), Cyprus (-178.52 kt CO_2eq) and Romania (-761.16 kt CO_2eq). (iv) Integrating extended Pinch Analysis and mathematical optimisation for biomass allocation, considering the fluctuating supply and demand, are optimised by minimising transportation and GHG externality cost to 0.51 €/t. (v) The developed waste management system structure by P-graph suggests the identified optimal treatment system could avoid an estimated 411 kg CO_2eq/t of processed MSW and achieves a potential profit of 42 € /t of processed MSW. (vi) Applying to the pre-and post-treatment assessment, the biological and physical pre-treatments alternatives are identified to have lower environmental impacts. H_2S removal with amine scrubbing has a better performance for post-treatment. For future study, comprehensive economic feasibility assessment can be conducted where localised data inputs fed into the proposed methodologies for a customised and thorough solution, as the current case studies considered only the operating cost. A monitoring framework supported by a combined index (economic, environmental footprints, and material balance) can be developed for a sustainable Circular Economy.

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