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A Heuristic-Based Technique for Carbon Footprint Reduction for the Production of Multiple Products

Jane Y. Yap[a], Jully Tan*[,a], Dominic C.Y. Foo[b], Raymond R. Tan[c], Stavros Papadokonstantakis[d], Sara Badr[d]

[a]Department of Chemical and Petroleum Engineering, Faculty of Engineering, Technology and Built Environment, UCSI University, No.1, Jalan Menara Gading, UCSI Heights,56000 Cheras, Kuala Lumpur, Malaysia
[b]School of Chemical and Environmental Engineering, University of Nottingham (Malaysia Campus), Jalan Broga, 43500 Semenyih, Selangor Darul Ehsan, Malaysia
[c]Center for Engineering and Sustainable Development Research, De La Salle University, 2401 Taft Avenue, 0922 Manila, Philippines
[d]Department of Energy and Environment, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden
tanjully@ucsiuniversity.edu.my

Carbon footprint (CF) reduction is a common trend for many industrial processes in recent years. However, not many analytical tools have been developed for visualising CF reduction at enterprise level. A graphical technique known as the CF Composite Curves to aid decision making in CF reduction at enterprise level has been developed in previous work. However, the method was limited to the production of a single product. In this paper, the CF reduction procedure is extended to the more general case of multiple products. The CF of shared and independent facilities are analysed. An illustrative example shows that for cases when the CF intensity of shared facilities is higher than that of the independent facilities, CF reduction should focus on the shared facilities, before efforts are put forward for the independent facilities. In contrast, when the CF intensity of independent facilities is higher than that of the shared facilities, it is necessary to explore ways to reduce CF of the independent facilities.

1. Introduction

In the past decades, the issue of climate change has been addressed with increasing concern. As the effects of global warming become more eminent, more efforts are being implemented to reduce the emissions of greenhouse gases (GHGs) such as CO_2, CH_4 and NOx. The global net emissions of CO_2 have been reported to increase by 42 % between 1990 and 2010, which comprises about three-fourths of total global emissions (EPA, 2016). A systematic carbon emissions analysis and holistic planning of industrial processes will contribute to achieving the Goal 13 of Sustainable Development Goals (SDGs). Goal 13 targets climate change issue where urgent action must be taken to combat climate change and its impacts by regulating emissions and promoting developments in renewable energy (Ansuategi et al., 2015). In this context, it is important to integrate climate change measures into strategies and planning, as well as to improve institutional capacity on climate change mitigation, adaptation, and impact reduction.

Increased environmental awareness has led to greater interest in the adoption of low-carbon and CO_2-neutral energy technologies. These technologies include non-combustion sources with inherently low carbon emissions footprints (CF) (e.g., renewable energy sources such as wind, solar or nuclear), as well as combustion-based technologies with reduced CF due to upstream or downstream carbon sequestration, such as biofuel burning and fossil fuel-fired systems with carbon emissions capture and storage (CCS) (Foo and Tan, 2016).

CF measurement and reduction methods have been developed to support stakeholders in decision making. However, not many analytical tools have been developed for visualising CF reduction at the enterprise level. Carbon Emissions Pinch Analysis (CEPA) was first developed by Tan and Foo (2007) based on the application of conventional Pinch Analysis techniques commonly utilised as a Process Integration tool by chemical and process engineers. The original technique makes use of the Energy Planning Pinch Diagram, where Demand

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and Source Composite Curves are both plotted to identify the minimum amount of low-carbon or CO_2-neutral energy sources required to meet the emissions limit. Ideally, it is desirable to maximise the use of renewable energy sources to replace conventional fossil fuel sources with high carbon intensity; however, such low-carbon or CO_2-neutral energy technologies are usually more expensive or controversial as compared to fossil fuels. In addition, in the short term it is often necessary to manage the transition to increased low-carbon emissions energy utilisation to minimise disruptions in energy supply or price. There is great interest in identifying the minimum amount of low-carbon emissions or CO_2-neutral energy sources needed to meet the CO_2 emission limits in many planning scenarios (Tan and Foo, 2007).

Over the years, CEPA approach has been extended to applications in various sectors with strategic modifications. For instance, in energy sector planning, the minimum amount of zero-carbon energy resource required is determined using CEPA to achieve the overall emissions target for a region, or for cases where different regions have distinct targets but share a common energy resource, the allocation of energy resource is applied (Tan and Foo, 2007). This methodology has seen meaningful applications in the emissions targeting and macro-scale planning for the New Zealand electricity (Atkins et al., 2010) and transportation sectors (Walmsley et al., 2015). Lee et al. (2009) extended the CEPA targeting technique to handle cases with low-carbon sources for energy planning. The CEPA approach evaluates and visualises the CF reduction options available for a given process, making it a useful tool for energy sector planning that simultaneously takes into account the environmental and economic constraints. In a later work, Tjan et al. (2010) extended the work to reduce CF for product manufacturing. This approach was based partly on a graphical technique for benchmarking firm-level carbon intensity with industry average values (Tahara et al., 2005). Decision makers can implement different strategies to achieve the desired CF reduction, ranging from management-based (e.g., material selection or selective procurement of inputs from suppliers based on CF) to technology-based solutions (e.g., process retrofits for energy conservation, heat recovery, on-site combined heat and power generation, etc.). It is essential to identify a sensible approach which can be prioritised for implementation.

However, the work of Tjan et al. (2010) for product CF reduction is limited to single product scenario. In other words, it is not applicable for multiple-process case. For this reason, in this work, extended procedure is developed to systematically reduce CF for the production of multiple products, based on the previously developed method. In the following section, the methodology for CF reduction for the production of multiple products is outlined. The technique is then demonstrated using a case study on softwood pre-treatment.

2. Methodology

Strategies for CF reduction illustrated using a generic manufacturing process is shown in Figure 1 that follows. As shown, raw materials 1 and 2 are sent to processes A, B and C to produce product X. The intermediate product from process B will be sent to process D to produce product Y.

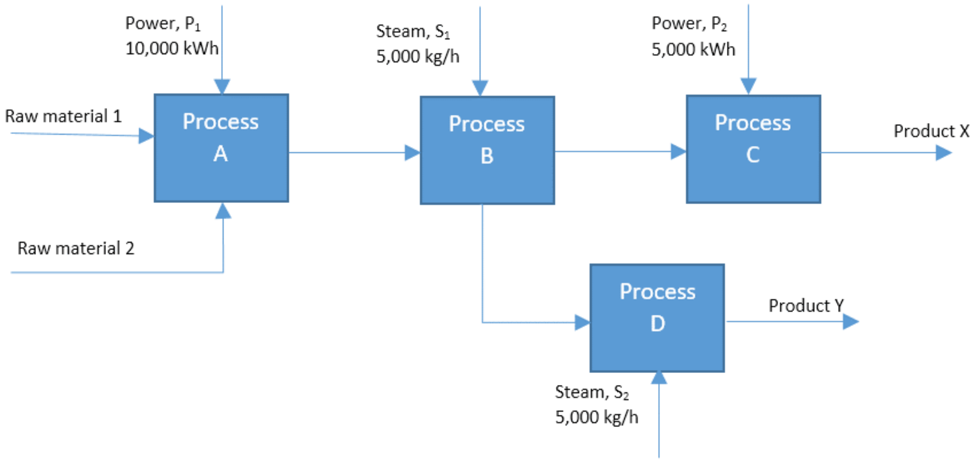
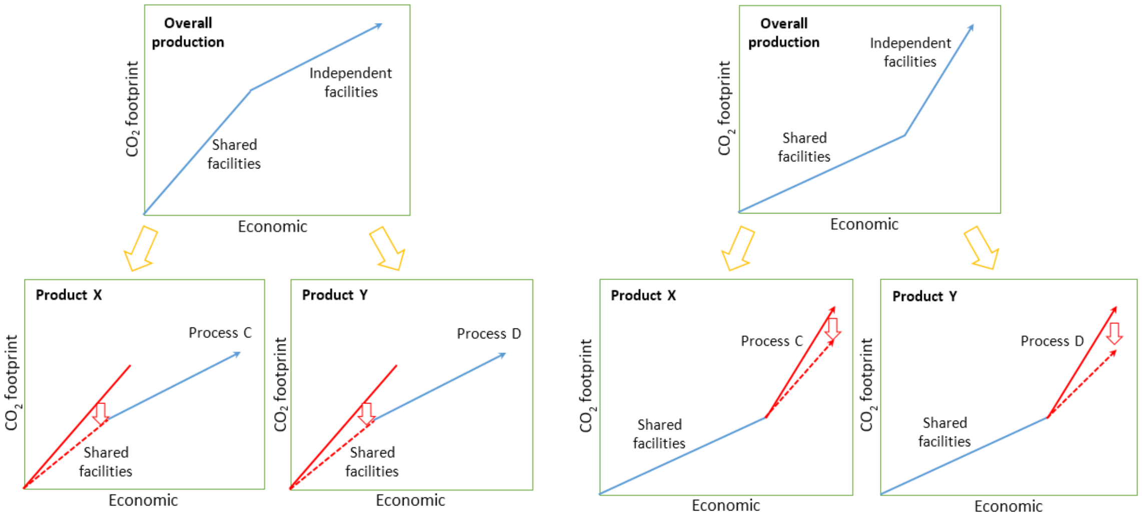


Figure 1: Multi-product system

For cases where CF intensity of the shared facilities (e.g. processes A and B) is higher than that of the independent facilities (e.g. processes C and D), we shall look at ways to reduce CF for the shared facilities, before efforts are put forward for independent facilities. The Composite Curves for Scenario 1 are shown in Figure 2a. On the other hand, for cases where the CF intensity of independent facilities (e.g. processes C and D) is higher than that of the shared facilities (e.g. processes A and B), it is necessary to reduce CF for the independent facilities, as shown in Figure 2b (Scenario 2). Note that the CF intensity is represented by the slopes of the individual segments.



(a) (b)

Figure 2: CF reduction strategies for: (a) Scenario 1 and (b) Scenario 2

3. Case Study: Multi-production of GROT

A case study on the pre-treatment process of GROT ('Grenar och Toppar' in Swedish, refers to the tops and branches of softwood such as Norway spruce) is considered. The composition of softwood used is 41.75 % cellulose, 31 % lignin, 22.25 % hemicellulose, and 5 % extractives. Figure 3 shows the simulation flowrate of GROT pre-treatment process to produce syngas and dry pulp, modelled in SuperPro Designer v9.

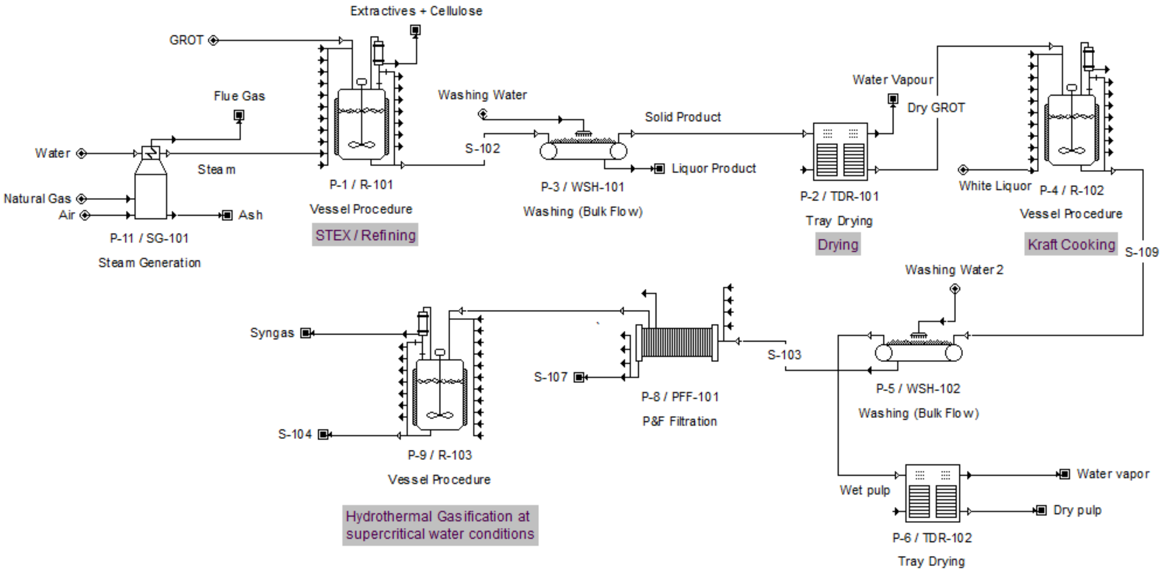


Figure 3: Process flow diagram of GROT production

GROT is first fed into steam explosion (STEX) treatment in the form of air-dried wood chips. Mild steam explosion (STEX) is a hydrothermal treatment that can make the structure of wood more accessible and facilitates the subsequent isolation of wood components. STEX is a three-step process: (i) treatment with pressurized steam for a specific duration, (ii) explosion through quick pressure release and (iii) impact of softened wood chips with each other and the walls of the equipment (Kerstin, 2014). The material is subjected to steam explosion at 7 bar and 140 °C for 10 min. Compounds from hemicelluloses and wood extractives are released into the condensed steam, whereas lignin and cellulose in the wood are not affected to any substantial extent.

The steam-exploded GROT is washed with distilled water to produce solid and liquor products. The solid product is sent for drying to obtain dried GROT (about 69 % its initial weight). Kraft pulping process is then used where white liquor (NaOH, Na_2S and Na_2CO_3) with carbonate concentration of 0.1 M is charged at a liquor-to-wood ratio of 9:1 (kg/kg) to the dried GROT. The Kraft cook takes place in a steel autoclave placed in a pre-heated bath at 80 °C for 20 min. At a heating rate of 0.8 °C/min, the cooking temperature is raised to 170 °C and maintained for 60 minutes. After the cook, the pulp is washed with water and separated from the black liquor. The wet pulp is then air-dried to obtain 45.7 % of weight of dried GROT.

The weak black liquor containing about 90 wt% of Kraft lignin from dried GROT and water content of about 83 % is filtered. Hydrothermal gasification in supercritical water conditions is carried out at 650 °C, 300 atm and 11.5 wt% liquor concentration for 120 s (Sricharoenchaikul, 2009). The composition of the syngas obtained is approximately 34.8 % H_2, 28.5 % CO, 33.6 % CO_2, 1.4 % CH_4 and 1.7 % C_xH_y.

The CF Composite Curves are used to analyse the total CF of the overall process. The CF of shared and independent facilities are plotted against the economic value of the utilities, as shown in Figure 4.

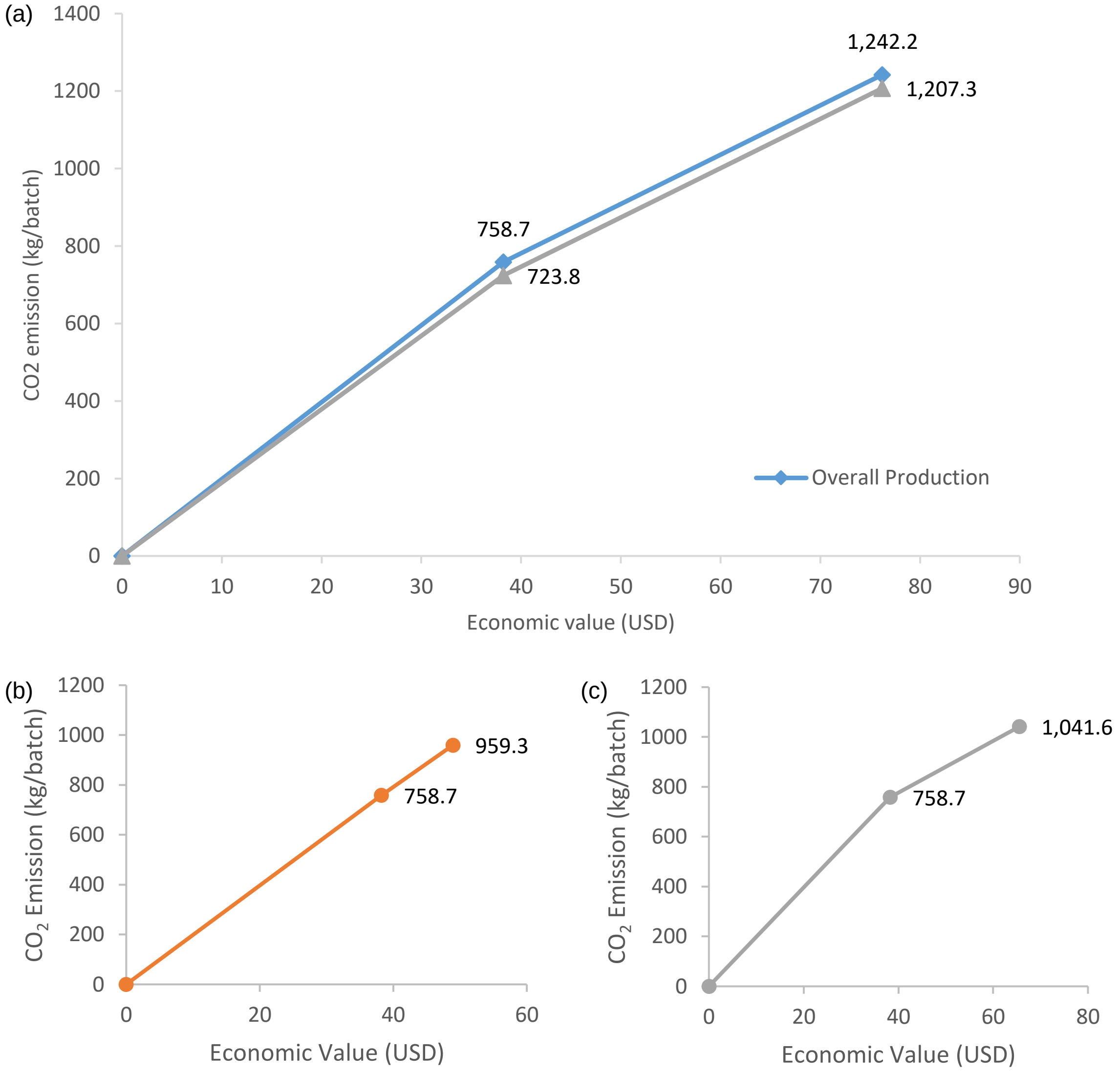


Figure 4: Carbon Emissions Footprint Composite Curves for case study: (a) Overall production, (b) Production of dry pulp, (c) Production of syngas

Note that CF of the shared facilities is contributed by STEX, drying, and Kraft cooking processes. On the other hand, the CF of the independent facilities is contributed by the drying process for the production of dry pulp, and filtration and gasification processes for the production of syngas. For steam production, CF of 0.17 kg CO_2/kg steam (Wang, 1999) is used in this study. The overall CF of Malaysian power mix is calculated from the weighted average of the different energy sources, including natural gas, coal, hydropower and oil, which is determined as 0.622 kg CO_2/kWh (Tjan et al., 2010). The unit cost for electricity is taken as USD 0.06/kWh, and that of steam is taken as USD 0.0042/kg (Tjan et al., 2010). The data of steam and electricity required for the process operations was obtained from simulation study. The utility cost and the corresponding CO_2 emission are calculated and tabulated in Table 1.

Table 1: Economic value and carbon emission of case study

Facility	Utility	Usage	Unit	Economic value (USD)	Carbon emission (kg CO_2)	Aggregate carbon intensity (kg CO_2/USD)
Shared	Steam	2,864.74	kg	12.03	487.01	19.84
(STEX → Drying → Kraft)	Electricity	436.84	kWh	26.21	271.71	
			Total	38.24	758.72	
Independent: Dry Pulp	Steam	709.58	kg	2.98	120.63	18.76
(Drying)	Electricity	128.61	kWh	7.72	80.00	
Independent: Syngas	Steam	-	kg	-	-	10.37
(Filter → Gasification)	Electricity	454.78	kWh	27.29	282.87	
			Total	37.98	483.50	

As shown in Figure 4a, the CF intensity of the shared facilities segment is higher than that of the independent facilities. Hence, CF reduction efforts should focus on the shared facilities. The strategy is to reduce the slope of the shared facilities segment, which can be achieved by utilising cleaner energy. One of the strategy is to make use of syngas, which is one of the products of this process. The syngas product can be co-fired in coal power boiler to produce steam, supplying a portion of the steam required by the process operations, which is conventionally produced by fossil fuel-power boilers. This practice can reduce the CF of shared facilities. The lower heating value (LHV) of syngas is taken as 4.847 MJ/kg (Ostrowski et al., 2017), and furnace thermal efficiency as 38.6 % (Wu et al., 2004). Based on the total available syngas of 120.6 kg/batch, a total of 225.6 MJ of steam can be generated, which can replace 112.8 kg/batch of steam generated by fossil fuel-power boilers. Additionally, a heat exchanger can be installed to recover energy to the GROT drying process using the hot syngas stream from the gasification process that is operated at 650 °C. This results in an amount of 185.02 MJ of energy recovery, replacing 92.5 kg/batch of steam required for the drying process.

These strategies lead to a reduction of 2.8 % of total CF reduction. Other options may be considered in order to further reduce the overall CF, for instance, increased utilisation of renewable energy resources (e.g. hydropower, solar) in power generation mix. Efforts should also be put forward for CF reduction of the independent facilities.

4. Conclusions

CF reduction for the production of multiple products using Carbon Emission Pinch Analysis (CEPA) technique have been presented in this work, because the reported work on CF reduction by Tjan et al. (2010) is limited to only single product, and does not work for cases with multiple products, especially for those with shared and independent facilities. The approach in this work decomposes the footprint into shared and independent facilities, and subsequent graphical display of the CF Composite Curves facilities decision making in choosing the priority process operations for footprint reduction. Case study of GROT pre-treatment process illustrates how this extended CEPA method can address more complex systems that produce more than one product and implement a systematic approach to reduce the CF of selected process operations. CF reduction target can be set through rigorous analysis, by taking into consideration technological feasibility, as well as economic merits of the proposed solutions. It is possible to look into multiple strategies. However, it depends on case-to-case scenarios. Future work shall look into simultaneous footprint reduction, such as water and carbon emissions footprints, as GHG footprint contributed by CO_2 is less than 2/3 of all GHG emissions.

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