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Development of a Sustainable Supply Chain Network for Microfluidic Devices Made from Recycled Materials

Krystal Faith B. Javier*, Butch G. Bataller, Maria Victoria Migo-Sumagang

Department of Chemical Engineering, University of the Philippines Los Baños, Laguna, Philippines
kbjavier@up.edu.ph

Meeting the global diagnostic and monitoring demand has been a challenge, especially in places with limited laboratory facilities. To address this, microfluidic devices have been integrated into the diagnostic framework. Due to the nature of their usage, however, microfluidic devices for diagnosis and monitoring should be single-use and disposable. Since these devices are commonly made from thermoplastics derived from unrecyclable and/or nonrenewable sources, their production, use, and disposal are accompanied by a high carbon footprint. Using a Design for Sustainability approach, this work presents an optimization model for the development of a supply chain network that considers both the economic and the carbon footprint as objectives. The model is demonstrated using data derived from literature and the industry. Results of the analysis indicate that the entire polymer feed required for the hypothetical manufacturing plant can be composed solely of recycled polyethylene terephthalate regardless of which optimization parameter was prioritized. The models developed in the study reveal that production of the microfluidic device using recycled polyethylene terephthalate is accompanied by 0.13 kg CO_2-eq/d per unit of product when carbon footprint is prioritized. This amount of emission also corresponds to a cost per unit of product of 0.0546 $/d when the minimization of the cost objective is prioritized. This proves that the use of recycled polymers can be a way to reduce the dependence of the microfluidics industry on unsustainable materials.

1. Introduction

Microfluidic devices, according to Convery and Gadegaard (2019), have the potential to outperform classical techniques used in research for biomedicine and chemistry owing to the development of new microfabrication methods. Since the introduction of the first lab-on-chip (LOC) device in 1979, microfluidics has evolved from basic laboratory procedures to complex systems capable of operating on whole organs or bodies on a single chip (Kumar et al., 2024).

The development of point-of-care (POC) devices which are portable analytic devices designed to detect infections, has expanded the reach of diagnosis to households and remote areas (Jiang et al., 2021). These devices are commonly made from plastics such as polydimethylsiloxane (PDMS), cyclic olefin copolymer (COC), polymethylmethacrylate (PMMA), etc. (Ongaro et al., 2022). While these materials are suitable for use due to their chemical and mechanical resistance, they are petroleum-derived, non-biodegradable, and have a large CO_2 footprint. Reducing the field's dependence on non-renewable resources should be one of the first steps in making these devices more environmentally friendly (Wan et al., 2017).

Ongaro et al. (2022) stated that plastics, such as single-use tests, make up 5-20 % of the waste produced by the biomedical industry. It is then recommended to adapt methods to reduce reliance on non-renewables to decrease CO_2 emissions from using these devices. Additionally, future manufacturers and stakeholders should consider the use of design approaches that prioritize effects on society and the environment as well as their economic impacts, such as the Design for Sustainability (D4S) approaches. Built on the concept of ecodesign, D4S methodologies allow for the assessment of the sustainability of a manufacturing process at the design level instead of retrospectively and can be used in small- and medium-sized enterprises (SMEs) in developing countries (Clark et al., 2009*)*. Since microfluidics is still a growing field of study, research on innovations, including the use of sustainable materials, will greatly benefit from D4S approaches. In this study, the D4S new

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product development approach was used by considering the impacts of using more eco-friendly alternatives like recycled plastics.

Emerging sustainable materials for microfluidic device production include recycled plastics, bio-derived and biodegradable plastics, and natural fibrous substrates. In their study, Ongaro et al. (2022) indicated that while recycled plastics do not remove the industry's reliance on non-renewable materials, their use is a suitable short-term solution to reduce the negative environmental impacts caused by using these devices.

A study by Wan et al. (2017) shows that multiple recycling cycles in the laboratory setting do not significantly affect the performance of devices made from recycled plastics. It was found that the qualities of recycled PMMA (rePMMA) are retained after four cycles of mechanical recycling of devices used for basic cell-based assays. A study by Ongaro et al. (2018) demonstrated the suitability of chemically recycled PMMA in the production of microfluidic devices. Other polymers, such as high-density polyethylene (HDPE) and polyethylene terephthalate (PET), which already have established recycling streams, are also viable alternatives. The study of Jackson et al. (2016), which features a DNA purification microdevice, illustrates the use of PET in microdevices.

While there are studies on the applicability of recycled materials for microfluidic applications, there is no study regarding the optimization of a supply chain network for the use of such materials to date. To address this gap, this study uses a D4S approach to develop a supply chain network that considers both the economic and environmental impacts of using different types of polymers to develop a supply chain model evaluating the economic and environmental impacts of using various polymers, including recycled PET and PMMA. The proposed model can be adapted for different polymer types and supply scenarios and can guide future microfluidic manufacturing plants in evaluating their material choices. The approach used in this study can be adapted by future microfluidic manufacturing plants in the planning stage to compare the impacts of different polymer types.

The succeeding sections of this paper discuss the problem statement in Section 2. The methods used for the model formulation, results, and conclusion and recommendations for future work are presented in Section 3, Section 4, and Section 5.

2. Problem statement

This study considers a microfluidic device manufacturing plant in its early planning stage. Given a set of suppliers that can provide the raw material, which can either be only PMMA or only PET, needed to produce microfluidic devices, a supply chain network model is generated. Each demand for raw material (j) from source (i) has a corresponding CO_2 emission (e_{ij}), purchase cost (c_{ij}), and topological connectivity value (b_{ij}), which is a binary variable that ensures that there is a connection between supplier i and the demand for raw material j.

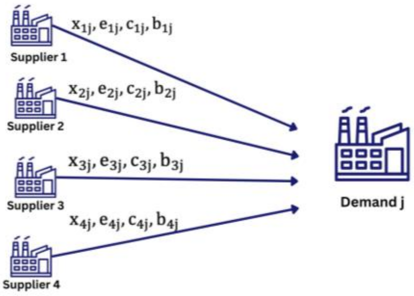


Figure 1: System in consideration

The system considered in the study is shown in Figure 1. Here, a manufacturing plant for each of the pristine plastics and a recycling plant for each of the polymers are considered. Supplier 1 is a manufacturing plant for pPET, while Supplier 2 represents a recycling plant for PET. Supplier 3 and Supplier 4 is a manufacturing plant for pristine PMMA (pPMMA) and a recycling plant for PMMA. Demand j can either represent Demand 1 which is the demand for PET, or Demand 2 which is the demand for PMMA. The aim of this study is to determine the amount of raw materials (x_{ij}) purchased from each supplier that will minimize the cost or CO_2 emission while meeting the demand.

3. Model formulation

Two optimization models were developed using the following assumptions: (1) a unit of each final product requires a certain number of raw material j, (2) the amount of the final product is known, (3) the differences in the production process and efficiency of each supplier i lead to differences in production cost and CO_2 emission per raw material, and finally (4) this study considers a manufacturing plant that acquires raw materials locally. Thus, there is no significant difference between the transportation cost or other types of cost.

The first model, shown in Eq(1), minimizes the total purchase cost of raw materials, constrained by supplier capacities (CAP_i), demand requirements (DEM_j), and non-negativity as represented in Eq(3), Eq(4), and Eq(5). The topological connectivity between suppliers and demand points is a binary variable and is equal to 1 when there is a connection between the supplier and demand otherwise it is set to 0. The second objective function shown in Eq(2) minimizes the CO_2 footprint and is subject to the constraints in Eq(3), Eq(4), Eq(5), and topological constraints. Both models use linear programming (LP). Data for supplier capacities, demand, costs, and carbon emissions are sourced from industrial reports and literature, as shown in Table 1 and Table 2. The cost model was tested through sensitivity analysis to ensure robustness. The calculated demand for PET is 2,023.31 kg/d and 1,646.20 kg/d for PMMA.

Table 1: Data used for the calculation of the capacity of each supplier and demand for each of the polymer types.

Parameter	Value	Reference
Dimension of the microfluidic device, mm×mm×mm	148 × 98 × 10	(Zeon Corporation, 2024)
Average density PET, g/cm^3	1.395	(Braun, 2013)
Average density of PMMA, g/cm^3	1.135	(Pita and Castilho, 2017)
Production rate of PET, kg/d	5.00×10^6	(Statista, 2023)
Production rate of PMMA, kg/d	3.33×10^5	(LX MMA, 2021)
Recycling rate of PET, %	15	(Karidis, 2022)
Recycling rate of PMMA, %	10	(Sponchioni and Altinok, 2022)

Table 2: CO_2 footprint and purchase cost associated with each type of raw material.

Material	CO_2 footprint (kg CO_2-eq/d)	Purchase cost ($/kg)
rePMMA	6.15 (Heijden, 2021)	3.60 (Ongaro et al., 2022)
rePET	0.62 (REMONDIS, 2022)	0.27 (EMB Central Office MRF, 2016)
pPMMA	8.43 (Mahmud and Farjana, 2021)	3.00 (Business Analytiq, 2024)
pPET	2.90 (Mahmud and Farjana, 2021)	0.94 (Business Analytiq, 2024)

$$\min Z_c = \frac{\sum_i \sum_j x_{ij} c_{ij} b_{ij}}{DEM} \tag{1}$$

$$\min Z_e = \frac{\sum_i \sum_j x_{ij} e_{ij} b_{ij}}{DEM} \tag{2}$$

$$\sum_j x_{ij} b_{ij} \le CAP_i \qquad \forall i \tag{3}$$

$$\sum_i x_{ij} b_{ij} = DEM_j \qquad \forall j \tag{4}$$

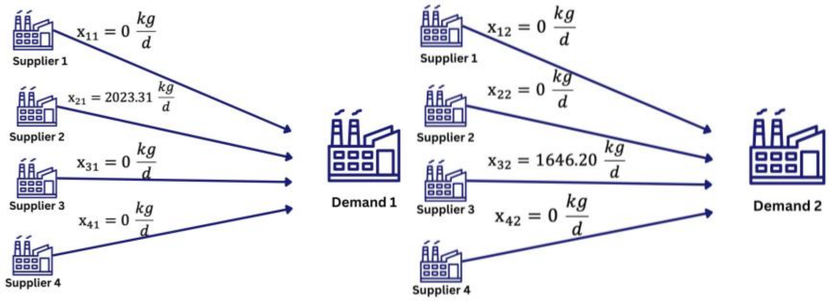
$$x_{ij} \ge 0 \qquad \forall i, j \tag{5}$$

The constraints used for the model formulation ensures that the minimum value of the objective functions satisfy the demand for the raw material, is within the capacity of the supplier and is non-negative. For instance, Eq(3) shows that the total amount sourced from supplier i is equal to or less than its capacity of production for each raw material j. The constraint described by Eq(4) ensures that the demand for raw material j from a set of suppliers is satisfied. Lastly, Eq(5) ensures that the amount of raw material j from supplier i can only be either equal to 0 or any positive integer. The system was solved using Excel Solver.

4. Results and discussion

The models developed in the study adapted the models used by Isafiade (2023) and Cruz and Tan (2022). Hypothetical data derived from industries and literature were used to demonstrate the use of the models. The problem assumes that each supplier manufactures polymers with different selling prices and carbon footprints and was solved using Excel Solver. Identification of the minimum values of the cost objective function and CO_2 emission objective functions were determined by solving one objective function at a time while the other objective function served as a system variable. Sensitivity analysis was also done to determine the effect of varying the purchase costs of the pristine materials that reflects real-world scenario on the values of the objective parameters.

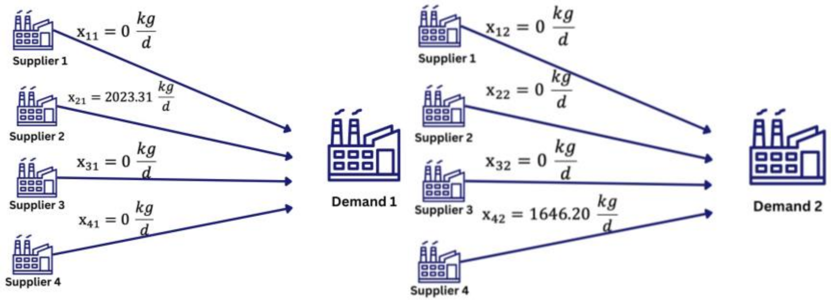
Figure 2 shows the supply chain network diagram when minimization of cost is prioritized. Using PET as raw material shows that all the polymer feed could be sourced from Supplier 2. The minimum cost per unit of product produced is 0.0546 $/d accompanied by 0.13 kg CO_2-eq/d per unit of product produced, as shown in Figure 2a. On the other hand, using PMMA will require that all the polymer feed be sourced from Supplier 3. Which shows that, when prioritizing cost, using pPMMA is more beneficial since it is cheaper than its recycled counterpart. In this case, the minimum cost per unit of product produced is 0.493 $/d accompanied by 1.39 kg CO_2-eq/d per unit of product produced, as shown in Figure 2b.



(a) *(b)*

Figure 2: Supply chain network diagram when the minimization of cost is prioritized using (a) PET or (b) PMMA as raw material.

Results for prioritizing minimization of emissions are shown in Figure 3. It was observed that having PET as the raw material will yield similar results as when prioritizing cost minimization. This indicates that in both objectives, the use of rePET is the most beneficial regardless of which objective function was prioritized in the study. When PMMA is used as raw material, Figure 3b shows that all of the polymer feed should be sourced from Supplier 4. This is due to the lower CO_2 footprint of recycled PMMA. In this case, the minimum CO_2 footprint per unit of product produced is 1.01 kg CO_2-eq/d accompanied by 0.593 $/d per unit of product produced.



(a) *(b)*

Figure 3: Supply chain network diagram when the minimization of emissions is prioritized using (a) PET or (b) PMMA as raw material

Figure 2 and Figure 3 shows the supply chain network if the cost objective and the CO_2 footprint objective was prioritized. It was observed that in both cases, the use of rePET would satisfy the demands of the microfluidic device manufacturing plant while minimizing both the CO_2 footprint and the purchasing cost. Since recycling streams for recyclable plastics such as PET are already established and readily available, rePET should be considered as an alternative to other non-recyclable thermoplastics. It is important to note, however, that fabrication technologies for microfluidic devices using hard plastics like PET mostly rely on machine-operated cutting tools. Due to this, rePET, which is not readily available in sheet form, has still not been widely used by microfluidic researchers and manufacturers. On the other hand, the additional cost from purchasing commercially available rePMMA can be offset by providing incentives to encourage manufacturers to use rePMMA. Advances in technology and infrastructure are still needed to develop an effective collection and recycling system. The models developed can be used as decision-making tools to help future manufacturers compare the environmental and economic impacts of using certain kinds of polymers.

Sensitivity analysis was done to determine the sensitivity of the models developed by determining the effect of the cost of the pristine materials on the objectives of the study. The purchase costs of the pristine materials are allowed to vary within a $\pm 1.0\%$ range of the original purchase cost. Results indicate that only the scenario where cost was minimized using PMMA changes with change in the cost of the pristine material. However, despite the change in the value of the minimum cost, the analysis revealed that it is still more beneficial to opt to source all PMMA from Supplier 3 when prioritizing cost for the range considered in the study.

Results of this study are consistent with the study of Ongaro et al. (2022), which also recommends the use of recycled plastics as a sustainable solution to reduce the carbon emissions and plastic pollution caused by these devices.

5. Conclusion

This study presents two optimization models developed considering capacity, demand, topological, and non-negativity constraints. The study can be used as a decision-making tool when selecting suppliers. The approach used for optimization can be used to compare different suppliers and types of polymer feed and can be further extended to evaluating other sustainable materials such as biodegradable polymers and paper with regards to different objective parameters as demonstrated in this study. Results indicate that the current capacity of plants processing rePET is sufficient to satisfy the demand for the polymer feed used in microfluidic manufacturing plants. Using rePET for the manufacture of microfluidic devices corresponds to the minimum cost per unit of product of 0.0546 $/d, accompanied by emitting 0.13 kg CO_2-eq/d per unit of product. These results indicate that recycled polymers for the microfluidic industry can be a suitable alternative to other unsustainable materials for mass production in terms of their environmental and economic impacts. However, the development of robust standards regarding the collection, recycling, use, and disposal of the polymer should still be studied. Finally, it was demonstrated that the models developed are not susceptible to changes in the purchase cost of the pristine materials.

Future work can focus on developing a more detailed supply chain network by considering the emissions and costs attributed to each raw material used from the collection to the disposal of microfluidic devices and developing standards on the recovery and recycling of polymers for disease diagnosis and monitoring. Reducing the two objective functions into one equation using multi-objective optimization approaches can also be done. Other considerations may include minimizing the water footprint and energy requirements, as well analyzing the emissions and costs associated with the use of other biobased materials.

Nomenclature

i - index for supplier i

j - index for raw material j

Z_c - purchase cost per unit of product produced per day, $/d-unit

Z_e - total CO_2 footprint per unit of product produced per day, kg CO_2-eq/d-unit

min Z_c – minimum purchase cost per unit of product produced per day, $/d-unit

min Z_e – minimum total CO_2 footprint per unit of product produced per day, kg CO_2-eq/d-unit

DEM_j - demand for raw material j, kg/d

CAP_i - total capacity of supplier i for raw material j, kg/d

x_{ij} - amount of raw material j to purchase from supplier i, kg/d

c_{ij} - purchase cost of raw material j from supplier i, $/kg

e_{ij} - CO_2 footprint of raw material j from supplier i, kg CO_2-eq/d

b_{ij} - binary variable (1 if supplier i can supply raw material j to the microfluidic manufacturing plant, 0 otherwise.)

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