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A Game Theoretic Approach for Plastic Life Cycle Assessment

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Plastic production and its end-of-life management pose a significant environmental footprint. The mitigation strategies of the plastic industry are comparatively attainable than the other hard-to-abate sector. However, the involvement of different stakeholders is needed. The life cycle analysis proposed in this study allocated the environmental footprint to stakeholders based on the game theory concept. It addresses the limitation of previous approaches that do not guarantee the stakeholders from different stages will participate in the initiatives with the lowest net environmental footprint due to the dissatisfaction or imbalance in the allocated unburdening footprint (benefit) and burdening footprint. The applicability of the proposed approach is demonstrated through a plastic recycling case study. An allocation of 82 % of environmental benefit to the producer, 14 % to the manufacturer, and 4 % to the user are suggested to achieve efficiency (lowest external interference) and stable cooperation (participation in recycling). This work serves as an initial assessment in demonstrating the integration of the game theory concept in environmental footprint allocation or Life Cycle Assessment.

1. Introduction

Life Cycle Assessment (LCA) and environmental footprint assessment are the fundamental methods to measure the sustainability of mitigation and reduction strategies. The quantitative measurement serves as an indicator in monitoring and supporting the implementation of sustainability policies. It is also helpful as a basis for incentives and taxation planning (Huang et al., 2022). LCA application has been common with plenty of significant advances, and it has been recognised as a valuable tool for evaluating the environmental impacts of products across their entire life cycle (Nickel, 2023). However, there are still research gaps that need to be addressed further to improve the accuracy and effectiveness of the identified measurement. One of the challenges has been the LCA allocation (Ekvall et al., 2020) which is subject to different interpretations with no general agreement on the best approach (Wilfart et al., 2021). LCA allocation refers to a step in partitioning the environmental impacts that have multiple inputs or outputs on its part or activities.

Although a hierarchical process and avoidance are recommended by ISO 14044 (2006), LCA allocation and system expansion is unavoidable when (a) two or more products or co-products are produced in a process and (b) when involving the end-life stages where the post-consumer product in a life cycle is recovered as a resource for the next life cycle. The environmental impacts and resource use in the entire life cycle will be attributed to specific stages or products by applying LCA allocation, which provides insight into the environmental footprint of different components or processes. For instance, Rice et al. (2017) applied different allocation methods to quantify the greenhouse gas from livestock systems with multifunctional processes (e.g., milk and meat from dairy cows), highlighting the potential bias to one of the products by different methods. Malabi et al. (2020) discussed the need for LCA allocation in the context of the built environment, which has buildings, components, and materials embedding multiple uses (multi-cycling) and life cycles. Hermansson et al. (2020) applied LCA allocation focusing on lignin utilisation and indicating how important the choice of allocation method is in assessing lignin as a substitute for other raw materials. The LCA allocation has to be conducted under such discussed circumstances despite the fact that the allocation rules could be subject to different interpretations (Wilfart et al., 2021). Given the urgent global concerns surrounding plastic pollution and waste management

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(Kousemaker et al., 2021), the research on environmental impact allocation is particularly crucial for the life cycle of plastics, especially its end-of-life management. The life cycle of plastic involves multiple stages (raw material acquisition, production, use and disposal etc.) and often more than one life cycle, especially under the current promotion of recycling initiatives. By distributing environmental impacts to relevant stakeholders, their responsibility can be emphasised for proper mitigation actions in achieving a sustainable circular economy.

Allocation of environmental impacts between different product systems in LCA is the common means to account for the recycling (or end-of-life) stages. It has been discussed for many years, but there is no consensus on different approaches in the literature. The challenges are achieving (a) a representative and fair burden and credit distribution and (b) avoiding double-counting (Civancik-Uslu et al., 2019). LCA allocation is a dynamic process (Shimako et al., 2018) with different modelling approaches, providing a different degree of motivation to recycle and use the recycled material. Figure 1 summarises the existing allocation methods and their strength and weakness by Fan et al. (2022). If a less suitable method is applied, it could create a loophole to manipulate the actual environmental performance of a product or service and, eventually, less suitable mitigation strategies. An appropriate method encourages all the stakeholders to select the alternatives with the lowest net environmental footprint. However, defining "fair" or "stable" allocation is challenging due to subjectivity, with still no agreement. A previous study by Fan et al. (2023) highlighted the drawbacks of several methods and highlighted the importance of responsibility-based allocation instead of the life cycle stages, which are in the cases of all of the mentioned methods in Figure 1. The environmental performance allocation, especially for multiple-cycle recycling that involves a broader number of stakeholders, assembles the cooperative game theory problem. However, it has yet to be assessed from this perspective, and cooperative game theory has not been commonly applied to environmental footprint allocation compared to the cost allocation problem. One of the closest studies has been Rehberger and Hiete (2020) development. The game theoretic approach based on the concept of the Core (Shapley, 1955) and the Shapley Value (Shapley, 1953) is followed in assessing the wood cascade scenario. However, the environmental impact allocation is by life cycle instead of distribution among stakeholders.

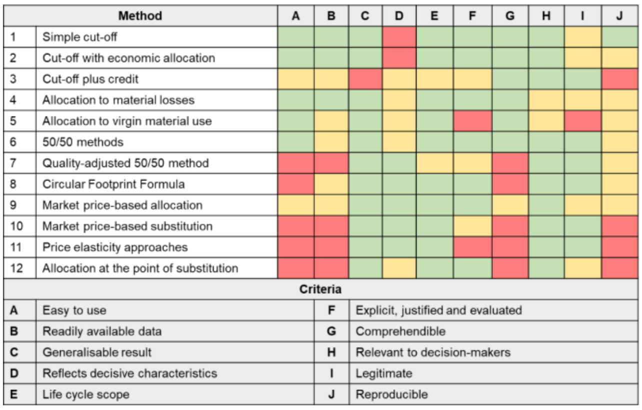

Figure 1: LCA allocation methods (Ekvall et al., 2020). Light green =fulfilled, Light yellow =partially, pink =not fulfilled. Diagram adapted from Fan et al. (2022)

This study aims to develop an LCA allocation method based on a cooperative game theoretical approach, which incentivises all stakeholders to choose alternative options with a lower environmental performance by allocating the environmental footprint. A crucial consideration based on cooperative games is the stability of distribution schemes, which is guaranteed by the Core (if it exists) (Shapley, 1955). The Least Core (Drechsel and Kimms, 2010), one of the methods based on the cooperative game theoretic applied in this study, represents the smallest core within a cooperative game, which is preferred by all stakeholders due to its stability. The method could ensure that a) all the gains from the grand coalition could be distributed to the related stakeholders. b) each stakeholder involved in the grand coalition could get certain benefits gained from the cooperation. Such allocation based on the roles and responsibilities concept could empower stakeholders to improve efficiency according to the defined expectations or goals and minimise the loophole, which could encourage less sustainable yet economically feasible solutions.

2. Method

The Game Theory approach applied in this study is based on the concept of the Least Core method (Drechsel and Kimms, 2010), computational by Linear Programming with modification in the equations to fit our specific assessment. This method, as shown in Eq(1), is suitable to apply to cases where the monotonicity and superadditivity (Lozano et al., 2022) requirements are not met, in contrast to the Shapley Value method, which relies on such assumptions in the allocation. For example, when the gains of the coalition PM is less than the non-coalition, $P + M$, the coalition is not likely to form automatically unless an external interference such as ε is added to $P + M$, and make it lesser than PM. The reason for applying external interference is to drive the formation of the coalition when the coalition (e.g., participating in recycling) would offer a higher benefit than the conventional approach (e.g., landfill). However, not all stakeholders are motivated to participate voluntarily due to the unfavourable or imbalanced initial allocation of environmental footprint (e.g., based on the simple cut off method). This is the basis of the formulation of Eq(1) where the ε is minimised while meeting the constraints as stated in Eq(1.1) – Eq(1.4). This approach ensures efficiency where the environmental benefit is achieved with minimal external interference, such as economic cost. It also proposes a stable solution where no coalition members can gain more environmental benefits by leaving the coalition and forming a new one.

$$\min\{\varepsilon: \varepsilon \geq PM - P - M,\ \varepsilon \geq PU - P - U,\ \varepsilon \geq MU - M - U\} \quad (1)$$

$$PMU = P + M + U \quad (1.1)$$

$$P_0 \geq P > 0 \quad (1.2)$$

$$M_0 \geq M > 0 \quad (1.3)$$

$$U_0 \geq U > 0 \quad (1.4)$$

P, M, U represent the allocated environmental footprint (e.g., Greenhouse Gas, GHG) of different stakeholders after the cooperation, which are the dependent variables to be determined. P_0, M_0, U_0 are the original environmental footprint of different stakeholders before the cooperation (non-coalition). PM is the environmental footprint of the coalition formed (e.g., collaborate and participate in recycling) by P and M, PU is the environmental footprint of the coalition formed by P and U. MU is the environmental footprint of the coalition formed by M and U. Eq(1.2-1.4) are the constraints of the assessed case study where the allocated environmental footprint of the stakeholders should be higher than 0 and lower than its original environmental footprint before cooperation. Table 1 shows the illustrative case study assessed in this study. Three stakeholders, the material producer, product manufacturer, and user, are involved in the assessed plastic bottle case study.

Table 1: The data input and description of the assessed case study

Coalition	Value (kg CO_2eq)	Remarks	Reference
P_0	2,735.74	GHG of material (polyethylene terephthalate) production with P as producer (Stakeholder A)	
M_0	333.5	GHG of the product (bottle) manufacturing with M as the manufacturer (Stakeholder B)	Fan et al. (2023)
U_0	105	GHG of disposal to the landfill with U as a user (Stakeholder C)	
PM	3,069.24	Cooperation between P and M – recycling cannot occur without U disposing of the waste appropriately.	
PU	462.50	Cooperation between P and U. The assumption in material saving is that recycled material could replace 95 % of raw material[a]. The burdening footprint is accounted for based on mechanical recycling[b]	Broeren et al. (2022)[a] Fan et al. (2023)[b]
MU	659.21	Cooperation between M and U. The burdening footprint is accounted for based on mechanical recycling	Fan et al. (2023)
PMU	796.00	The grand coalition – Cooperation among P, M and U. The assumption in material saving is that recycled material could replace 95 % of raw material[a]. The burdening footprint is accounted for based on mechanical recycling[b]	Broeren et al. (2022)[a] Fan et al. (2023)[b]

3. Result and discussion

The proposed game theory-based approach is applied to a case study described in Table 1. Figure 2 shows the environmental footprint results of recycling and non-recycling options, which could affect the decisions of stakeholders A, B, and C on whether to cooperate in recycling or not to cooperate. The preferable decision for society should be based on the net environmental performance (unburdening minus burdening). By comparison, the recycling option has a lower net environmental footprint (green bar minus red bar) than the non-recycling option (grey bar). However, the preferable option is not necessarily in favour of all the stakeholders as some of them might have to bear the burden of recycling processes without having the environmental benefit from the use of recycled materials.

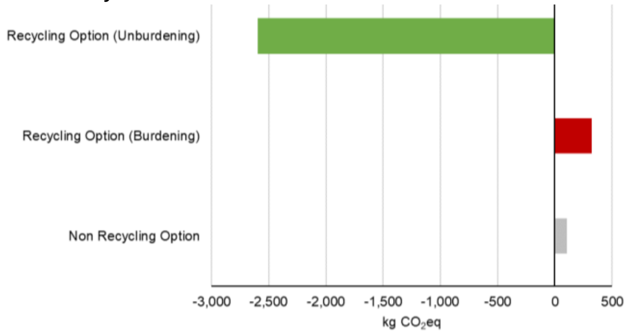

Figure 2: The environmental footprint (kg CO_2eq) of two end-of-life management options. The recycling option is assumed to be mechanical recycling, non-recycling is referred to as disposal (see Table 1). The negative value refers to the emission savings contributed by the virgin material replacement

Figure 3 shows the breakdown of the environmental footprint for the life cycle, from material production to product manufacturing and end-of-life management, assigned to different stakeholders. The environmental footprint is accounted for based on the most common accounting, the simple cut-off concept. Stakeholder A (Producer) and Stakeholder B (Manufacturer) are likely to participate in recycling as it offers a lower or at least the same environmental footprint compared to the non-recycling option. However, based on the current accounting, Stakeholder C will likely refrain from participating in recycling as there is no environmental benefit (and incentive) to cooperate. The environmental footprint of Stakeholder A and Stakeholder B could only be reduced with the participant of Stakeholder C by sharing part of the benefits gained from using recycled material with Stakeholder C.

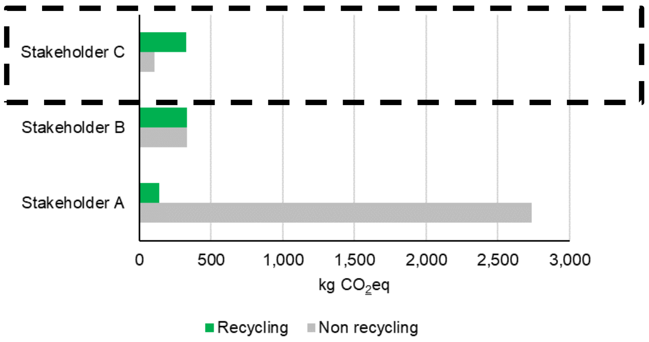

Figure 3: The environmental footprint of different stakeholders based on the typical accounting concept – the simple cut-off method

Figure 4 shows the environmental footprint assigned based on the proposed method. Referring to the green bar (allocated benefit, reported in negative value), 82 % of the total net benefit of recycling (1,941.74 kg CO_2eq) is assigned to Stakeholder A, 14 % (332.5 kg CO_2eq) to Stakeholder B and 4 % (104 kg CO_2eq) to Stakeholder C. The allocation is limited by a non-negative value (> 0) for the net environmental footprint of stakeholders (blue dot). A negative value could be expected if this constraint is removed. The constraint is introduced to minimise the confusion about the negative value that represents environmental saving (Fan et al., 2020), which could be interpreted wrongly as more consumption or production will bring more benefit. The wrong interpretation will discourage waste reduction and assume that recycling has more environmental benefits than waste reduction. The blue dot in Figure 4 shows the final environmental footprint of stakeholders. All the blue dots have a lower value than the black dot, which represents the non-recycling option, indicating that recycling is indeed a more environmentally friendly option. The new accounting motivates all the stakeholders to work together and participate in the recycling option by reallocating the unburdening. It should be noted that allocation is not changing the total environmental footprint of all stakeholders but the distribution of environmental footprint among stakeholders.

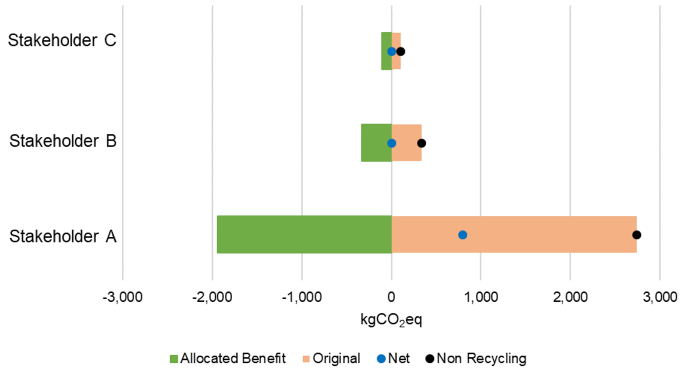

Figure 4: The environmental footprint of different stakeholders based on the proposed game theory-based accounting—the Least Core. Original = environmental footprint before cooperation (without recycling). Allocated benefit = the environmental saving allocated after cooperation. Net = the environmental footprint after recycling

The proposed allocation could encourage stakeholders to play their part and make efforts to recycle from the view of environmental sustainability, as their cooperation could lead to lower environmental impacts. It could also provide an economic motivation if incentives or taxation such as carbon taxes (Ahmadi et al., 2022) are introduced. This is important as recycling could hardly happen if one of the stakeholders is not cooperating. Extended producer responsibility (EPR) (Favot et al., 2022), which suggests the critical roles of other stakeholders beyond the consumer, has been highlighted as an effective mitigation strategy. The involvement of the producer in taking responsibility for the waste generated at its end of life could motivate redesign for an easy-to-separate product (Dumée, 2022). The EPR scheme could also motivate producers to use recyclable materials (Law and Narayan, 2022). Larrain et al. (2022) stated that although the EPR schemes have increased the amount of separately collected plastic waste, the effectiveness in increasing the recycling rate is still yet to be achieved due to the structure of the recycling industry. The demonstrated case study shows the applicability of the proposed method in promoting waste treatment alternatives with lower (or lowest) net environmental footprint by ensuring cooperation among the stakeholder for the environmentally friendlier alternative in their own individual interest and overall. It could contribute to the restructuring of the recycling industry, particularly in planning economic interventions proposed by Larrain et al. (2022).

4. Conclusions

The proposed cooperative game theory-based approach shows the driving potential in promoting the alternatives (processes) with a lower net environmental footprint to the stakeholders. The allocation method follows the least core concept of minimising the cost required to form a grand coalition without compromising the individual and overall interest. By allocating 4 % (104 kg CO_2eq) of the unburdening footprint, originally assigned to Stakeholder A, to Stakeholder C, and allocating 14% to Stakeholder B, all stakeholders are motivated to participate in the cooperation to recycle. In comparison to the simple cut-off method (the conventional method by stages), Stakeholder C will have no interest in joining the coalition due to the higher environmental burden incurred, and all the environmental benefit of recycling (the use of recycled material) is allocated to the other stakeholders. The absence of stakeholder C will hinder the recycling process, which is supposed to contribute to a lower net environmental footprint. Future work will evaluate the suitable policy, including its elasticity, and extending the assessed footprints (beyond CO_2eq), the number of stakeholders involved in the multiple cycle or cascade recycling and the other game theory approaches. The applicability of the identified footprints could be further enhanced by economic instruments, such as adding taxes to the allocated environmental footprint, as not all of the stakeholders are interested in achieving a lower environmental footprint. It is also worthwhile to consider expanding the model to other domains. For instance, exploring the potential of applying similar allocation methods in areas beyond solid waste recycling to encourage stakeholders to be involved in sustainable circular economy initiatives.

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