DEVELOPING NETWORK MODELS OF INDUSTRIAL SYMBIOSIS

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Abstract*:* This study aimed to examine whether industrial symbiosis (IS) could be applied on the Point Lisas Industrial Estate (PLIE) in Trinidad and Tobago for the reuse of process carbon dioxide (CO_2) within the estate. To acquire optimal networks, initially simplified petrochemical complexes were posed as transportation-type problems and solved with linear programming and mixed integer linear programming techniques. Network models were developed in which process CO_2 was optimally allocated between existing ammonia (sources) and methanol plants (sinks) on the PLIE. Multiple scenarios were considered including possible restrictions on CO_2-transfers from sources or to sinks. The functionality of the developed network models was confirmed with three test cases. Multi-objective optimization (MOO) was applied to a fourth model, with a secondary objective of minimising operational network costs. In the second stage, an enterprise input-output (EIO) model was developed from both process engineering and economic data. It incorporated performance indicators, which had been proposed in the literature, to calculate the level of industrial symbiosis and benefits - based on "the three pillars of sustainability" - realized in the representative industrial network. On the representative petrochemical network, 17% of the process CO_2 emissions were reused in chemical manufacturing and the eco-connectance, which is one measure of the level of IS, was determined as 1.33. This demonstrates the presence and level of IS in the industrial park. Furthermore, optimized flow networks were created, with and without a CO_2-reusing propylene carbonate plant. MOO was used to determine how to add the CO_2-reusing plant to the industrial network to minimize both CO_2 emissions and implementation costs. The addition of a CO_2-reusing plant reduced the CO_2 emissions by 1.1%, demonstrating there is scope for improving the existing IS network.

Keywords: *Industrial symbiosis, Carbon dioxide utilization, Multi-objective optimization.*

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1. Introduction

Industrial symbiosis (IS) occurs when wastes are reused in a network of separate commercial operations, so resources remain in productive use for longer and the need for virgin resources is reduced. IS is considered an effective approach to waste management [1] delivering both economic and environmental benefits. Here carbon dioxide (CO_2) was selected as the resource, whose exchanges would be modelled, since waste CO_2 emissions contribute significantly to global warming. Waste CO_2 could be monetised by treating it appropriately and using it as a feedstock in a neighbouring chemical plant – i.e. CO_2 utilization. The majority of the petrochemical industry in Trinidad and Tobago (T&T) is housed in the Point Lisas Industrial Estate (PLIE), which contains several ammonia and methanol plants. This study sought to examine how CO_2, produced on the PLIE, could be reused within the estate through exchanges between various petrochemical plants and secondly to assess the level of industrial symbiosis occurring in the industrial park. The aim was to develop a simple representative model of this nascent symbiotic industrial system, in terms of CO_2 exchanges at PLIE. Our model was then used to perform an integrated process engineering and economic analysis to quantify the level of exchanges and benefits beneath "the three pillars of sustainability" and thence determine the scope for improvement.

In part because there are currently no legislative restrictions on CO_2 emissions in T&T, PLIE is not thought of locally as being a bastion of progressive industrial ecology. Although PLIE was not originally planned for industrial symbiosis, waste CO_2-streams have been shared amongst plants since 1983 [2] when the Trinidad and Tobago Urea Company plant was commissioned to use waste process CO_2, ammonia and some facilities from a nearby separately-run Fertrin ammonia plant to produce urea. The current "self-organized" state of sharing of waste streams developed over the years, rather like early sharing at archetypical eco-industrial park (EIP) at Kalundborg, Denmark [3], in that each additional exchange in the park was an independently negotiated business deal, which was established only if expected to be commercially beneficial.

Few studies have been conducted on the application of industrial symbiosis in T&T. In 1998, four companies in PLIE were evaluated in terms of waste management and the study [2] found that there was potential for the waste reduction by reusing and recycling, although the study did not consider CO_2 as a waste resource. An inventory of CO_2 resources in Trinidad was compiled in 2008 [4], in which the emissions from the chemical plants at PLIE were calculated with appropriate stoichiometric ratios for the relevant reactions.

2. Methodology

There is no standard methodology for measuring the level of IS in an industrial network or park. Some authors use economic, environmental and social indicators to show how IS improves a park by comparing the indicators for the park with and without IS activities. However, this does not give an actual measure of the level of IS. Some of the proposed measures for industrial symbiosis are eco-connectance, by-product and recycling rate [5], eco-efficiency [6], environmental impact momentum [7] and technical exchange efficiency [8]. A comprehensive list of indicators that can be used when considering industrial symbiosis [7] was published in 2016.

Material flow analysis (MFA), enterprise input-output (EIO) tables, life cycle analysis (LCA), eco-efficiency, eco-connectance and waste recovery are some of the tools which have been used in reducing waste in a system in a sustainable manner. MFA, LCA and eco-efficiency are not preferred since they do not consider the whole picture.

In this study, the process CO_2 emissions for selected plants were evaluated based on reported information about the various technologies employed and the plant capacity. Flue-gas CO_2 emissions were excluded from this study, because of the much lower CO_2-purity of these streams. Potential means for improving the sharing and reusing of CO_2 to create shared value, that is the IS level, were considered.

Firstly, representative network models were developed in which process CO_2 was optimally allocated between existing ammonia (sources) and methanol plants (sinks) on the PLIE. The formation of a feasible IS network can be treated, in its simplest form, as a transportation problem. A transportation problem involves optimization of the supply of a commodity from several potential sources to meet demands for the commodity from different destinations or sinks. This optimization typically involves minimising overall transportation cost from sources to sinks. Using an approximate linear model for the petrochemical complex network, linear programming techniques, such as the simplex method, can be employed to find an optimal solution.

Optimization of a petrochemical complex was computed in the chosen modeling environment, MATLAB® (ver. R2019a) by considering the amount of waste CO_2. Single objective optimization was carried out to minimize waste CO_2 using linear programming (LP) and mixed integer linear programming (MILP). Three test cases were examined in which the total process CO_2 available from the sources was greater than the total CO_2 demand, less than the total CO_2 demand and equal to the total CO_2 demand respectively. For the test case in which total CO_2 demand exceeded total process CO_2 supply, fresh supply sources were incorporated in the optimized network. For the test case in which total process CO_2 supply exceeded total CO_2 demand, dummy sinks which correspond to either emitted or stored process CO_2 were incorporated in the optimized network.

In conjunction with the three test cases, multiple scenarios were considered involving possible restrictions on CO_2-transfers from sources or to sinks, using binary variables with MILP. Restrictions may be necessary to prevent the uneconomical splitting of streams from an initial source through numerous pipelines to various sinks. Restrictions may also be imposed to eliminate the establishment of impractical pipeline networks between sources and sinks. For instance, the number of pipelines, which may be connected to a single sink, may be limited by space and safety considerations.

For the LP and MILP cases, the dual-simplex algorithm and the branch and bound algorithm were respectively utilized. Finally, multi-objective optimization (MOO) was applied using the genetic algorithm in the MATLAB function *gamultiobj* to minimize the amount of waste CO_2 and the secondary objective of minimising operational network costs. The cost of CO_2 transfer between plants was assumed to be \$1.04 per tonne of CO_2 transferred. In the process the Pareto front was generated. US dollars were used for all prices and costs in this study.

In the second stage, ecologically-enhanced EIO analysis was applied to similar ammonia-methanol flow networks using the software tools from the first stage, while various IS measures and sustainability indicators were evaluated. Nine petrochemical plants in PLIE were selected as being representative of the industrial park. The plants considered were ammonia, methanol and urea. Later a CO_2-reusing plant for propylene carbonate was included in the flow networks. Additionally, more detailed modelling of the levelised CO_2-transportation costs [9] were included and MOO was used again to reduce transportation costs whilst maximising the CO_2 flow between plants. The flows from source to sinks were constrained by the CO_2 requirements of the sinks and in this case, the transportation cost was not constant but was dependent on the flow of CO_2 and the distance between the sources and sinks.

An EIO table for the industrial park was developed in MATLAB. It is assumed that there is only one main product for each process. For each process three constant matrices: a technical coefficient matrix, a resource intensity matrix and a waste intensity matrix are created from typically observed or calculated values for a specified process technology. Therefore, if process demand is changed, the outputs from the process would change correspondingly.

Three EIO tables were developed for a *base*, *current* and *proposed* case. The base case was one in which there was no symbiosis occurring and this was used as a baseline in the study. In the current case, the existing symbiosis was shown and in the proposed case, a CO_2-reusing plant was added to the industrial park. Material and energy flows for the base and current cases were estimated on the basis of the average production rate of the various plants over a three-year period. There are several ways in which CO_2 can be utilized, and various CO_2-consuming plants were considered, such as manufacturing processes for biofuels [10], propylene carbonate [11] and polyethercarbonate polyols [12]. Because many of these CO_2-consuming processes are emerging technologies, it is difficult to obtain reliable information about them. The propylene carbonate plant was selected based on the feasibility and the availability of published performance information. Demirel's [11] data was used to simulate and cost the plant in Aspen Plus® (ver. 10). For all the cases, the direct and total coefficients were determined. Besides the evaluation of the direct and total coefficients, the level of industrial symbiosis occurring in the various scenarios was evaluated using various industrial symbiosis measures and sustainability indicators.

In this study, the focus was on the exchange of process CO_2 amongst the plants. The CO_2-rich process streams, which originated from the ammonia plants, were supplied to the sinks at an assumed CO_2-purity of 99 wt%. The price of CO_2 supplied to the sinks was determined from the calculation of the levelized cost of CO_2 transportation and an assumed raw material cost for CO_2, to buttress the mutualism of the IS. Consequently, pipelines from the CO_2 sources to sinks were evaluated. The equation developed by McCoy and Rubin [13] was used to estimate the diameter of the pipelines required for the sink flows. The costs associated with purification and compression of the CO_2 were taken into consideration and together with the diameter and length of the pipeline, these were used in the determination of the levelized cost of CO_2 transportation (\$ tonne^{-1} of CO_2).

3. Results and Discussion

In the preliminary stage, the functionality of the approximate linear model for the petrochemical complex network models was confirmed with three test examples. The network generated from solving a simple transportation problem is shown in shown in Fig. 1. Thus, simple linear programming techniques can be used to optimize CO_2 allocation from ammonia to methanol plants, situated in an industrial cluster.

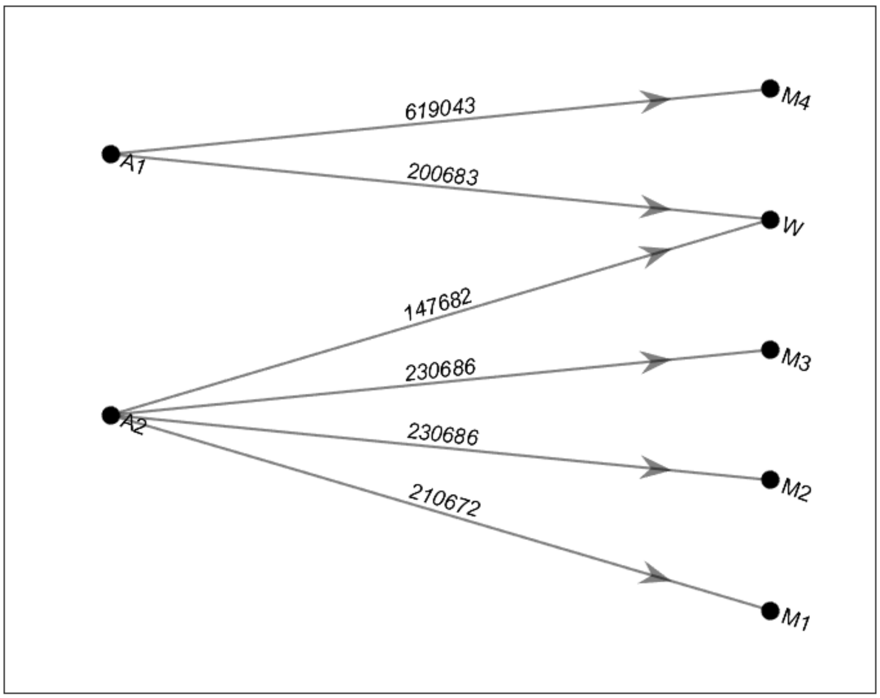

Figure 6: Optimal CO_2 allocation (t/y) for simple transportation-problem example.

Key: A – ammonia plant; M – methanol plant; W – waste.

Based on the simple linear transportation problem to minimize waste CO_2 a multi-objective model was developed, with an additional objective of minimising network operating costs, which are dependent on the quantity of CO_2 being transferred through a potential source-sink link. When MOO was applied the CO_2 emissions obtained for the optimal allocation, coincided with the minimum emissions obtained when only the single objective function was considered - i.e. to minimise CO_2 emissions. However, the optimal networks for the single and multi-objective functions differed.

Hence, having shown that the available software tools could be manipulated, in the second stage, the process CO_2 emissions for selected plants were evaluated based on reported information about the various technologies employed and the plant capacity. Three test cases were considered. In the base case, it was assumed that there were no exchanges amongst the plants. The values obtained for the current case show that there is some level of industrial symbiosis occurring and those for the proposed case indicate that the addition of a plant which utilizes CO_2 as a raw material can lead to increased levels of industrial symbiosis.

For this study, it was proposed that a propylene carbonate plant, which had a capacity of approximately 10,500 kg/h and consumed 4,500 kg/h of CO_2, be introduced to the PLIE. The capacity was determined in accordance with the current market for propylene carbonate. The economic feasibility of such a plant is highly dependent on the price of the catalyst since this was a very expensive component of the costs.

Material and energy flows were calculated for the input and output of the plants in the industrial park. These flows were then used to generate the EIO tables for the base, current and proposed cases. The cases showed that from the ammonia plants, there were approximately 416,300 kg/h of nearly pure CO_2 being produced. The EIO for the current case indicated that approximately 17% of the CO_2 was reused in methanol and urea plants in the industrial park and the remainder was vented to the atmosphere. Introducing a new plant, which reused CO_2 from the industrial park, increased the CO_2 usage by approximately 1.1%, thereby reducing the amount of CO_2 emitted to the atmosphere. From the EIO table, the direct and total coefficients were determined. Analysis of the direct coefficients showed that the largest direct coefficient for the by-products and waste was attributed to the nearly pure CO_2 being emitted from the ammonia plants. The core EIO model gives an idea of the material and flow exchanges within the network, but does not measure the level of industrial symbiosis. The calculated values for the performance indicators, used to measure IS in these three cases, are shown in Table 1. The values obtained for the current case show that there is some level of industrial symbiosis occurring and those for the proposed case indicate that the addition of a plant which utilizes CO_2 as a raw material can lead to increased levels of industrial symbiosis.

Table 3: Industrial Symbiosis Performance Indicators.

Industrial Symbiosis Indicator	Base	Current	Proposed
Eco-connectance	0	1.33	1.80
Environmental impact momentum	0	0.21	0.22
Fraction of waste CO_2 utilized	0	0.17	0.18

Attention was then focused on minimizing the flow of waste CO_2, which would not be reused, and minimizing the CO_2-transportion costs for the current and proposed cases. The levelized cost of transporting the CO_2 was calculated and hence pipelines from the CO_2 sources to the sinks were considered. The transportation costs of CO_2 ranged from \$9 per tonne to \$50 per tonne of CO_2. The higher end of the costs was attributed to smaller flows in the pipelines and hence due to a fixed cost recovery period, the price would consequently be higher. It should be noted that the costs obtained were derived from a fixed flow in the pipeline and did not take into account the change in the flow rate and the cost. This was done to ensure that the optimization model remained linear. According to literature, there is no fixed cost for CO_2 since it is dependent on the purity of CO_2, distance and the state in which the CO_2 is transported.

Various optimization cases were considered using the current and proposed data. In the first scenario, minimization of waste CO_2 was carried out. MILP and LP were used to solve the optimization models for the base and proposed cases. Results from the LP case with the current data indicated that the CO_2 from two out of the five plants should be sent to the CO_2-consuming sinks. The MILP results differed, indicating that CO_2 from three out of the five plants should be sent to the sinks. For the proposed cases, similar results were obtained. It is suggested that some flows be sent from each plant since the existence of a plant venting all its CO_2 to the atmosphere would increase the environmental burden for that particular plant. For all the cases, the waste CO_2 remained the same but the allocations differed (see Table 2).

Table 2: Summary of Optimization Values

Objective	Optimization Method	Units	Current Case	Proposed Case
Minimise CO2 emissions	LP and MILP	t/h	345	340
Minimise cost	LP	Million $	11.5	13.3
	MILP		11.2	13.3
Dual	MOO	t/h	345	340
		Million $	11.4	13.6

The optimal annual cost for the current case was $11.2 million per year and $13.3 million per year for the proposed case when MILP was used. It is evident that in the current case, the transportation cost for CO_2 is less since there are less sinks which require CO_2. It should also be noted that for the proposed case, there would be some additional expenditure in constructing and maintaining the propylene carbonate plant. MOO to minimize the CO_2 waste and cost was also performed for both cases. The optimal CO_2 allocation for the current case based on the dual objectives, is shown in Fig. 2.

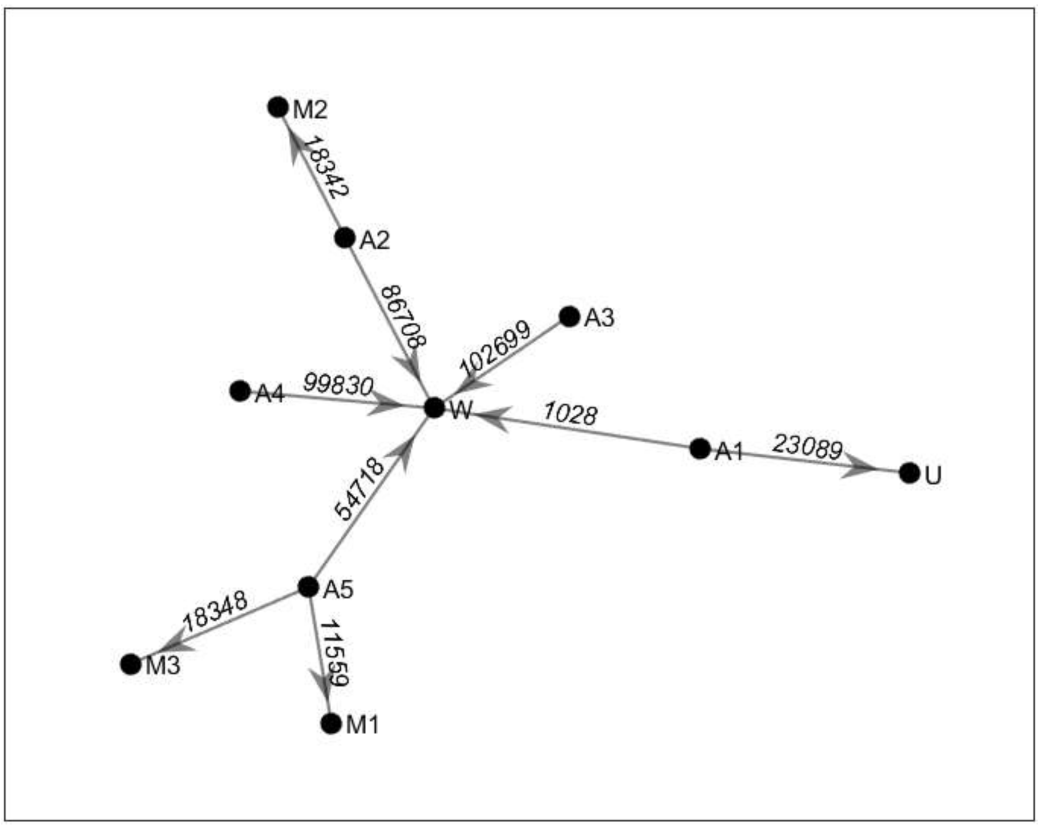

Figure 7: Optimal network for current case showing inter-plant CO_2 flows (kg/h).

Key: A, M & W – see Fig. 1; U – urea.

The equivalent optimal network for the proposed case is shown in Fig. 3. The annual costs for each case were $11.4 million per year and $13.6 million per year, respectively.

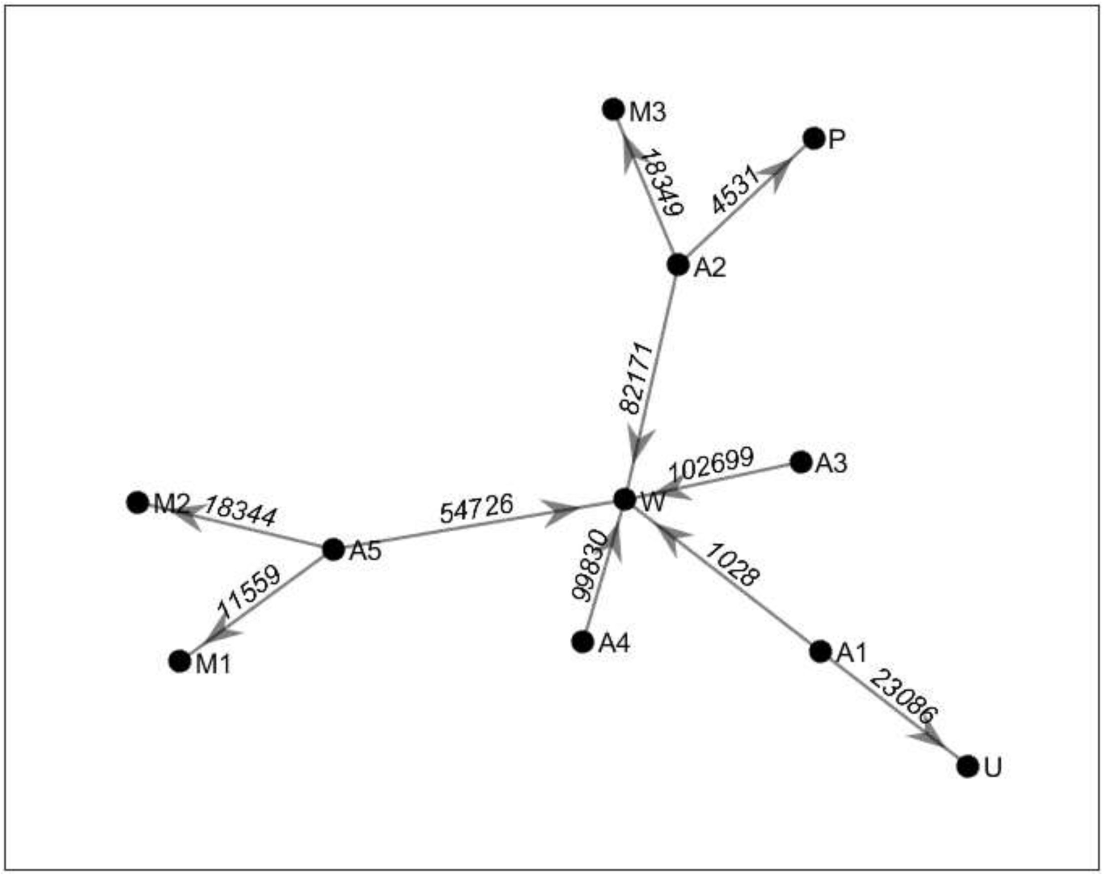

Figure 8: Optimal network for proposed case showing inter-plant CO2 flows (kg/h).

Key: A, M, & W – see Fig. 1; U – see Fig. 2; P – propylene carbonate.

To further assess the optimized cases obtained by MOO, sustainability indicators were evaluated (see Table 3). The eco-efficiency was determined as a ratio of the annual production to the amount of CO_2 used. The new plant led to a reduction in the overall CO_2 emissions thereby increasing the amount of CO_2 being reused. Addition of the propylene carbonate plant resulted in a decrease in eco-efficiency. Nevertheless, it would lead to an increase in jobs and would create an increased level of industrial symbiosis in the industrial estate.

Further work may investigate the actual linkages amongst the plants and determine the capacities of the existing pipelines. Additionally, exchanges of other materials and energy from the industrial park need to be included to get a fuller picture of how industrial symbiosis is being and could be put into practice. The EIO analysis indicates 17% of the process CO_2 emissions is being reused in chemical manufacturing, so whilst some of the remainder may being reused in technological applications (e.g. food and beverage), that means the order of 16,500 t/d of high-purity CO_2 could be available for other CO_2 utilization options. It would also suggest that a 'mimic men' [14] attitude to addressing CO_2 capture and reuse, which first focusses on capturing low-purity flue-gas CO_2 emissions at PLIE, would be probably misguided.

Table 3: Sustainability Indicators.

Indicator	Sustainability Dimension	Units	Current Case	Proposed Case
Eco-efficiency	Environmental	-	10	9.5
CO_2 emissions	Environmental	t/h	345	340.5
Resource efficiency	Environmental	t/h	0	4.5
Relative change of CO_2 recycling	Environmental	%	17	18
Total Capital Investment (CO_2 transport and equipment)	Economic	Million $	14.7	18
Total Capital Investment (new plants)	Economic	Million $	-	17.2
Profit as a result of IS activities	Economic	Million $/y	3.5	(3.7+3.6)
Job Creation	Social	-	No	Yes
Creation of Industrial Symbiosis	Social	-	4	5

4. Conclusions

This research shows Trinidad's PLIE has some of the characteristics of an EIP. The model indicates that current partners in the on-going industrial symbiosis at the PLIE ought to be achieving sustainable benefits. Operating costs were found to depend on the amount of CO_2 exchanged. The estimated levelized cost for CO_2 transportation ranged from $9 per tonne to $50 per tonne of CO_2. While introducing a CO_2-reusing process into a network increased the transportation cost, it reduced the amount of CO_2 emitted by 1.1% for these scenarios. The introduction of a few chemical manufacturing plants reusing CO_2 should lead to increased IS indicator values and further triple-bottom-line benefits, even though it would only make a small dent in the quantity of as yet unused process CO_2. The integration of data from process engineering models into EIO models provides a means to analyze and optimize potential IS scenarios.

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