Resources, Conservation & Recycling 150 (2019) 104436

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Materials flow analysis in support of circular economy development: Plastics in Trinidad and Tobago

Sherwyn Millette[a,*], Eric Williams[a], Clyde Eiríkur Hull[b]

[a] Golisano Institute for Sustainability, Rochester Institute of Technology, 190 Lomb Memorial Drive, Rochester, NY, 14623-5608, United States
[b] Saunders College of Business, Rochester Institute of Technology, 190 Lomb Memorial Drive Rochester, NY, 14623-5608, United States

ARTICLE INFO

Keywords:
Material flow analysis
Circular economy
Plastic flows
Developing economy
Recycling

ABSTRACT

Can material flow analysis (MFA) support strategic decisions necessary for the development of circular economy (CE) in a developing country? MFA can be an essential tool in providing necessary data inputs for decisions related to the development of CE. Data-poor environments in developing economies, however, e.g. lack of data on physical flows in manufacturing, pose challenges to doing MFA. Other data however, in particular trade statistics accounting for shipment mass, are often available. We undertake a case study to characterize plastic flows in Trinidad and Tobago (T&T) for 2016, demonstrating how leveraging such data enables MFA. A notable result from the MFA is that much (48%) of the landfilled plastic in T&T comes from plastic packaging for imported products rather than intentional domestic use. This is an example of what is probably a typical CE challenge for island nations: Importing materials with limited domestic demand at end-of-life. We use the MFA results to propose suggestions for a more circular flow of plastics in T&T. First, there is potential to divert plastic waste (including packaging plastic) for use as feedstock in a local cement plant. Second, the scale of PET plastic flows is of sufficient scale (26,000 metric tons annually) to make domestic recycle feasible. Techno-economic studies are needed to properly develop and evaluate these proposals, the role of the MFA here is to identify promising directions.

1. Introduction

Amidst calls for improved environmental performance, economies are faced with the environmental impacts of a linear approach (take, make, dispose) to production and consumption (Bocken et al., 2016, Ghisellini et al., 2016, MacArthur, 2013, McKinsey, 2012). As with advanced economies, developing economies must find ways to improve their environmental performance while balancing continued economic development and avoiding a linear economic approach to development. The implementation of circular economy (CE) is an option to achieve this. CE is the antithesis of the traditional linear economy (Ness, 2008), drawing heavily on industrial ecology (Frosch and Gallopoulos, 1989). Through the development of closed loop systems and improving resource efficiency, CE seeks to reduce the anthropogenic impact on the environment from production and consumption without compromising economic growth (Pratt et al., 2016), decoupling economic growth from environmental impacts. CE aims to establish balance between economy, environment, and society (Ghisellini et al., 2016), and by redesigning products with the goal of minimizing inputs and the resulting waste (D'Amato et al., 2017, Ghisellini et al., 2016, Ellen Macarthur Foundation, 2013, McKinsey, 2012). By developing closed loop systems for various materials, CE also promotes the use of waste as inputs for industries, promoting inter industrial cooperation (D'Amato et al., 2017); diverting waste materials with potential value from landfills.

The development of closed-loop systems is predicated upon an understanding of what materials flow within the system. The development and use of MFA are thus important to quantify flows through that environment. MFA can be useful in providing opportunities for legal, policy and efficiency interventions, detecting environmental problems, and providing needed technical data for decision making and planning. These benefits may be more impactful for developing economies where environmental standards are often weaker, and these interventions can lead to badly needed environmental protection standards, economic resilience, and some level of economic stability by the identification of entrepreneurial opportunity, and resource optimization. In developing nations there also exists opportunities for innovation and the development of infrastructure grounded in new technology, as opposed to developed nations who must deal with lock-in effects from antiquated infrastructure. MFA results can be used to indicate economic

* Corresponding author. Present address: Pierre Road Connector, Chaguanas, Trinidad and Tobago.
E-mail addresses: sm2004@rit.edu (S. Millette), exwgis@rit.edu (E. Williams), chull@saunders.rit.edu (C.E. Hull).

https://doi.org/10.1016/j.resconrec.2019.104436
Received 15 November 2018; Received in revised form 13 July 2019; Accepted 2 August 2019
Available online 05 September 2019

opportunities directly linked to environmental impacts, providing for the development of e**co-f**riendly business that has a triple bottom-line focus of environment, economy, and social concerns. MFA is a key tool in the identification of CE opportunities and the eventual decisions for the CE management of waste.

There are two main goals in applying MFA to promoting CE in developing counties. The first goal is the address the challenge of limited data. Paucity of data is a general challenge in both the completion of the MFA and the validity of its results (Danius and Burström, 2001, Lassen et al., 2000). The credibility of results is due to the process used in gathering and analyzing often conflicting data from various data sources (Chen and Graedel, 2012). Data concerns impact the confidence placed in the results of the MFA (Laner et al., 2016). For developing countries, the data challenge is often larger. A common problem is lack of resolved data on the physical inputs and outputs of manufacturing. Characterizing production at a national scale relies on data collection efforts at the federal level. Many surveys of national production are limited in coverage of number of individual products characterized and often do not cover physical data, only economic. Available production data focuses on goods contributing (significantly) to the GDP. While it is expected that data collection efforts will expand as a country becomes wealthier, in the meantime is it important to build capacity to do MFA given currently available data. The second goal is to specifically apply MFA to informing CE development. In principle MFA provides valuable information in planning reuse and recycling systems. In practice, it has yet to be sufficiently used for this purpose.

Here we undertake a case study of plastic flows in Trinidad and Tobago (T&T) to address both goals: developing capacity to do MFA in data constrained situations and to apply MFA for CE. Like many developing economies, T&T collects limited information on the mass and flow of materials within the economy, only tracking a few commodities that contribute significantly to GDP such as oil and natural gas. This lack of production data limits MFA, but also like a number of developing nations, T&T has rich trade data (Central Statistical Office of Trinidad and Tobago, 2016) as well as detailed waste characterization data (CBCL, 2010), in such an environment it could be possible to construct an MFA. We thus aim to use leverage this data to explore a detailed product-level MFA at the national level. While there are many prior MFAs, none have provided the level of product-level detail for a developing economy, details that are helpful in CE planning. The leveraging of data here is generalizable to other developing economies with similar data availability challenges as T&T.

The management of plastics is a practical issue facing the country. Plastic account for 19% of municipal solid waste (MSW) in landfills in T &T (Rajkumar et al., 2011, CBCL, 2010). For an island environment such as T&T, there are challenges associated with disposal sites without adequate environmental protection, which is increasing the level of pollution in surrounding surface and ground water (Beckles et al., 2016) coupled with the inability to establish new landfills due to land availability (Government of Trinidad & Tobago, 2015, Marzolf et al., 2015). The results of the MFA are used to identify opportunities for CE interventions that can have positive impacts for developing economies via economic development and entrepreneurial activity, increased employment and revenues, improved economic stability and resilience to external factors, and the development of environmental policy that protects the environment and promotes eco-friendly business activity.

2. Literature review

The practice of MFA has grown over the last several decades and has been applied to various materials and substances in different geographical aggregations (Van Eygen et al., 2017, Pauliuk et al., 2013, Zhou et al., 2013, Park et al., 2011, Sarkar et al., 2011, Kuczenski and Geyer, 2010, Yellishetty et al., 2010). The MFA literature focuses on Europe and the U.S., however there is a growing body of work addressing the developing world, especially China and India (Bao et al., 2010). Prior studies in the developing world include studies focused on PVC in China (Zhou et al., 2013); international trade relations for Chile (Giljum, 2008); plastics flows in India (Mutha et al., 2006); some with a focus on islands such as biomass and petroleum flows in Trinidad and Tobago and Iceland (Krausmann et al., 2014); industrial ecology, industrial symbiosis, and sustainability in Puerto Rico (Chertow et al., 2008, Deschenes and Chertow, 2004); household solid waste and marine litter on Kayangel Island in Palau (Owens Emily et al., 2011); and waste tires in Dominica (Sarkar et al., 2011).

Reviewing studies in geographical proximity to T&T, an MFA by Krausmann et al analyzed flow of biomass, petroleum, minerals flow in T&T and Iceland (two small island economies), (Krausmann et al., 2014). The purpose was to track aggregated material flows over time, finding e.g. that T&T has become increasingly petroleum dependent. Tailored for its purpose, the MFA is not resolved to inform implementation of CE for a particular commodity.

Another study of an island economy, Dominica, uses MFA to project the accumulation of waste tires (Sarkar et al., 2011). The MFA was used to establish the base flow upon which two methods for projecting future accumulations were then applied. The construction of the MFA was based exclusively on the use of trade data (import/export) for tires to the island as none are produced locally. The authors discuss the potential for recycling waste tires on the island and conclude that the required investment expenditure to start recycling would not be justifiable and suggest that waste tires from nearby islands be imported to realize economies of scale (Sarkar et al., 2011). It is probable that many Caribbean countries would be in a similar situation due to the small populations and solutions to waste accumulation on the islands would be a growing concern.

MFA is often limited by data availability (Dahlström and Ekins, 2006), the problem is compounded in many developing countries. For some developing economies, the only data collected on material production is linked to select materials/industries that contribute significantly to GDP. This data, while providing economic information, does not inform mass flows within the economy. Trade data on the other hand, is more often collected and reported in detail. Trade data can be used in MFA to characterize input/output of material flows, e.g. the study of waste tires in Dominica (Sarkar et al., 2011). Curiously, detailed mass flow trade data is sometimes more available in developing countries than developed. The U.S. and Japan, for example, collected detailed trade data but only publicly release economic, but not mass flows. Table 1 indicates that availability of detailed mass trade data but poorly resolved production data, is a common situation in a number of developing countries.

2.1. Contribution to the body of knowledge

The objectives of this case study are to a) show that a detailed MFA of a substance can be done by leveraging material trade data, and b) illustrate that the resulting MFA results can be used to develop strategies for the development of CE.

Contribution to methodology: As discussed previously, data

Table 1
Data availability in production sector versus trade for a number of developing nations - Number of products for which materials data is published (UNSD (United Nations Statistic Division), 2016).

Country	Number of product categories included in:	
	Annual Economic Report	Trade Data
Trinidad and Tobago	30	5300
Peru	49	6000
Zimbabwe	30	5500
Nigeria	21	5500
Columbia	57	6000

availability can be a major challenge in conducting MFA (Dahlström and Ekins, 2006) more so in a developing economy where the institutional statistical gathering capacity may be underdeveloped. This article uses rich trade and waste data to construct an MFA, providing a method and assumptions that can be replicated in similar data poor environments (Table 1 above for examples). The use of trade data is not uncommon, Krausmann et al., 2014, use trade statistics as part of their examination of the material flows for biomass and petroleum. In Dominica, because tires are not manufactured locally, the material flows are exclusively based on trade data (Sarkar et al., 2011) and to establish the flows of used personal computers (PC) in Peru trade statistics were again used (Kahhat and Williams, 2009). While this study is not the first to use trade data, it is the first to use disaggregated trade data as a key element to construct a detailed MFA. By linking this rich source of information with a detailed waste characterization data, we develop a resolved MFA for plastic flows in T&T. While waste characterization is often used in the management of landfills, they are limited in that they do not provide information on the origin of the waste generated by various sources. Coupling the two can provide local authorities with an understanding of the origin of the waste and allow for more effective management of materials that are present in the waste stream.

The study is generalizable because the data situation of T&T is not unique. Table 1 shows that a number of other countries are similar, with limited production data but rich materials trade data. The methodology we develop below (Section 3) can be used in these situations.

Contribution of case study: There are prior industrial level MFAs done for a number of material flows in developing countries: China (Zhou et al., 2013), PVC; Chile (Giljum, 2008), international trade relations; and India (Mutha et al., 2006), plastic flows to list a few. These studies do not, however, explicitly propose changes using MFA results. Our goal here is to connect the MFA results to specific proposals to improve circular flows, in this case, plastic.

3. Data and methodology

3.1. Data acquisition

Import / Export data: Disaggregated trade (import/export) data for T&T was obtained for the year 2016 from the T&T's government Central Statistical Office (CSO); this information included data on products imported (34,700) and exported (17,650) from the island. For each product, data on country of origin, the harmonized system (HS) code, mass in kg and value in TT$ is included. The HS codes (product trade codes) were mapped to product descriptions (Government of Trinidad and Tobago, 2007) for ease of use and understanding, then used to categorize material by product type with total flows obtained for each group. Plastics are listed under trade code HS 39, which contains 140 disaggregated products. Some products are inputs to industry (e.g. '3901.10.00', polymers of ethane) others are consumer and/or commercial products (e.g. '3923.21.00', Sacks and bags … of polymers of ethylene). By examining the product category names, we sort each product as either an input to manufacturing or consumption. The manufacturing phase represents domestic production of plastic products in which plastic polymers or semi-finished goods are imported for domestic manufacturing. We also sub-divided consumer plastics into durable and non-durable types. Durable refers to products typically used more than once, e.g. plastic pipes, dishes. Non-durable products are one-time use such as packaging, straws and disposable cups. The durable/non-durable distinction is useful to characterize the potential of interventions such as plastic bag bans to reduce material flows.

Waste data: In 2010 a detailed characterization for municipal solid waste in T&T was done (Rajkumar et al., 2011, CBCL, 2010). This study involved sampling of landfill waste and detailed analysis of its material composition. Plastics were divided into several categories (such as clear PET containers, colored HDPE containers, tubs and lids (HDPE, PP, LDPE, PS), LDPE film, and PS containers (foam)) and annual content of waste estimated. Total plastic waste was estimated to account for 19% of the waste received and landfilled. The estimation was for MSW only and did not include industrial and commercial (I&C) waste, which is collected and treated by private third-party entities prior to delivery to the nation's landfills. Industrial and other waste accounted for roughly 33% of the total waste received in landfills for 2010. There are no available characterized reports for MSW in 2016, the target year of our study. Conversations with the Quality Health Safety and Environment Manager at SWMCOL indicated that waste processed in T&T landfills has been roughly constant, 750,000 metric tons annually (Allong, 2018). We thus assume the 2010 results are a reasonable representation of 2016 plastic waste.

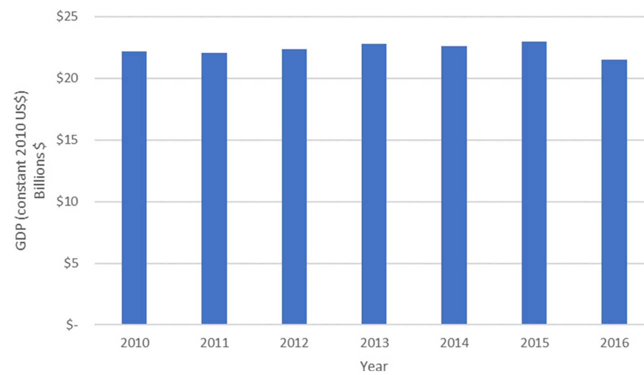

Fig. 1. Gross Domestic Product Trinidad and Tobago 2010–2016 adapted from (International Monetary Fund, 2018 M01, Trinidad & Tobago Central Bank, 2016).

3.2. Methods and data processing

A single-year MFA is conducted for T&T of direct flows of plastic in 2016. In the process of completing the MFA, data constraints led to assumptions. Major assumptions are outlined and justified below Fig. 1.

a *Trade statistics are accurate:* It is assumed that the government of T&T is able to record trade statistics with reasonable accuracy.
b *The system is in equilibrium:* i.e. there are constant flows of plastic in and out of the system. One implication of this assumption is that we use results for waste characterization in 2010 to reflect 2016. This assumption is justified by the observation that industrial and commercial activity between the years 2010 and 2016, as measured by GDP, is nearly static for this period (see 1 Fig. 2 below). Population growth was at 0.3% during the period 2010–2016 (Central Statistical Office of Trinidad and Tobago, 2018). In addition, plastic imports for this period are relatively stable averaging US$219 million. We therefore argue it is reasonable to assume that flows into the consumption phase are in equilibrium and any additions to stock as discussed in (Fischer-Kowalski et al., 2011) via durable goods/products replaces obsolete end of life (EOL) plastics.
c *End use for imported pre-cursor plastics:* Finished plastic goods can be characterized easily based on their product title, e.g. dishware, cups, pipes. In contrast, it is difficult to know precisely what products plastics precursors (such as ethylene polymers) end up in. We propose final products manufacturing from imported plastic materials based on a review of most popular uses of different polymers and a review of T&T manufacturing infrastructure. For example, polymers of vinyl chloride are generally used to produce PVC piping and there are facilities in T&T that manufacture PVC pipes and other goods. Therefore, polymers of vinyl chloride are assumed to be used for making PVC pipes. Another example is alkyl resins, which are often used in the manufacture of heat resistant paints, assumed to be used in its manufacture locally because of the presence of paint manufacturers in T&T and as such is categorized as durable.

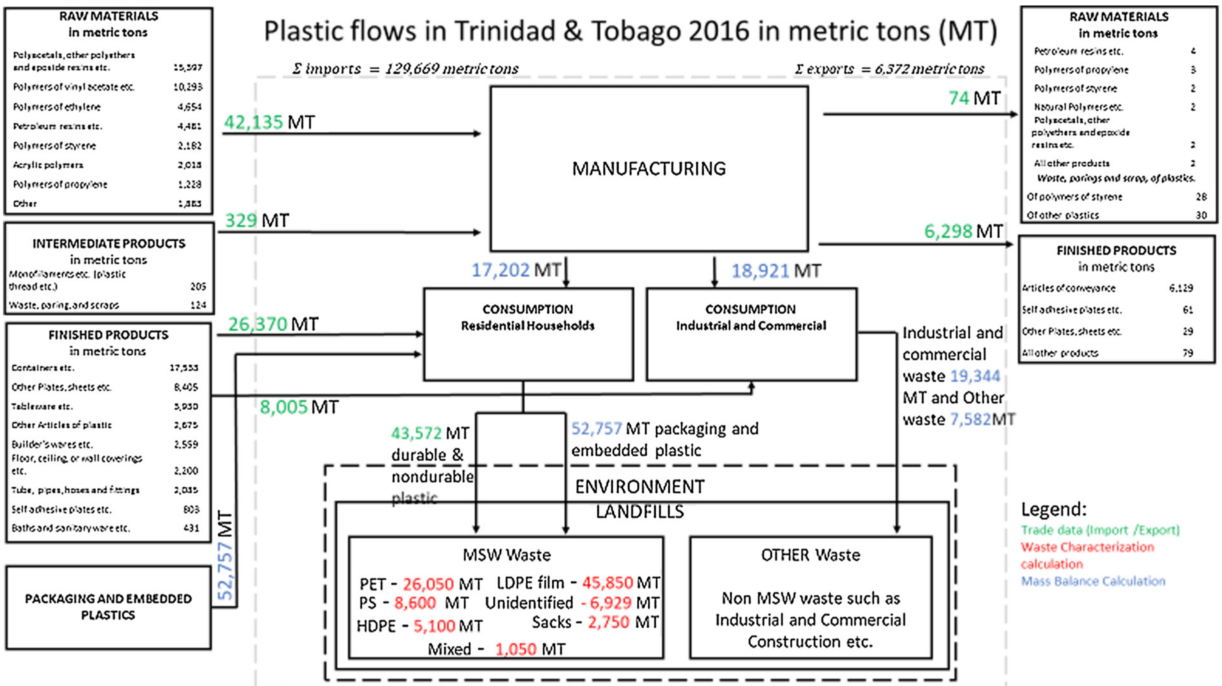

Fig. 2. Material flow analysis (MFA) for plastics flow in Trinidad and Tobago for 2016.

d *Unquantified plastic waste in the landfills:* The calculations presented below represent plastic waste from MSW only (CBCL, 2010). The disposition of industrial and commercial waste has not been characterized in T&T. It is assumed that plastic from these sources are landfilled.

3.3. Using MFA to identify CE opportunities

The results from the MFA can be analyzed to identify CE planning opportunities. By providing quantifiable data, specific actions can be taken to close material loops, (in this case plastic) via legislative and policy initiative, as well as entrepreneurial activity involving locally generated waste. The approach to this analysis is to examine waste streams and consider alternatives such as recycling or waste-to-energy. MFA results inform scale questions on feasibility, e.g. if a flow or combination of flows is of sufficient scale to justify capital investment in recycling. The MFA based on both trade and waste data provides opportunities for CE, where the quantities of materials can be quantified, and the trade information also provides basic market information.

4. Results and discussion

4.1. MFA for plastic in T&T

Fig. 2 shows the MFA results. Numerical values from flows come from either trade data, waste characterization or materials balance Table 2. Import and export flows are shown in green on Fig. 2. Subtracting exports (6372 metric tons) from imports (42,464 metric tons) to manufacturing gives the flow of plastics from the manufacturing to the consumption sector (36,092 metric tons). The flows into the consumption phase are split between residential household consumption (17, 202 metric tons) and industrial and commercial consumption that included construction materials (18,921 metric tons). The plastics import data indicates a flow of finished products to consumption of 34,375 metric tons (26,370 metric tons to residential household consumption and 8005 metric tons to industrial and commercial consumption). Combining this with flows from manufacturing gives 70,498 metric tons flowing into consumption from imports and domestic manufacturing.

As discussed in Section 3.2, above, the system is assumed to remain in equilibrium; therefore, any plastic flows to the consumption phase will replace end-of-life (EOL) or obsolete plastics which will in turn flow to MSW management for disposal. The waste characterization study shows 96,329 metric tons of plastics from residences entering landfills. The data indicates that 34,375 metric tons of plastic waste will flow from residential consumption to municipal solid waste (MSW) systems to the landfill. The disparity in quantities in the MSW plastic waste (96,329 metric tons received, and 34,375 metric tons generated) indicates an additional source of plastic waste. A large share of plastic waste received in the landfills is LDPE film (45,850 metric tons), used in product packaging. The presence of a large quantity of LDPE film and packaging in the landfills point to indirect plastic flows entering the system. As is the nature of island environments, much of the products consumed is imported and would contain a requisite packaging, and it is logical this indirect source of plastic waste in the form of LDPE film and plastic packaging will find its way to landfills. Using a mass balance calculation, 52,757 metric tons of LDPE film and packaging materials enter the system indirectly.

As discussed in Section 3.2, we assume that plastic waste from industrial and commercial sources not unaccounted for in the 2010 characterization report (CBCL, 2010) end up in landfills. As there is no data source directly informing this flow, we use materials balance to determine this flow: 19,344 metric tons of industrial and commercial waste as well as 7582 metric tons of miscellaneous waste (consisting of plastics suspended in fluids, solvents, paints etc.) flows out of the consumption phase, much of which will end up in landfills and is not quantified by available characterizations.

Total direct flows of plastic waste from the residential household consumption phase accounts for 45.2% of landfilled MSW plastic waste with the balance 54.8% being derived from plastic packaging. The use of plastic film and plastic packaging has been steadily growing (Mutha et al., 2006) and as such is increasingly a major source of plastic waste (Hopewell et al., 2009), for 2016, it is estimated that packaging and embedded waste accounted for 52,757 metric tons of indirect flows of waste plastic into MSW management system accounting for as much as 54.8% of the plastic waste present in the landfills for 2016. This

Table 2
Data methodology for plastic flows in Fig. 2 – Material flow analysis (MFA) for plastics flow in Trinidad and Tobago for 2016.

Flow from	Flow to	Method	Source
Raw Materials	Manufacturing	Primary data	(Central Statistical Office of Trinidad and Tobago, 2016)
Intermediate	Manufacturing	Primary data	(Central Statistical Office of Trinidad and Tobago, 2016)
Finished Products	Consumption	Primary data	(Central Statistical Office of Trinidad and Tobago, 2016)
Manufacturing	Raw Material Export	Primary data	(Central Statistical Office of Trinidad and Tobago, 2016)
Manufacturing	Finished Product Export	Primary data	(Central Statistical Office of Trinidad and Tobago, 2016)
Manufacturing	Consumption	Mass balance: residual of imports – exports to manufacturing	
Consumption	MSW Management	Mass balance	
MSW Management	Export Waste	Primary	(Central Statistical Office of Trinidad and Tobago, 2016)
MSW Management	Landfill	Processed from waste characterization data	(Allong, 2018, CBCL, 2010)

estimate is comparable to the UK with 58% (Hopewell et al., 2009) of its plastic waste made up of LDPE film and plastic packaging of various polymers.

Total direct and indirect plastic flows within T&T for 2016 is 129,669 metric tons of plastics, with outflows from the system primarily through the local disposal of post-consumer plastics (96,329 metric tons). While not included, there is a degree of pollution to the environment, but with no available data, it is not captured in the system flow graphically represented in Fig. 3 below (Table 3).

4.2. Using MFA to identify CE opportunities

The MFA clarifies the composition and sources of plastic wastes in T&T. Table 4 summarizes waste quantities by type. These results can be used to inform feasibility of different circular strategies for collection and management of local plastic waste.

The results of the MFA for plastic in T&T yield various insights that can be used in the CE planning for the management of plastic waste in T&T. Specifically, we consider the following strategies that can have an impact:

- Ban of polystyrene
- Recycling of PET, HDPE, and other plastics
- Use of LDPE plastics as an alternative fuel in cement production

Ban ofPolystyrene (PS): A variety of products ranging from food containers to product packaging are manufactured using PS materials. In 2016, T&T imported 2182 MT of PS in primary form with 8600 MT of PS accumulating in the nation's landfills that year pointing to other sources of PS is entering the MSW stream, most likely from product packaging as part hidden plastic flows. The recycling of PS is possible, but has been considered difficult to do so (Hopewell et al., 2009, Marten and Hicks, 2018) and is not a common practice (Marten and Hicks, 2018). The light weight of PS makes the recycling of the material economically infeasible (Hopewell et al., 2009). Considering the

Table 3
Estimated composition of plastic waste in Trinidad and Tobago landfills for 2016 in metric tons (MT) based on (CBCL, 2010). polyethylene terephthalate (PET), Low-density polyethylene (LDPE) High-density polyethylene (HDPE).

Material	Quantity	% of plastic waste
PET	26,050 MT	27%
LDPE film	45,850 MT	47.6%
Polystyrene (PS)	8600 MT	8.9%
HDPE	5100 MT	5.3%
Sacks	2750 MT	2.9%
Mixed	1050 MT	1.1%
Unidentified	6929 MT	7.2%

Table 4
Projection of plastic waste diversion from landfills in Trinidad and Tobago including projected substitution rates for alternative fuels in local cement plant. (Polystyrene (PS), polyethylene terephthalate (PET), High-density polyethylene (HDPE).

Activity/Impact	60% recycling Diverted plastic waste
Importation ban PS	2182 MT
Recycling (PET, HDPE)	18,690 MT
Waste to energy (cement) & Construction additive	29,160 MT
Diverted plastic	50,032 MT
Total in Landfill plastics	46,297 MT
% diverted	48.1%

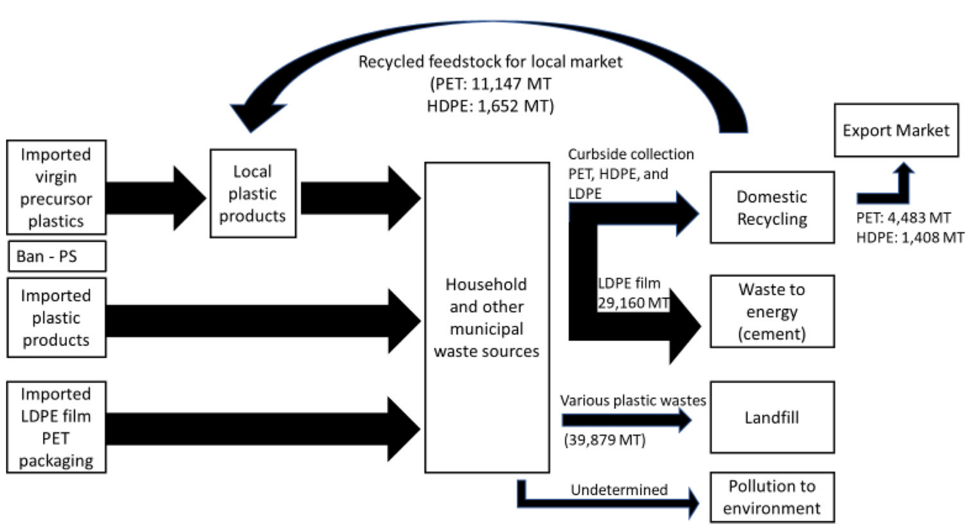

Fig. 3. Proposed plastic management for Trinidad and Tobago.

relative small percentage of PS in landfill waste (8.9% in 2016), it is impractical to recycle this material on the island in these quantities (8600 MT in 2016).

Therefore, the management of PS waste requires a different approach. As part of the strategy for the management of plastic waste, the banning of PS materials via imports is proposed. In 2019, T&T has done so (MPD, 2019), and in so doing, has joined an increasing number of territories in the region (St. Vincent and the Grenadines, Grenada, and Guyana) to ban PS. Alternatively, plant based plastic materials are being used as a substitute for traditional PS products for food containers. This ban on importation of PS only addresses the direct import of the material (2182 MT), and it is assumed that a large proportion of the 8600 MT of PS sent to the landfill in 2016 is in product packaging. T &T as a small consumer has no influence over packaging decisions made in larger economies where products originate. The potential impact of the ban would be a diversion of the 2182 MT of imported PS from the waste stream.

Opportunity for PET recycling: 26,000 metric tons of PET including packaging material was disposed of in 2016, indicating adequate feedstock for domestic recycling of PET that can replace a significant portion of imported virgin plastic and recycled product that can be exported regionally. PET recycling plants start at a capacity of approximately 2000 metric tons annually and can range to a capacity of 6600 metric tons (Beston (Henan), 2018). 100% collection is presumably impractical, but 60% recovery has been achieved in other recycling systems, e.g. Switzerland, Denmark, and Germany (Hopewell et al., 2009). The supply of PET practically available for recycling is thus 15,630 metric tons, sufficient to justify a domestic recycling facility. The next question to address is to what extent recycled PET feedstock would be demanded domestically. T&T currently consumes 11,147 metric tons of PET products, lower than the supply of recycled feedstock. Feasibility of the recycling facility thus depends either on the expansion of domestic PET use or export of excess PET feedstock.

LDPE used in waste to energy: 45,000 MT of LDPE film is the largest proportion of local plastic flows. The presence of a significant portion of LDPE plastic film in the plastic waste stream has challenges, providing the film can be removed effectively from other waste, it can be recycled (Achilias et al., 2007). LDPE film and packaging present a challenge for collection and sorting due to its light making it a more investment intensive to recycle, and the process of separating material types impractical and as such not beneficial (Hopewell et al., 2009, Barlow and Morgan, 2013). It is worth noting that if the LDPE film were from industrial sources it can be effectively sorted and may be more commercially viable to recycle. Reducing the use of the material is limited as T&T is dependent upon imports for most of the goods and products consumed locally and has no market influence on international shipping and packaging practices. The reuse of packaging materials is also limited due to the customization needed for specific packages. Therefore, there are limited avenues available for the reduction, reuse, or recycling of LDPE film and packaging locally, however, if collected, it may be possible to use this LDPE film and packaging as a co-fuel in a waste to energy strategy.

The use of waste as an alternative fuel in cement production is a well-established approach in both Europe and the US (Chatziaras et al., 2016, Rahman et al., 2015, Lamas et al., 2013), and it may well be more cost-effective to adapt a cement kiln to waste incineration rather than to build a new waste-to-energy facility (Mokrzycki and Uliasz-Bocheńczyk, 2003). T&T has a cement plant (Trinidad Cement Limited (TCL)) that has a capacity of producing 1.2 million metric tons of cement annually. Cement production requires substantial fuel inputs both to produce heat and as a source of carbon for the required chemical reactions. It is possible to substitute a variety of carbon-rich waste products, including waste plastic, as an alternative fuel to cement production (Rahman et al., 2015, Lamas et al., 2013, Rahman et al., 2013, WBCSD, 2009). It is important to compare the scale of waste plastic that the cement plant could take with the scale generation. To characterize the former, the target substitution rate of 25–35% (WBCSD, 2009) using MSW as the AF is used in projecting the amount of waste needed to satisfy the fuel needs for the local cement kiln. The TCL cement plants consumes, 13,015,169 MJ/day (Government of The Republic of Trinidad and Tobago, 2017), replacing 25–35% of this input translates to the combustion of between 69,724 MT – 97,614 MT of MSW respectively per year, based on the calorific values for MSW (Garg et al., 2009). The potential mass of diverted plastic using MSW as the alternative fuel is 16,497 MT (post removal of recyclable content). With the curbside collection of LDPE film and sacks 29,160 MT of plastic waste is available for use as an alternative fuel for the local cement kiln. The use of this alternative fuel can substitute 19% of the energy requirements for the kiln based on the calorific values for LDPE film (Themelis et al., 2011). In addition to its use as an alternative fuel, LDPE can be used as an additive to various construction products such as asphalt pavers and cement (Siddique et al., 2008, Saikia and de Brito, 2012, Dhawan et al., 2019).

Alternative fuel use in the cement industry does present benefits outside of the obvious reduction in primary fuel consumption, including the reduction of costs and contributing to the disposal waste (Lamas et al., 2013) as the waste residue from incineration can be incorporated into cement clinker (Murray and Price, 2008). While the combustion of plastic or other waste contributes to the reduction of landfilled waste, it is expected that incineration occurs in appropriate facilities where requisite filters and scrubbers are in place to handle the resulting emissions with oversight from the appropriate environmental agencies to protect the health of residents.

Fig. 3 describes a proposed system for the management of plastic waste in T&T including reductions in the import of various plastics including an importation ban on PS plastics. As described above, the use of strategies such as a tax on single-use plastic bags as well as a ban on PS materials is geared to a reduction in the consumption of PS and PET materials. The collection and domestic recycling of plastics include PET, HDPE, and LDPE materials collected via co-mingled curbside collection will be processed at local material recovery facilities (MRF), with PET and HDPE being sorted and processed for recycling and the LDPE diverted to waste to energy after separation for use as an alternative fuel at the local cement manufacturer.

Table 4 below, summarizing the impact of potential CE interventions on the management of plastic waste in T&T. With a 60% recycling rates as a target by the government (Government of Trinidad & Tobago, 2015), 18, 600 MT of the 26,000 MT of PET and HDPE that flows to the landfill can be potentially diverted and recycled providing material for local and regional markets. Based on the discussion above pertaining to the use of LDPE film and packaging as an alternative fuel in waste to energy strategies, some 29,000 MT of this material can be used by the local cement plant. The quantity of LDPE film diverted in this manner can be increased providing it is adopted by other heavy energy users locally. Based on these initial recommendations, the diversion of 50,000 MT of plastic from the landfill is possible accounting for 48.1% of plastic waste received in 2016. In addition, consideration and use of other strategies such as consumption taxes can further reduce the consumption of various plastics locally diverting plastic waste from MSW.

Industrial and commercial waste needs characterization. With no available characterization for industrial and commercial waste in T&T, this MFA projects that 19,344 metric tons of the 247,000 metric tons of industrial and commercial waste disposed of in landfills in 2016 is plastic materials including PVC and paints. The presence of polyvinyl chloride (PVC) which requires separation from other plastic waste to be recycled (Nakem et al., 2016, Menges, 1996) but can pose challenges (Ciacci et al., 2017, He et al., 2015). To fully appreciate the challenges and the management approached available, further study is required.

5. Conclusion

We demonstrated that a combination of detailed trade data and a waste characterization study are sufficient to enable a resolved national-level MFA. This case study addressed plastics, but the datasets enables study of many other substances as well. As mentioned earlier, a number of other countries have data availability situations similar to Trinidad and Tobago and this or a similar approach should enable MFA studies in these countries as well. Note that trade statistics are generally collected annually, so analysis of trends in a more dynamic situation is possible, with the caveat that waste characterization studies are usually done sporadically at best.

The use of MFA can inform decisions related to waste management and the development of circular economy in Trinidad and Tobago and other economies. We compared the scales of flows from the MFA (e.g. PET plastic) with the possible scales of solutions (e.g. a domestic recycling facility). Had less PET plastic been generated in T&T, for example, this would indicate recycling would be better done through export and aggregation from T&T and perhaps other countries. T&T having a large cement facility and large flow of difficult to recycle plastic suggests the potential of waste-to-energy/fuel. We emphasize that our circular economy "proposal" is a suggestion of promising options, not an assertion. More specific economic and technical study is needed to evaluate establishment of a domestic PET recycling facility and diversion of plastic waste to the cement plant.

As developing economies enhance their ability collect, analyze, and produce data reports, improvements to MFA construction will positively impact the results leading to a better analysis and a more refined output. For T&T, additional characterization of plastic waste flows from industrial and commercial sources is warranted as well as research into creating support for and the application of CE in small developing economies to provide alternatives in meeting sustainable development goals.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2019.104436.

References

Achilias, D.S., Roupakias, C., Megalokonomos, P., Lappas, A.A., Antonakou, E.V., 2007. Chemical recycling of plastic wastes made from polyethylene (LDPE and HDPE) and polypropylene (PP). J. Hazard. Mater. 149, 536–542.
Allong, M., 2018. RE: Quality Health and Safety Manger SWMCOL. Type to MILLETTE, S.. .
Bao, Z., Zhang, S., Chen, Y., Liu, S., Zhang, Y., Wang, H., 2010. A Review of Material Flow Analysis.
Barlow, C.Y., Morgan, D.C., 2013. Polymer film packaging for food: an environmental assessment. Resour. Conserv. Recycl. 78, 74–80.
Beckles, D.M., Cox, L., Bent, G.-A., Ramtahal, G., Cooper, V., Banerjee, K., Dawkins, D., Hosein, N., Samaroo, A., Davis, E.M., Clarke, R., Chadee, X., Mahabir, S., Allong, M., Farrell, D., 2016. The Impact of the Contaminants Produced by the Guanapo Landfill on the Surrounding Environment. Final Report. The University of the West Indies, St. Augustine, Trinidad and Tobago.
Beston (Henan), M.C.L., 2018. Waste Plastic Recycling Plant Manufacturers. [Online]. Available. Plastic Recycling Equipment. https://bestonpyrolysisplant.com/waste-plastic-recycling-plant/.
BOCKEN, N.M.P., DE PAUW, I., BAKKER, C., VAN DER GRINTEN, B., 2016. Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. 33, 308–320.
CBCL, 2010. Trinidad Solid Waste Management Program Waste Characterization and Centroid Study Final Report. The Government of the Republic of Trinidad and Tobago, Ministry of Local Government.
Central Statistical Office of Trinidad and Tobago, 2016. In: Office, C.S (Ed.), Trade Data 2016. Ministry of Planning.
Central Statistical Office of Trinidad and Tobago, 2018. Population Mid Year Estimates [Online]. Available. Ministry of Planing and Development. http://cso.gov.tt/data/?productID=31-Population-Mid-Year-Estimates.
Chatziaras, N., Themelis, N.J., Psomopoulos, C.S., 2016. Use of waste derived fuels in cement industry: a review. Manag. Environ. Qual. Int. J. 27, 178–193.
Chen, W.-Q., Graedel, T.E., 2012. Anthropogenic cycles of the elements: a critical review. Environ. Sci. Technol. 46, 8574–8586.
Chertow, M., Ashton, W., Espinosa, J., 2008. Industrial symbiosis in Puerto Rico: environmentally related agglomeration economies. Reg. Stud. 42, 1299–1312.
Ciacci, L., Passarini, F., Vassura, I., 2017. The European PVC cycle: in-use stock and flows. Resour. Conserv. Recycl. 123, 108–116.
D'amato, D., Droste, N., Allen, B., Kettunen, M., Lähtinen, K., Korhonen, J., Leskinen, P., Matthies, B.D., Toppinen, A., 2017. Green, circular, bio economy: a comparative analysis of sustainability avenues. J. Clean. Prod. 168, 716–734.
Dahlström, K., Ekins, P., 2006. Combining economic and environmental dimensions: value chain analysis of UK iron and steel flows. Ecol. Econ. 58, 507–519.
Danius, L., Burström, F., 2001. Regional Material Flow Analysis and Data Uncertainties: Can the Results Be Trusted. 2001. pp. 10–12.
Deschenes, P.J., Chertow, M., 2004. An island approach to industrial ecology: towards sustainability in the island context. J. Environ. Plan. Manag. 47, 201–217.
Dhawan, R., Bisht, B.M.S., Kumar, R., Kumari, S., Dhawan, S.K., 2019. Recycling of plastic waste into tiles with reduced flammability and improved tensile strength. Process. Saf. Environ. Prot. 124, 299–307.
Ellen Macarthur Foundation, 2013. Towards the circular economy. J. Ind. Ecol. 23–44.
Fischer-Kowalski, M., Krausmann, F., Giljum, S., Lutter, S., Mayer, A., Bringezu, S., Moriguchi, Y., Schütz, H., Schandl, H., Weisz, H., 2011. Methodology and indicators of economy-wide material flow accounting. J. Ind. Ecol. 15, 855–876.
Frosch, R.A., Gallopoulos, N.E., 1989. Strategies for manufacturing. Sci. Am. 261, 144–153.
Garg, A., Smith, R., Hill, D., Longhurst, P.J., Pollard, S.J.T., Simms, N.J., 2009. An integrated appraisal of energy recovery options in the United Kingdom using solid recovered fuel derived from municipal solid waste. Waste Manag. 29, 2289–2297.
Ghisellini, P., Cialani, C., Ulgiati, S., Nationalekonomi, Högskolan, D., Akademin Industri Och, S, 2016. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. 114, 11–32.
Giljum, S., 2008. Trade, materials flows, and economic development in the south: the example of Chile. J. Ind. Ecol. 8, 241–261.
Government of The Republic of Trinidad and Tobago, 2017. Consolidated Monthly Bulletins January – December 2016. Ministry of Energy and Energy Industries.
Government of Trinidad & Tobago, 2015. In: Ministry of Planning and Development (Ed.), National Waste Recycling Policy.
Government of Trinidad and Tobago, 2007. In: Ministry of Trade and Industry (Ed.), T&T HSTariff07 Final.
He, Z., Li, G., Chen, J., Huang, Y., An, T., Zhang, C., 2015. Pollution characteristics and health risk assessment of volatile organic compounds emitted from different plastic solid waste recycling workshops. Environ. Int. 77, 85–94.
Hopewell, J., Dvorak, R., Kosior, E., 2009. Plastics recycling: challenges and opportunities. Philos. Trans. R. Soc. B: Biol. Sci. 364, 2115–2126.
International Monetary Fund, 2018. In: Fund, I.M. (Ed.), M01. International Financial Statistics (IFS). IMF.ORG..
Kahhat, R., Williams, E., 2009. Product or waste? Importation and end-of-life processing of computers in Peru. Environ. Sci. Technol. 43, 6010–6016.
Krausmann, F., Richter, R., Eisenmenger, N., 2014. Resource use in Small Island States material flows in Iceland and Trinidad and Tobago, 1961–2008. J. Ind. Ecol. 18, 294–305.
Kuczenski, B., Geyer, R., 2010. Material flow analysis of polyethylene terephthalate in the US, 1996–2007. Resour. Conserv. Recycl. 54, 1161–1169.
Lamas, W.D.Q., Palau, J.C.F., Camargo, J.R.D., 2013. Waste materials co-processing in cement industry: ecological efficiency of waste reuse. Renew. Sustain. Energy Rev. 19, 200–207.
Laner, D., Feketitsch, J., Rechberger, H., Fellner, J., 2016. A novel approach to characterize data uncertainty in material flow analysis and its application to plastics flows in Austria. J. Ind. Ecol. 20, 1050–1063.
Lassen, C., Hansen, E., Cowi, C.E., Planners, A.S., 2000. Paradigm for substance flow analyses. Guide for SFAs Carried Out for the Danish EPA. Environmental Project.
Macarthur, E., 2013. Towards the circular economy. J. Ind. Ecol. 23–44.
Marten, B., Hicks, A., 2018. Expanded polystyrene life cycle analysis literature review: an analysis for different disposal scenarios. Sustain. J. Rec. 11, 29–35.
Marzolf, N.C., Casado Cañeque, F., Klein, J., Loy, D., 2015. A Unique Approach for Sustainable Energy in Trinidad and Tobago. Inter-American Development Bank.
Mckinsey, 2012. Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition. The Ellen MacArthur Foundation. www.ellenmacarthurfoundation.org.
Menges, G., 1996. PVC recycling management. Pure Appl. Chem. 68 (9), 1809–1822.
Mokrzycki, E., Uliasz- Bocheńczyk, A., 2003. Alternative fuels for the cement industry. Appl. Energy 74, 95–100.
MPD, 2019. Government Approves Ban of Styrofoam in T&T by 2019. [Online] Available:. Ministry of Planning and Development. https://www.planning.gov.tt/content/government-approves-ban-styrofoam-tt-2019.
Murray, A., Price, L., 2008. Use of Alternative Fuels in Cement Manufacture: Analysis of Fuel Characteristics and Feasibility for Use in the Chinese Cement Sector.
Mutha, N.H., Patel, M., Premnath, V., 2006. Plastics materials flow analysis for India. Resour. Conserv. Recycl. 47, 222–244.
Nakem, S., Pipatanatornkul, J., Papong, S., Rodcharoen, T., Nithitanakul, M., Malakul, P., 2016. Material flow analysis (MFA) and life cycle assessment (LCA) study for sustainable management of PVC wastes in Thailand. In: Kravanja, Z., Bogataj, M. (Eds.), Computer Aided Chemical Engineering. Elsevier.
Ness, D., 2008. Sustainable urban infrastructure in China: towards a Factor 10 improvement in resource productivity through integrated infrastructure systems. Int. J. Sustain. Dev. World Ecol. 15, 288–301.
Owens Emily, L., Zhang, Q., Mihelcic James, R., 2011. Material flow analysis applied to household solid waste and marine litter on a small island developing state. J. Environ.

Eng. 137, 937–944.
Park, J.-A., Hong, S.-J., Kim, I., Lee, J.-Y., Hur, T., 2011. Dynamic material flow analysis of steel resources in Korea. Resour. Conserv. Recycl. 55, 456–462.
Pauliuk, S., Wang, T., Muller, D.B., 2013. Steel all over the world: estimating in-use stocks of iron for 200 countries. Resour. Conserv. Recycl. 71, 22–30.
Pratt, K., Lenaghan, M., Edward, T.A.M., 2016. Material flows accounting for Scotland shows the merits of a circular economy and the folly of territorial carbon reporting. Carbon Balance Manag. 11, 1–15.
Rahman, A., Rasul, M.G., Khan, M.M.K., Sharma, S., 2013. Impact of alternative fuels on the cement manufacturing plant performance: an overview. Procedia Eng. 56, 393–400.
Rahman, A., Rasul, M.G., Khan, M.M.K., Sharma, S., 2015. Recent development on the uses of alternative fuels in cement manufacturing process. Fuel 145, 84–99.
Rajkumar, W., Bachan, N., Clarence, C., Chin, X., Montano, K., Maharaj, L., Sam, S., Assiu, R., 2011. State of the Environment Report. Environmental Management Authority.
Saikia, N., De Brito, J., 2012. Use of plastic waste as aggregate in cement mortar and concrete preparation: a review. Constr. Build. Mater. 34, 385–401.
Sarkar, S., Chamberlain Jim, F., Miller Shelie, A., 2011. A comparison of two methods to conduct material flow analysis on waste tires in a small island developing state. J. Ind. Ecol. 15, 300–314.
Siddique, R., Khatib, J., Kaur, I., 2008. Use of recycled plastic in concrete: a review. Waste Manag. 28, 1835–1852.
Themelis, N.J., Castaldi, M.J., Bhatti, J., Arsova, L., 2011. Energy and Economic Value of Nonrecycled Plastics (NRP) and Municipal Solid Wastes (MSW) That Are Currently Landfilled in the Fifty States. Columbia University, New York, NY.
Trinidad & Tobago Central Bank, 2016. National Accounts. [Online]. Available: http://www.central-bank.org.tt 2018. .
UNSD (United Nations Statistic Division), 2016. United Nations Commodity Trade Statistics Database (UN Comtrade). United Nations Statistical Division, New York.
Van Eygen, E., Feketitsch, J., Laner, D., Rechberger, H., Fellner, J., 2017. Comprehensive analysis and quantification of national plastic flows: the case of Austria. Resour. Conserv. Recycl. 117, 183–194.
WBCSD, I.E.A., 2009. Cement Technology Roadmap 2009: Carbon Emissions Reductions up to 2050. World Business Council for Sustainable Development and International Energy Agency http://wbcsdcement.org/pdf/technology/WBCSD-IEA_Cement%20Roadmap.pdf.
Yellishetty, M., Ranjith, P.G., Tharumarajah, A., 2010. Iron ore and steel production trends and material flows in the world: is this really sustainable? Resour. Conserv. Recycl. 54, 1084–1094.
Zhou, Y., Yang, N., Hu, S., 2013. Industrial metabolism of PVC in China: a dynamic material flow analysis. Resour. Conserv. Recycl. 73, 33–40.