Designing a supply network for sustainable conversion of agriplastics into higher value products

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Abstract

This study addresses the problem of agricultural plastic waste being a major stream of waste landfilled. The developed model is designed to optimise the supply chain of converting plastic waste into energy through pyrolysis and applied in a case study of the Scottish agricultural sector to showcase its potential in assessing the feasibility and financial viability in addition to the positive environmental impact of agricultural plastics supply networks. Based on the results this study discusses the benefits of using such a model for decision making purposes, the potential for waste reduction and the implications for the farmer operations.

Keywords: Supply Network Design, Facility Location, Supply Chain

Introduction

Agricultural plastics are a major waste stream in Scotland, with an estimated volume to around 23000 tonnes per year (Zero Waste Scotland, 2012). Scotland is home to over 1500 small and large farms, which due to a relatively cold climate utilise a relatively large amount of plastic in order to create warmer microclimate or stretch the harvesting period on for colder months of the year. Currently, 82% of the agricultural plastics in Scotland end up in landfills or incineration. The farmers have to pay a fee for disposing of the waste plastics they use in agricultural operations as well as the transportation to the landfill. The plastic waste has to be removed promptly from the fields to facilitate other agricultural operations.

Economically viable technologies to process this waste stream into products that can be used in other sectors already exist, but are not in use largely due to the lack of robust methods that would help to design the supply network in an optimal way, considering both the upstream supply network (farmers that generate waste) and the downstream customers (buyers of the products generated by the waste processing). Optimising the design of such a system can lead to higher potential for financial feasibility as well as environmental benefits. Challenges in the design of such a supply network are the dispersed nature of plastic waste availability, due to the remoteness of many farm locations, the seasonality in material availability, and the contamination of the material with soil that may prevent some types of processing.

Therefore, the aim of this work is to present a robust method for optimally designing a supply network for processing agricultural plastic waste into commercial products, considering both the upstream plastic waste and the downstream product supply chain.

Achieving this aim will contribute to moving towards a more circular economy approach in agricultural operations, by creating useful products from a current waste stream.

The rest of this paper is structured as follows: firstly, it provides a brief literature review on the existing related optimisation models on supply chain design, then it discusses the methodological considerations and the case study application, then it outlines the proposed solution, and finally, it presents a case study with the results that were achieved, followed by the conclusions.

Literature review

The model that is being designed in this study is intended for the upgrading of plastic waste generated in the agricultural sector to higher value products, in a circular economy perspective. Therefore, the literature review was initially driven by the intersection of these two areas. The search for "agricultural plastic waste supply chain" in Google Scholar and Scopus produced little result and was mostly focused on the plastic reuse in order to reduce food waste (Singh et al., 2016). When plastic waste and agricultural waste were addressed separately, with regards to the former the studies mainly reviewed the design of reverse supply chain (SC) (Bing et al., 2015), the review of SC at the conceptual level, like scenario planning or system design in waste-to-energy SC in urban environment as a part of recycling programme (Kinobe et al., 2015; Ohnishi et al., 2016; Santibañez-Aguilar et al., 2013) or technological aspects of waste recycling with the focus on a broader spectrum of waste (Mekonnen et al., 2014). Therefore, there is no model in the literature targeting specifically the SC design for agricultural plastic waste.

The literature on optimisation of waste processing supply networks design is also scarce. There is however a growing field of supply networks optimisation in the field of bioenergy and biofuels, including agricultural waste with organic content that are classified as biomass. These studies include the conversion of agricultural residues to energy (Iakovou et al., 2010) or to biofuel (Huang et al., 2010; ten Kate et al., 2017). The distinguishing characteristic of this type of supply chain research is a stronger focus on the economic viability of the system (Kim et al., 2011; Rentizelas et al., 2009), as the environmental effects of this type of organic waste are limited due to the renewable nature of the materials compared to the plastic waste. On the other hand, a number of studies combine both environmental and economic objectives in the optimisation model (Giarola et al., 2011; You et al., 2012). These models usually consider the facility location problem, with some of them also including the capacity and the variety of technological solutions in use, but the requirements of a biomass-based supply network differ from plastic waste in several respects, e.g. the range of products generated, the allowable facility locations, the transportation networks used, the material degradation properties, the need for pre-processing. However, the supporting SC of these models is more likely to be similar to the context of this study than that of the non-organic waste, since the latter mainly occurs in urban environments that are dense and have a significantly larger number of small players and different types of constraints to the agricultural rural environment.

The intended model is designed primarily to help making facility location decisions, i.e. strategic level decisions. These decisions are particularly relevant in greenfield applications, as is the case examined in this work. In the existing models on this level the decisions mainly include the choice of facility-related parameters, such as the facility location (Sharifzadeh et al., 2015; Walther et al., 2012), be it storage, pre-treatment or processing facility (De Meyer et al., 2014), the technology in use (Giarola et al., 2011; You et al., 2012), or the capacity of the facility (You and Wang, 2011). Other types of strategic decisions concern the input and the output of the SC, such as the types (De Meyer et al., 2014) and quantity (Bowling et al., 2011; Papapostolou et al., 2011) of biomass to be processed, and types (Kim et al., 2011) and the quantity of final products (Zamboni et al., 2009). However, some of the models include less frequently used variables, such as the demand for a final product (Huang et al., 2010) and financial risks (Dal Mas et al., 2010).

In terms of the optimisation methods, most of the models use a Mixed Integer Linear Programming (MILP) optimisation approach; however, optimisation models for strategic decision making can also employ other methods, such as mixed integer non-linear programming (Corsano et al., 2011) and a hybrid of genetic algorithms and sequential quadratic programming (Rentizelas and Tatsiopoulos, 2010).

The majority of the models aim at optimising the economic performance, e.g. maximising the NPV (Rentizelas et al., 2009; Walther et al., 2012) or minimising costs (Aksoy et al., 2011; Dunnett et al., 2008), but some of them incorporate environmental criteria too, such as greenhouse emissions converted into equivalent monetary value (Giarola et al., 2011; Zamboni et al., 2009), and even social objectives, such as maximising the number of jobs created (You et al., 2012).

With regards to the constraints, since the most frequent variables are related to the location of the facilities, constraints are related to the facilities as well, and normally include the capacity (Corsano et al., 2011; Rentizelas and Tatsiopoulos, 2010) and investment costs (Aksoy et al., 2011; Dal Mas et al., 2010; Sharifzadeh et al., 2015). When the models are designed to choose among multiple processing locations, quite often the number of locations is limited to one type of waste (Kim et al., 2011) or region (Akgul et al., 2010), or one technology per location (Bowling et al., 2011; You et al., 2012). In the models with a strong economic focus the constraints also include demand (Rentizelas et al., 2009), market parameters (Dal Mas et al., 2010), selling prices (Sharifzadeh et al., 2015), various incentives and subsidies (Bowling et al., 2011; Rentizelas et al., 2009), and taxation (Yazan et al., 2017). Since the proposed model in this work aims at estimating the economic viability of the proposed solution, some of these constraints need to be included in the formulation as well. Another group of constraints is associated with the environmental parameters and includes emissions and emission credits (Giarola et al., 2011; De Meyer et al., 2015) and sustainability targets (Dal Mas et al., 2010).

Ultimately, it can be concluded that there are a number of optimisation models available in the literature for supply network design of biomass to bioenergy or biofuels, but there is no work currently done for agricultural plastic waste to added value product supply network design optimisation that considers the specificities of this particular sector.

Methodology

A MILP optimisation model has been developed to support decision making in the design of the supply network of a new process that will redirect agriplastics from the current landfilling pathway to conversion into higher value products, such as liquid fuels, biochar and syngas that could be either commercially sold, used in situ in agricultural operations or to generate energy in the form of electricity and heat. The main decisions to be facilitated by the model, which constitute the variables of the model, are the processing facility location(s), the facility(ies) capacity(ies) and the optimum selection of downstream customers to supply with the higher value products produced. The primary objective is to maximise the system profitability. The model adopts a holistic supply network modelling perspective, as it includes both the upstream (farmers) and the downstream (markets for products generated) supply chain stages integrated around the focal processing facility.

Though the model presented is primarily at the strategic decision level, as it aims at choosing suitable location(s) for a waste processing facility, it can also support tactical decisions, such as the selection of customers whose demand will be met from each processing plant and which processing plant should each farm supply. In the current work, the proposed solution offers improved environmental performance by design as it allows adopting a circular economy approach compared to the baseline practice of landfilling the agricultural plastic waste; therefore, the environmental performance-related aspects are not included in the optimisation objective.

Below are the list of sets, variables and parameters, followed by the objective function and the list of constraints. The full mathematical formulation was not included into this paper due to the size limitations.

Index sets

C	Set of all the potential customers
I	Set of all farms
J	Set of all plastic types
L	Set of potential locations for pyrolysis plants
M	Months
P	Set of all the products of pyrolysis
Pl	Set of possible plant sizes

Decision variables

$Cloc_{l,c}$	existing link between the plant $l \in L$ and the customer $c \in C$ (binary)
$Floc_{i,l}$	existing link between the farm $i \in I$ and the plant $l \in L$ (binary)
$Loc_{l,pl}$	existing plant $l \in L$ of the size/capacity $pl \in Pl$ (binary)

Parameters

$Ainb$	inbound transportation cost (£/year)
$Alab$	labour cost (£/year)
Aop	operational cost (£/year)
$Amain$	maintenance costs (£/year)
$Aoutb$	outbound transportation cost (£/year)
Awh	storage cost (£/year)
Cap_{pl}	processing capacities of potential plant sizes (tn/month)
$Conv_p$	Conversion rate of 1 ton of plastic into product p (units/ton)
$D_{c,p}$	Demand of customer c for product p
Df	discounting coefficient
Inv	investments (£)
$Mpl_{i,j}$	mass of plastic $j \in J$ generated by the farm $i \in I$ yearly (tn/year)
$Rdisp$	revenues from saving on plastic disposal (conventional) (£/year)
$Rprod$	revenues from products (£/year)
Sub	subsidies (£)

$$NPV = Max\{(Rprod + Rdisp) * Df - Inv + Sub - (Ainb + Awh + Aop + Amain + Alab + Aoutb) * Df\} \quad (1)$$

Subject to

$$\sum_{l \in L} Floc_{i,l} = 1 \quad (2)$$

for all i ∈ I

$$\sum_{pl \in Pl} Cap_{pl} * Loc_{l,pl} * 10 \geq \sum_{i \in I, j \in J} Mpl_{i,j} * Floc_{i,l} \quad (3)$$

for all l ∈ L

$$\sum_{pl \in Pl} Loc_{l,pl} = 1 \quad (4)$$

for all l ∈ L

$$\sum_{i \in I, j \in J} Mpl_{i,j} * Conv_p \leq \sum_{c \in C, l \in L} D_{c,p} * Cloc_{l,c} \quad (5)$$

for all p ∈ P

$Loc_{l,pl}$, $Floc_{i,l}$, $Cloc_{l,c}$ – *binary* *for all* $i \in I, l \in L, c \in C$ (6)

The objective function (1) corresponds to the NPV and consists of the following annual cost elements: inbound and outbound transportation costs, storage costs for plastics, operational, maintenance and labour costs. It also includes investments for the processing facilities and potential subsidies on investment, and annual revenues from the products produced and savings from not having to pay to dispose the plastic waste, where annual costs and revenues are multiplied by an appropriate discounting coefficient to transform them to present values.

One of the decision variables of the model ($Loc_{l,pl}$) defines location and the choice of the capacity of the processing plant(s). As was stated above, the system is supply driven as the primary objective is to fully utilise the plastic waste in a circular economy perspective, which imposes several constraints on the system. In particular, the processing plant capacity should be sufficient to recycle the total annual amount of plastic available (3). Two months of the year are reserved for maintenance and unforeseen breakdowns, which is reflected in this constraint. Other constraints bound the number of plants supplied by any given farm to one (2), the sufficient number of established links between the plant(s) and the customers to sell all the products produced (5), and logical constraints ensuring that the model choses only one capacity for each pyrolysis plant location (4), and defining that the variables are binary (6).

Case study

The model presented has been applied for the collaborating farms associations in Scotland. The farmers use five types of plastic for different crops and purposes. At the moment the plastic waste is either landfilled or recycled by few recycling centres to be used as low value plastic feedstock. However, the recycling process is very resource-intense, requiring large amounts of water to wash the plastic from the soil contamination, and the recycled materials are usually shipped abroad for further processing.

The technology examined in this case study is slow pyrolysis of plastic, which requires less pre-treatment and produces products that can be consumed by the farmers locally (char, liquid fuels and syngas), therefore is less resource intensive and can potentially benefit the local agricultural sector by allowing the farmers to have an additional income. The authors would like to acknowledge that the model is still in the development phase as part of an ongoing project (see acknowledgements), and therefore only the option of generating heat and electricity from the pyrolysis outputs for covering existing electricity and heating needs of the facility where it is located, is considered in this work. In this case, the farmers will have savings from covering part of the facility electricity needs with self-generated electricity instead of purchased electricity from the grid, and heating needs displacing current kerosene burners. The alternative option of directly selling the products to customers will be considered in future work.

The model was applied for 37 farms in total. The values for the parameters were either derived from the interviews with farmers or adapted from the literature.

Parameters of the model

The model was applied for the period of 20 years, which is estimated to be an average lifetime of a pyrolysis plant (Shackley et al., 2011). The discounting coefficient for calculating the NPV was based on the inflation rate of 0.7% (an average of the year 2016 in the UK) and the interest rate of 8% (Shackley et al., 2011; Walther et al., 2012).

The distances between the farms and potential plant locations, as well as plant locations and potential customers were extracted using a GIS software. The amounts of plastic waste per farm were provided by the farms associations. The months in which each plastic is available, the total amount of each plastic waste available and the costs of transporting and disposing plastic waste were identified during the interviews with farmers (Table 1). Further parameters were derived from the information provided or adapted from the secondary sources (Table 2). The potential demand for products was jointly defined with the farm associations: in particular, the products of pyrolysis can only be consumed at the plant for heat and electricity generation for this case study, and therefore, the potential locations for plants were selected adjacent to the largest farms or processing facilities that had significant electricity and heat requirements. Table 3 includes final product related parameters: prices and conversion rates, based on current expenses for the former and the initial results of the lab experiments performed with the particular plastics for the latter.

Table 1. Plastic related parameters: seasonality, cost of disposing and transporting plastic.

	Seasonal availability of plastic material					Disposal cost (£/tn)	Transport cost for disposal (£/tn)	Total plastic tn/year
	April	May	June	July	August			
Plastic 1		0.2	0.8			1	10	70
Plastic 2	0.1	0.6	0.2	0.1		1	10	159
Plastic 3				0.3	0.7	1	10	142
Plastic 4		0.3	0.7			1	10	28
Plastic 5				1		1	10	134

Table 2. System-related parameters.

Parameter	Description	Value	Source
Tcost	cost of transporting plastic	0.375 £/km*tn	Derived from the current cost of transporting disposable plastic
Whcost	cost of storing plastic	1.4 £/tn*month	(Shackley et al., 2011)
Wage	Salary of a technician	22257 £/year	UK Payscale average[1]
Main	Annual maintenance cost (% of investment)	4%	(Sharifzadeh et al., 2015)
Pcost	Operating costs	21.1 £/tn	Calculations provided below

[1] http://www.payscale.com/research/UK/Job=Engineering_Technician/Salary

Table 3. Product related parameters: prices, conversion rates.

	p	$Price_p$ (£/kWh)	$Conv_p$ (kWh/tn)
Electricity	1	0.15	2912
Heat	2	0.044	4854

The investment costs were derived using values for existing slow pyrolysis plants as a baseline: $8 m for a 16000 tonne capacity (Shackley et al., 2011) and $55.5 m for a 255500 tonne capacity (Masek et al., 2010). A scale factor of 0.7 was used to calculate the investment costs for the potential five pyrolysis plant sizes from the baseline: 1000, 4000, 16000, 76000 and 255500 tn/year. In addition, the investment costs were complemented with the CHP unit that allows to convert the intermediary products (char, liquids and syngas) into the final products: heat and electricity. In this case, the baseline CHP facility was one of 2000 kWh_{el} output with a cost of £3.4 m, and a scale factor of 0.7 was used to approximate the cost for different sizes. It should be noted that the pyrolysis plant consumes part of the products to sustain the process, leading to a final yield of 75% liquids and 7% char. These products are then fed into the CHP unit that is assumed to have a typical 30% electrical and 50% thermal efficiency.

The number of staff required was approximated by linear interpolation from two sources of real personnel demand: 4 persons for a medium capacity of 16000 tonnes (Shackley et al., 2011) and 18 persons for a large capacity plant of 160000 tonnes (Svanberg et al., 2013). The minimum plant capacity was set to 1000 tn/year as it is the smallest size of commercially available pyrolysis identified (Jonsson, 2016).

Regarding operating costs, different sources of pyrolysis analysis suggest different values per tonne. Bridgwater (2009) suggested using 12% of the annual capital charge of 16% from investment, which should account for operations, labour and maintenance costs. However, this refers to fast pyrolysis plant with higher capital and lower operating costs. Shackley et al. (2011) provided total operating costs for the scale of 16 000 tonne (40 £/tn), which also included labour and maintenance and which were based on the real example, and derived operating costs for other capacities by dividing the absolute value of operating costs for this plant by the capacity of other plants. However, this approach does not take into account higher maintenance and labour costs for bigger plants. This value has been eventually used as a starting point in calculating operating cost which would take the capacity into account. For the given capacity of 16000 tonne given operating costs amount to 12% of the capital investments. Recommended maintenance costs account for 4% of the capital costs, which includes property tax and insurance, whereas labour costs comprise of the salaries of four technicians (Table 2). The remaining part of operating costs results in 21.1 £/tn, This value is adopted in this work as the variable production costs, irrespective of the pyrolysis plant size.

Results

The results of the optimisation model suggest that only one plant of the lowest capacity size is built in a location near one of the farms under the investigation. The proposed solution can result in a positive investment yield, with an NPV equal to £ 997288 over 20 years, which proves that the existing technological solution can potentially provide an economically viable system of plastic recycling with the volumes of plastic available. It should be noted that the plastic waste amount considered in this work is only 2.3% of the total agricultural plastic waste in Scotland. Of course this positive outcome is subject to ensuring that all electricity and heat is utilised in situ. Although this can be safely assumed for electricity, that can be fed to the grid if not used by the facility (but at a lower price than the displaced electricity assumed in this work), this is not always an accurate assumption for heat demand due to potential mismatch in heat production and demand profile at any given time. Therefore, this result can be interpreted as an upper bound valid in the case that electricity and heat demand are sufficiently larger than production, and therefore all amounts produced can be used in practice.

The amount of plastic that is generated by the 37 farms essentially utilises only half of the pyrolysis plant capacity; therefore, the suggested solution has the potential to increase profitability of the system if more farms join this network to spread the capital costs of the pyrolysis and CHP plants on a longer operational time window. As the developed model is generic and also scalable, it could potentially be used to evaluate the economic viability of plastic processing at a macro level, such as the whole agricultural sector in the UK or in other countries. It could also be used for considering different technologies instead of pyrolysis with a different product mix and conversion factors.

In this case study it was assumed that the intermediary products of pyrolysis (char, syngas and liquids) are only used in a subsequent CHP process to produce heat and electricity in situ. However, further work is in progress to investigate whether some of these products can be applicable for other purposes, e.g. liquids as a fuel for blending with diesel or used for heating. These alternative exploitation pathways will be explored in the future using the same model described in this work.

Conclusions

This work has demonstrated that more sustainable agricultural operations can lead to a win-win situation of increasing the farmer income while at the same time diverting a current waste stream from landfilling and using it to create higher-value added products within the context of a circular economy. The option of using agricultural waste plastics to generate heat and electricity for agricultural processing facilities is financially viable, even though the pyrolysis plant proposed was not used to its full capacity. It is therefore apparent that economies of scale will be prominent when expanding the scale of the farms participating in such a project. However, as this assessment was based on a number of parameters with uncertain values, a sensitivity analysis should be performed to investigate the potential impact of uncertainty on the investment yield.

Academic contribution

This work applies an established OR technique (MILP) in a new context, aiming to present a successful case of solving a network design problem, consisting of facility location and suppliers and customers allocation problem, for the specific context of the agricultural sector and the plastic waste upgrading to higher-value products objective. The model implementation entails the development of customised constraints and objectives for the particular context and can be applied in other cases of reverse supply chains, such as waste collection and processing, recycling, biomaterials, biochemicals biofuels etc. It can also be applied to showcase how OR techniques can be used to maximise the performance of similar reverse supply chains through optimising the network design, while at the same time contributing to enhanced sustainability of the whole system examined.

Contribution to practice

The work provides an example of a win-win situation where the objectives of providing an additional income (or reduced expense) for farmers can be combined with the environmental benefit of diverting a stream of waste from landfilling. It therefore contributes to increasing the value captured by local economies while at the same time applying circular economy principles in the agricultural sector, leading to more sustainable agricultural operations. Supply chains on re-manufacturing, recycling and waste processing could benefit from the application of the proposed model, when decisions about locating a new processing facility need to be made together with allocation of a large number of distributed suppliers as well as potential customers. The proposed model provides decision making support both at the strategic level (facility location) and the tactical level (allocation of material suppliers and of customers and markets to supplying facilities).

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