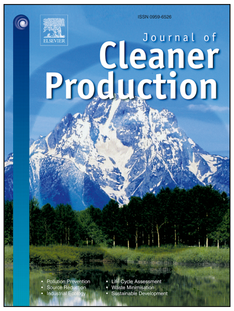

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Anaerobic Digestion of Food Waste: Eliciting Sustainable Water-Energy-Food Nexus practices with Agent Based Modelling and Visual Analytics

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Anaerobic Digestion of Food Waste: Eliciting Sustainable Water-Energy-Food Nexus practices with Agent Based Modelling and Visual Analytics

Abstract

Food waste is a problem for which solutions are recognised but not readily put into practice. What should be the primary objective, reducing or eliminating surplus food production, requires great change within social, cultural and economic structures. The secondary approach of redistributing surplus food to areas of deficit (in terms of socio-economic groups and/or geographic regions) involves a significant logistical burden, and suffers the same issues as with the elimination of waste. The least desirable, but perhaps most practicable approach, is the use of food waste as a feedstock for Anaerobic Digestion (AD). The strategic adoption of AD can therefore be seen as an important step towards mitigating food waste, but the implementation of efficient AD systems on a large (county/region) scale involves significant complexity. The optimal number, size and location of AD plants, and whether they are centralised versus decentralised, may be determined by considering factors such as supply and proximity to feedstock, transport links, emission hazards and social impact. Reaching balanced and objective decisions when faced with such disparate criteria is inevitably very difficult. To address this problem we prototype and evaluate a decision support tool for county-scale AD planning. Our approach is a hybridised Agent Based Model (ABM) with a Multi Objective Optimisation. We capture the spatio-temporal dependencies that exist in the water, energy and food systems associated with energy derived from food waste using Agent Based Modelling (ABM). The use of Interactive Multi Criteria Analysis as visual analytics offers a means to communicate the co-benefits and trade-offs that may emerge, as well as prioritise the AD strategies, based on the weighting of criteria. Specifically, the method supports exploration of the social, environmental and economic impact of different AD strategies and decisions, linked to current issues, namely AD scale and adoption. The results highlight a trade-off between transport costs and social acceptability for the AD centralised versus decentralised strategies. When low carbon options are weighted higher then slow, steady and aggressive decentralised strategies are the best strategic adoption of AD. Conversely, when Energy production is considered with a greater weighting, then aggressive scaling up in a centralised approach is best with slow and steady approaches being further from the ideal. The framework has demonstrated that it permits a space for dialogue and transparent prioritization of AD strategies based on WEF nexus impacts.

Keywords: agent-based model, decision support tool, nexus, water, energy, food, hybrid approaches, uncertainty, complex systems.

1 Introduction

There is a clear need for Decision Support Tools (DST) that can be applied to WEF nexus challenges (Daher et al., 2017) including the evaluation of potential innovations, and support exploratory investigations into the societal, economic and environmental impacts of associated regulatory or policy initiatives. An example of a WEF innovation is Anaerobic Digestion (AD) of food waste/surplus food, which seeks to improve and work positively across sectors by recovering energy from food waste, which would otherwise be sent to landfill, using the minimal amount of water. Ideally only unavoidable food waste would be redirected to AD for energy recovery, rather than being sent to landfill. Recent research has shown that substantial shifts in social, cultural and economic structures will be required (Schanes et al., 2018) to achieve the latter. AD therefore can be considered part of the suite of solutions deriving value from food waste. In addition to AD being a WEF innovation, it was selected as a case study as data is available, albeit fragmented, that can be used to inform aspects of the modelling based on current waste production patterns in the UK, which would enable the wider impact of AD diffusion to be assessed (Hoolohan et al., 2018a).

Most AD DSTs proceed from an economically-driven viewpoint and a single WEF lens, usually energy (Karellas et al., 2010; Karagiannidis and Perkoulidis, 2009), or water (Nicklow et al., 2010), or in some cases two lenses, energy and water (Chen and Chen, 2016) . However, there is a paucity of work exploring the role of AD deriving value from food waste, whilst also considering both the environmental impact in terms of emissions and the social responses to AD which constrain the strategy employed. This effort is broader than life cycle assessment as it need to account for water, energy and food interdependencies.

Given the diversity of potential AD strategies e.g. centralised versus decentralised approaches based on feedstock supply, transport costs (emissions) and social acceptability, we apply an Agent Based Model to account for the interdependencies amongst the water, energy and food systems and to determine the social, environmental and economic impact. ABM allows us to consider social responses to AD which constrain location and size of AD plant installation. For example, the numbers of AD plants depend on management preferences for plant sizes, AD technology scales from micro to large with respect to energy generation capacity. AD plant numbers will be constrained by the supply and volume of food waste available; however if there is ample feedstock then the uptake of AD can be slow, uniform or aggressive. To facilitate discussions and decisions, around prioritising and identifying solutions that minimise trade-offs and conflicts, we apply Interactive Multi Criteria Analysis, a type of Multi Objective Optimization (MOO).

Combining ABM and/or MOO has been widely applied in the water sector where ABM's have been used to describe the biophysical systems and multi objective optimisation is used to explore system trade-offs (Hadka et al., 2015; Maier et al., 2014; Hurford and Harou, 2014). This framework can be applied at the county-scale to identify and prioritise AD strategies. Such strategies are related to rate of uptake of AD (slow, mid, aggressive) and centralised versus decentralised approaches.

1.1 Foodwaste as Feedstock

Anaerobic Digestion (AD) is a biological process that breaks down organic material via microorganisms in the absence of oxygen. AD produces biogas, a methane-rich gas that can be used as a fuel, and digestate that is a source of nutrients that can be used as a fertiliser. Biogas can be converted to heat and electricity through combined heat power (CHP) engines, whilst the digestate can be further processed to recover the solid nutrients and the water embodied in the digestate using techniques such as electro-coagulation (Reilly, 2017). AD is increasingly being used to convert organic waste into renewable energy (NNFCC, 2018). This technology is scalable from small, community plants (< 1kW) to large commercial plants (> 1MW), and is sustainable compared to energy production from fossil fuels (Minde et al., 2013). Micro AD plants have several advantages over commercial size AD plants, including reduced transport requirements and the potential for community involvement (Walker et al. 2017). AD plants have been operating within the UK since the 1980s mainly fed by wastewater sludge. Since 2004, the number of AD plants has increased substantially as has the diversity of feedstock such as agricultural, industrial and municipal/commercial food waste (see Figure 1). The total number of AD plants increased from 70 to 640 between 2004 and October 2018 (https://anaerobic-digestion.com/anaerobic-digestion-plants/anaerobic-digestion-plants-uk/) in part due to support from subsidies, namely the Feed-in Tariff (FiT), the Renewable Heat Incentive (RHI) or the Renewables Obligation (RO) (More and Noyce, 2016).

Currently in the UK, AD plants operate on multiple different feedstocks and generate 708MW of energy (Parkin, 2016). The current status of bioenergy production using AD technology in the UK is reviewed in detail by (Chowdhury et al., 2018). In this study only AD operations fed by food waste from municipal and supermarket sources are considered. The number of operational AD plants in the UK is shown below in Figure 1, showing the different feedstocks.

Figure 1: The number of operational AD Plants in the UK by feedstock sectors based on ADBA Annual Report

More recently AD has been an effective solution to waste management, with less organic matter being sent to landfill, less harmful greenhouse gases are emitted to the environment (estimated at over 25 million tonnes) (WRAP, 2017) and the end product, i.e. biogas, being a useful energy source. Micro AD may also support a circular economy by offering the ability to dispose of local waste, utilise energy and produce a natural fertiliser (digestate) that could be used in urban agriculture or horticulture, or even hydroponics (Fuldauer et al., 2018). Ten million tonnes of food is currently wasted in the UK each year, with a further predicted increase of around 10 % (or 1.1million tonnes) by 2025 (UK Environment, Food & Rural Affairs, 2017). The UK government and WRAP have been tackling this issue of food waste by setting targets for reduction and initiatives such as 'Love Food Hate Waste' (https://www.lovefoodhatewaste.com). Conventional waste management practices often prove insufficient to address the resource management challenges that the UK is currently facing, and AD could be a strategic and cross-sectoral solution (Voulvoulis, 2015).

1.2 Regulatory and policy initiatives

In addition to household waste and consumption patterns regulatory and policy drivers have an influence on the viability, adoption and uptake of AD plants. It is a complex area as the generation of bioenergy from AD is intrinsically linked to energy policy (Edwards et al., 2015) but is also affected by other policies across the WEF nexus, related to feedstock supply and quality derived from food waste.

A major driver in favour of AD is avoiding the costs of disposing food waste into landfill. There is a financial saving as gate fees are approximately £100/t for landfill compared to around £40/t for AD (http://www.wrap.org.uk/sites/files/wrap/WRAP%20Gate%20Fees%202018_exec+extended%20summary%20report_FINAL.pdf) (Dick and Scholes, 2018). Plus there is the added environmental benefit through less leakage of methane gas to the environment at landfill sites. The UK has implemented national level policies to comply with the EU framework that aims to minimise the amount of biodegradable waste entering landfill. There are variations that exist between the UK regions. Scotland's Zero Waste Plan (Scot. Gov., 2010) defined the strategic direction for Scottish waste policy which bans all organic waste going to landfill, increasing the supply of food waste to AD plants. Scotland seems to be taking a centralised approach and supports fewer, large scale AD plants, with licensing policies in place to ensure that new AD plants are not competing for feedstock with existing plants. In England AD plant development is less tightly regulated, and as a consequence there is much more competition for feedstock which has driven down gate fees. AD operators also face competition from other waste disposal options, such as 'Energy from Waste' which generate energy from combustion but offers less nexus benefits (Hoolohan et al., 2018a).

As AD has evolved to favour maximum energy generation, the wider benefits that AD may have in terms of social and environmental gains may not be realised (Hoolohan et al., 2018a).

1.3 Agent-Based Modelling (ABM)

Agent-based models are useful for exploring “what if” scenarios to assess the impact of policy, governance or regulatory interventions. This is critical for nexus innovations as social, economic and environmental outcomes need to be evaluated. ABM can aid decision makers to select appropriate AD implementations. There are numerous examples of the ABM approach exemplified by Aulinas et al. (2009) in a review of forty-two applications applied to the environmental management domain, mainly aimed as decision support tools. ABMs have not been widely adopted in WEF nexus research.

1.4 Nexus Decision Support Tools: Dealing with Multi-Objective Optimisation

Multi Criteria Analysis (MCA), a branch of Multi-Objective Optimisation (MOO), has been applied to effectively manage natural resources with policy makers and technical experts as the end-users. The MCA used by Flammini et al. (2014) is based on an extensive set of Sustainability Indicators (SI) from which a subset of indicators is selected and prioritised as appropriate for the problem considered. It allows a comparative analysis of management options (strategies) compared to the baseline. The indicators used are collected and measured as part of a regional and national strategy; this data is not readily available for the various AD strategies across the WEF space and hence the use of the ABM to simulate this data.

The sustainability criteria and indicator approach used in MCA offers distinct advantages arising from low technical complexity e.g. accessibility to different specialists and low input data needs, if the data already exists. Multi Criteria Analysis (MCA) approaches often present a single aggregated measure, where both weighting and ranking of indicators (Flammini et al., 2014; Mohtar and Daher, 2016) are sought from decision-making and combined using various MCA methods. It is widely recognised that such aggregation strategies can be very subjective and varies across disciplines, however having different means to interactively explore and visualise the aggregated and underlying data is a potential solution. A means to interactively explore the effect of different weightings has been shown to be useful in our previous work.

There are few studies where ABMs, ideal for exploring alternative strategies based on underlying implementations of policy and regulatory interventions, are coupled with MCA; the latter serves to give structure and simplify the information presented, minimising biases, to support decision-making and to transparently and objectively evaluate and prioritise the various AD strategies (Gao and Hailu, 2013; Serova, 2013). Therefore, this paper aims to develop an innovative and exploratory hybrid ABM-MCA decision-making framework (henceforth hybrid ABM-MCA) which:

1. Explores and evaluates the effect of AD strategies (shape and uptake) based on food waste production linked to policy/regulatory interventions using the ABM incorporating social responses.
2. The Multi Criteria Analysis presents the ABM output in a structured but interactive manner by ranking the various alternatives based on importance and weighting of indicators; it also affords the opportunity to detect co-benefits and trade-offs. The effect of various weightings can be observed by selecting pre-sets and visualising the result.
3. Applies the hybrid ABM-MCA in a case study.

2 Methodology

Through stakeholder engagement comprising interviews and workshops, supplemented by a literature review, AD strategies were determined as part of the problem framing. Hoolohan et al., (2018b) describes in more detail how a transdisciplinary approach and considering the connections and interdependencies between the three component systems, enables complexities to be better understood and co-benefits to be determined. This stakeholder knowledge and understanding informed the potential AD strategies that were modelled and evaluated in the county-scale ABM. The steps in the problem framing, case study information and Hybrid ABM-MCA are described in following sections (Figure 2).

Figure 2: Steps associated with MCA framework and its links to ABM for supporting exploratory decision-making, e.g. comparing AD candidate solutions impact on WEF indicators based on a set of quantifiable objectives/criteria.

2.1 Problem Framing

Centralised versus decentralised approaches to AD implementation emerged in the stakeholder discussions as a major difference for geographical regions. National food waste collection practices are evident in Scotland and Wales, with fewer, but larger scale AD plants processing the waste. This 'centralised' approach entails developments at scales over 125 kWe (unit is Kilowatt-electric = 1000 watts of electric capacity) and limited small/micro scale development 5-15 kWe or equivalent (http://www.biogas-info.co.uk/resources/biogas-map).

Another theme was how to facilitate the adoption and creation of new AD plants subject to an adequate supply of food waste. This exposed recycling incentives, economic incentives and using only 'unavoidable' food waste as an AD feedstock. The AD strategies that were investigated are in Table 1.

Table 1 AD configurations/alternatives based on distribution and uptake.

The criteria for assessing the sustainability of an AD configuration was determined through a dialogue with relevant stakeholders and by reviewing the literature. The criteria/ indicators (Table 2) were then subsequently verified with a small group of stakeholders at another workshop. The stakeholders were diverse and consisted of AD entrepreneurs, AD experts with experience of small and micro scale AD, local council sustainability experts, ADBA employees and academics with specialist knowledge on sustainability and AD. Important AD drivers and barriers were discussed and criteria important to decision-making were refined using a combination of verification and ranking of importance along with an examination of everyone's decision-making journey. The criteria selected also align with the Triple Bottom Line approach and the three over-arching decision-making criteria: environmental, economic and social drivers. For example, sustainability criteria include environmental (water quantity, digestate produced), social (visual impact) and economic (operational and capital costs) impacts of the AD configuration.

Table 2 Mapping between sustainability indicators and parameters of the ABM.

2.2 Case Study

Lincolnshire is a county in east central England that has highest number of operational AD plants in Great Britain as of 2018 (see Figure 3), and as such makes a good case study location. The popularity of AD plants in the area is due to it being primarily an agricultural region, growing large amounts of arable and vegetable crops. Waste availability from the production of these crops may explain the prevalence of AD plant development in the region. The population of the county is around 1,040,000 at 28,316 postcodes. There are around 210 branches of supermarkets chains operating in the county. The total amount of estimated food waste generation potential from households and supermarkets is approximately 330 tonne per year. The potential food waste can be converted into 125,400 m^3 biogas, with an average food waste to biogas conversion rate of 380 m^3/tonne, which is equivalent of 752.4 MWh of electrical energy.

Figure 3: The total number of (non-sewage) AD Plants in Great Britain by county

2.3 Hybrid ABM-MCA

An integrated ABM-MCA to support decision makers to recognise the impacts of differing AD strategies on the WEF nexus is presented. Sections 2.3.1 to 2.3.4 explain briefly the agents, behavioural rules and processes involved in the ABM. Figure 4 presents a flowchart of the high-level ABM steps required to simulate and evaluate AD strategies/scenarios (Table 10.

Figure 4: Flowchart of the ABM depicting the systems model for eliciting sustainable energy production practices from food waste through AD. The inputs, outputs and ABM agents are presented. The scenarios evaluated are presented in Table 1.

2.3.1 Feedstock Supply and Transportation

The feedstock (food waste) sources, food waste collectors, and the AD plants are modelled as the agents of the model. The food waste from residential postcodes and supermarkets are modelled as sources. The population of the source agents is prepared in GIS based on Lincolnshire postcodes (http://geoportal.statistics.gov.uk), supermarkets (https://www.geolytix.co.uk) and census data (https://www.nomisweb.co.uk/census/2011/postcode_headcounts_and_household_estimates) and loaded from the GIS database into the ABM. There are 212 supermarkets out of 28,316 source agents populated for the case study area. Based on the report by WRAP (http://www.wrap.org.uk/content/household-food-waste-uk-2015-0) the estimated amount of household food waste (HHFW) in the UK for 2015 was 7.3 million tonnes or 112.6 kg per person per year, that is equal to 0.3085 kg/person/day. This average is used together with the total number of people at each postcode to estimate the food waste Generation Potential (kg/day). The number of postcodes and grocery stores does not change over time, however we assume a linear population growth (https://population.un.org/wpp/Graphs/Probabilistic/POP/TOT/) during the simulation period; this results in linear increase of food waste generated at each source.

It is estimated that approximately 200,000 tonnes of food is wasted per year at retail level by around 12,600 supermarkets in the UK. Therefore, the average amount of food waste produced by a grocery is 15.9 tonnes per year or 43.5 kg per day. Although the actual amount of food waste is expected to change widely depending on the circulated amount of food products at each grocery, in the absence of such detailed data a homogenous distribution of food waste is assumed among the supermarkets within the case study area.

The proportion of recycled food waste to the generated food waste is modelled with recycle ratio parameter in the model. The recycle ratio is varied in the model depending on various factors such as gate fee rates, advertisement, incentives for food waste recycling and social awareness of population. The recycled food waste is collected weekly by the collector agents and taken to the waste collection centres and then transported to the contracted AD plant after pre-sorting. Each collection and transportation results in operational cost as well as CO_2 emissions proportional to the distance travelled. The food waste is converted into biogas with an average conversion rate of 0.38 m^3 biogas per one kg of food waste (Agrahari and Tiwari, 2013)

2.3.2 AD Adoption Rate and Size

Adoption/uptake is defined as establishing new AD plants across the case study area. The adoption rate is the most significant parameter that determines how many new AD operations will be in place at the end of the simulation period, by controlling the search frequency, exploring the viability, of new collection areas and plants. The adoption rate can be slow (0.18 plant per year), steady (0.35 plant per year), or aggressive (0.88 plant per year), see Table 1. The study area is divided into 10 km grid areas and the amount of available food waste is calculated for each grid area (Figure 5a & 5b). A feasibility search is carried out to investigate the viability of installing new AD plants. If there is adequate food waste for a potential AD installation, then a new collector agent is populated at the centre of all the assigned sources. The study area is further divided into 1 km sub-grid areas to search for the nearest acceptable location for the new plant. AD Plants are required to meet certain criteria to be commissioned and these criteria also dictate some limitations regarding the location of the plant. Some of these criteria are related to visual impact of the nearby communities due to noise, odour and traffic that the plant will bring to the area. In order to model the selection of acceptable locations for AD plants, a disturbance index is calculated at each sub-grid area as a function of population and distance within the study area. The plant agent is populated at the centre of the nearest sub-grid areas that has a disturbance index below the determined threshold. The disturbance index for each sub-grid area is calculated as follows in Equation (1) below:

$$SI_i = \sum_{j\,=\,1}^{Number\ of\ subgridcells} \frac{Population_j}{Distance\ between\ i\ and\ j} \qquad (1)$$

The average uptake/adoption rates are estimated based on the frequency histogram of existing food waste fed AD Plants over time throughout the UK. These are normalized from UK to Lincolnshire using the total number of food waste plants in the UK and in Lincolnshire county (Figure 6). The availability of food waste acts as a limiting criterion for the proliferation of AD plants since food waste production can be projected in relation to the population growth and adoption of its recycling by communities.

Figure 5: The county boundary, 10 km grid and food waste source locations (a). The disturbance index heat map at 1 km resolution (b).

Figure 6: Frequency histogram of new food waste fed AD Plants over time throughout the UK based on the AD Plants database.

The processing capacity of plants are classified depending on their food waste intake, as micro (< 1 ton/day), small (1-50 ton/day), medium (50-150 ton/day) and large (> 150 ton/day). When new plants are generated the capacity of a new plant is randomly selected based on the preference for plant size which leads to the centralised versus decentralised strategies. The probability mass functions of these alternatives are shown in Figure *7*. Accordingly, the decentralised alternative is expected to result in higher numbers of micro and small plants and less medium and large plants, whereas in uniform distribution the number of plants at each capacity class is expected to be equal. The ABM limitations, assumptions and modelling platform are described in detail in Appendix A.

Figure 7: Probability Mass Functions for decentralised, uniform and centralized distributions of plant processing capacity.

2.3.3 Visual Analytics via a web-based Interactive MCA Method

TOPSIS was implemented to identify the 'best' AD strategy by ranking and weighting, reached via consensus, of sustainability indicators. TOPSIS is based on the concept that the chosen strategy should have the shortest geometric distance from the positive ideal solution (= 1), and the longest geometric distance from the negative solution (= 0) which is represented as the centre of the circle.

2.3.4 Visual Analytics for Interactive and Exploratory Decision Making

Due to the stochasticity of the ABM, the model runs each parameter over 100 samples assuming a uniform distribution with +/- 50% around the mean as in (Cazelles et al., 2013) where the mean value is derived from literature. The resulting distributions for each of the parameters was tested for Normality using Shapiro-Wilk test. In all cases, these distributions were non-Normal ($p < 0.05$), therefore, the median values for each sustainability indicator was selected as the central measure and used in the TOPSIS MCA for constructing the normalised decision matrix.

In order to facilitate discussion among stakeholders, a web-based visualisation tool was developed using the open-source library D3.js (https://d3js.org/) which allows for the TOPSIS analysis output data to be flexible and cross-browser using interactive vector graphics.

The interactive visualisation allows for different AD configurations to be evaluated according to various drivers and preferences expressed via weights, for example reducing CO_2 production from transportation. Some of the most common drivers are provided as easily selectable pre-sets (Table 4). In addition, the user can also customise and fine-tune the TOPSIS weightings facilitating sharing of perspectives. Crucially, multiple different sets of preferences can be compared across alternatives, initiating a starting point of discussion among diverse stakeholders and facilitating compromise and understanding. Furthermore, every alternative can be further examined by revealing the associated ABM outputs by clicking on AD strategy on the web-based tool. The visualisation tool can be accessed online (https://nikpanayotov.github.io/steppingup-topsis/).

Table 3 Weights explored based on different decision-making preferences and drivers e.g. economy, energy, waste or low carbon.

3 Results

3.1 ABM Outcomes

The WEF indicators: dumped food waste, consumed water, produced biogas, produced digestate, emitted CO_2, transport cost, capital and operating costs and disturbance index were explored for each AD strategy with the ABM. The normalised box plots show the variances in the indicator values within the scenarios (Figure 8). The results display significant variability and outliers in nearly all of the indicators.

Figure 8 Parameter distributions (n=100) across the nine AD scenarios

Figure 9 WEF indicator median values across alternatives – distributions do not follow a normal distribution hence median selected as the central measure.

The WEF indicators that are most sensitive to the various AD scenarios are dumped food waste, consumed water, produced biogas, emitted CO_2, transport costs, capital costs and disturbance index. These will be the focus of the exploratory visualisation. Figure 10 illustrates the visual output from the ANM model showing the spread of AD plants as governed by the developed model.

Table 4 Median values from ABM runs (n = 100) were selected as the central tendency measure for each parameter distribution. These are the TOPSIS inputs along with weights

Figure 10 GIS output of the ABM for Lincolnshire.

3.2 TOPSIS Outcomes and Exploratory Decision Making with Visual Analytics

Total disturbance and emitted CO_2 separate out the decentralisation and centralisation approaches to AD strategies, as can be seen by Figure 11. Alternatives 1 – 3, which have a decentralised approach, suffer from high visual impact (disturbance index) and low CO_2 (transport costs) whilst alternative 7 – 9, characterised by a centralised approach, have a low visual impact (disturbance index) and high CO_2. A similar trend can be observed for disturbance and produced biogas.

Figure 11: ABM output of 900 runs illustrating the trade-off between CO_2 and disturbance for the centralised/decentralised alternatives

The relationship between total capital costs or dumped food waste versus disturbance and biogas production as a function of the scenarios are shown in Figure 12. As less food waste is sent to landfill (transitioning from the red to the blue points then more biogas is produced), more is available for AD thus more biogas is produced and more CO_2 is emitted with an associated increase in transport costs. The effect of the decentralised versus centralised scenarios is clear. The AD uptake/adoption rate across centralised/decentralised alternatives adds more variability to the results. As diffusion rate increases then there is more variability in the data (alternatives 3, 6, 9).

Figure 12: Relationship amongst dumped food waste, total disturbance, biogas production and total capital costs.

3.3 Effect of different decision-making drivers on 'best' alternative and stakeholder stories

By changing the weightings of the sustainability criteria then different AD strategies become a better choice (Figure 13). When low carbon options are important then decentralisation is an ideal discriminator and slow, steady and aggressive decentralised options are the closest to the ideal strategies, with centralised aggressive being the furthest from the ideal – i.e. worst option. Conversely, when Energy production is considered with a greater weighting, then aggressive scaling up in a centralised approach is best with slow and steady approaches being further from the ideal. This sensitivity to the weightings suggests that the method can be used to support decision-making, and that it has sensitivity to different options having greater or lesser weightings and so producing informed choice as to what the best alternative would be in those circumstances. The aggressive diffusion and centralisation options tend to dominate in terms of being the best solutions over several different pre-set weightings including Biogas production (Energy) and Waste management, although when Transport costs or Carbon emissions are given a greater weighting then decentralised options suffice.

Figure 13: Results of the TOPSIS MCA method supplying input weights and median values as in Table 3 (a) & Table 4 (b) respectively.

The TOPSIS tool and associated data visualisation will help stakeholders understand the impact of the different choices regarding the scaling up of AD, for example – which distribution would be better? Would they be better to increase the number of plants in the area or to increase the size? From our stakeholder dialogue and interviews, several factors emerged that need to be considered when considering new regulation and/or policies.

Policies for separate food waste collection at a county level should increase the amount of food waste available for AD, however, it's not just the quantity but the quality of the feedstock that is vital, if it is too contaminated then it cannot be used. Waste Management Regulations at the Farm level also have an impact on AD viability, for example regulations relating to Digestate disposal exist to restrict the application of digestate to certain times of year (and limits the number of applications) to avoid nitrate leaching from soils, especially in Nitrate Vulnerable Zones (NVZs) which make up to 58% of the UK. This may necessitate the storage of the highly liquid digestate, which can be expensive (paying for storage tanks etc) and therefore not popular with farmers without financial support.

Some of the decision drivers are less clear-cut than others, for example, the production of digestate can be considered as a benefit if there is a readily available and reliable local market for it. As digestate has a high water content (by comparison with chemical fertilisers) it is more expensive to transport and the highly liquid format makes application more difficult (and may require more specialised equipment) than the equivalent chemical, granular fertiliser. Therefore, the production of large quantities of digestate could be a negative, rather than a positive driver, if it needs to be transported. The ABM-MCA tool can handle these cases when criteria can be either a benefit or penalty depending on local context.

The TOPSIS tool has therefore been designed to be sufficiently flexible to change the direction of each criterion's ideal (minimise or maximise). If we create a custom preference that prioritises digestate, we can then consider this effect.

Because of the complexities discussed above, the context in which the uptake of AD may evolve should also be considered, the drivers and barriers are not identical across the range of scales and current incentives favour large scale AD and energy production. Future policies should identify how support might be offered to help each scale to flourish. Incentives based purely on energy are inhibiting AD development at smaller scales and are also considered to be ineffective at producing the desired environmental benefits due to inefficiencies and inappropriate production (Hoolohan et al. 2018).

4 Conclusions

To overcome the technical complexity of ABMs and to widen their use in the decision-making process beyond those involved in its design and development, we advocate the use of ABMs as an “exploratory modelling” approach combined with visual and interactive MCA tools. Unlike other methods, our approach affords the opportunity to explore context (spatial, environmental, social, policy) through the coupling of ABM and MCA based on the decision maker’s needs.

We investigated two aspects of the hybrid ABM-MCA:

- The impact of county scale decisions - AD plant size and rate of adoption on the WEF global indicators. We found a trade-off existed between CO_2 produced and social impact.
- The prioritising of the AD strategies was affected by the indicator weightings. The interactive MCA demonstrated this. It also highlighted that local knowledge and context is important in determining the direction of each criterion’s ideal (minimise or maximise).

The hybrid ABM-MCA can be adapted to explore policy strategies to support innovation e.g. the Clean Growth Strategy aiming to ban waste food from landfills by 2020 and to support the Courtauld 2025 initiative (http://www.wrap.org.uk/food-drink/business-food-waste/courtauld-2025). This is a ten-year commitment to decreasing the amount of food waste in the UK by identifying priorities, developing solutions and implementing changes to cut the carbon, water and waste associated with food and drink by at least one-fifth in 10 years.

There is an urgent need to reduce the amount of food wasted in the UK, but also to ensure that any food that is wasted is treated appropriately; the best use of surplus food is to redistribute to people who do not have the means to buy it. Food redistribution is much better supported in other European countries such as France and Italy. Only food that is unfit for human consumption should be sent to AD. Subsidising the use of this (still edible) food to produce energy via AD does not reflect the best use of our valuable resources as well as being morally questionable. AD can be beneficial to our economy and the environment, but only if we more carefully consider the best use of our resources considering environmental, social and moral implications along with the more obvious financial ones. The hybrid ABM-MCA presented herein can be used to explore competing uses for food waste and investigate an optimal quantity and distribution of AD plants that would be driven by unavoidable food waste.

Finally, with decreasing financial drivers encouraging innovations such as AD, we now require a new nexus approach, where other benefits are considered, in addition to the Return on Investment (ROI) which could enable stakeholders to consider social and environmental benefits and begin discussions concerning the ‘best’ options in these terms.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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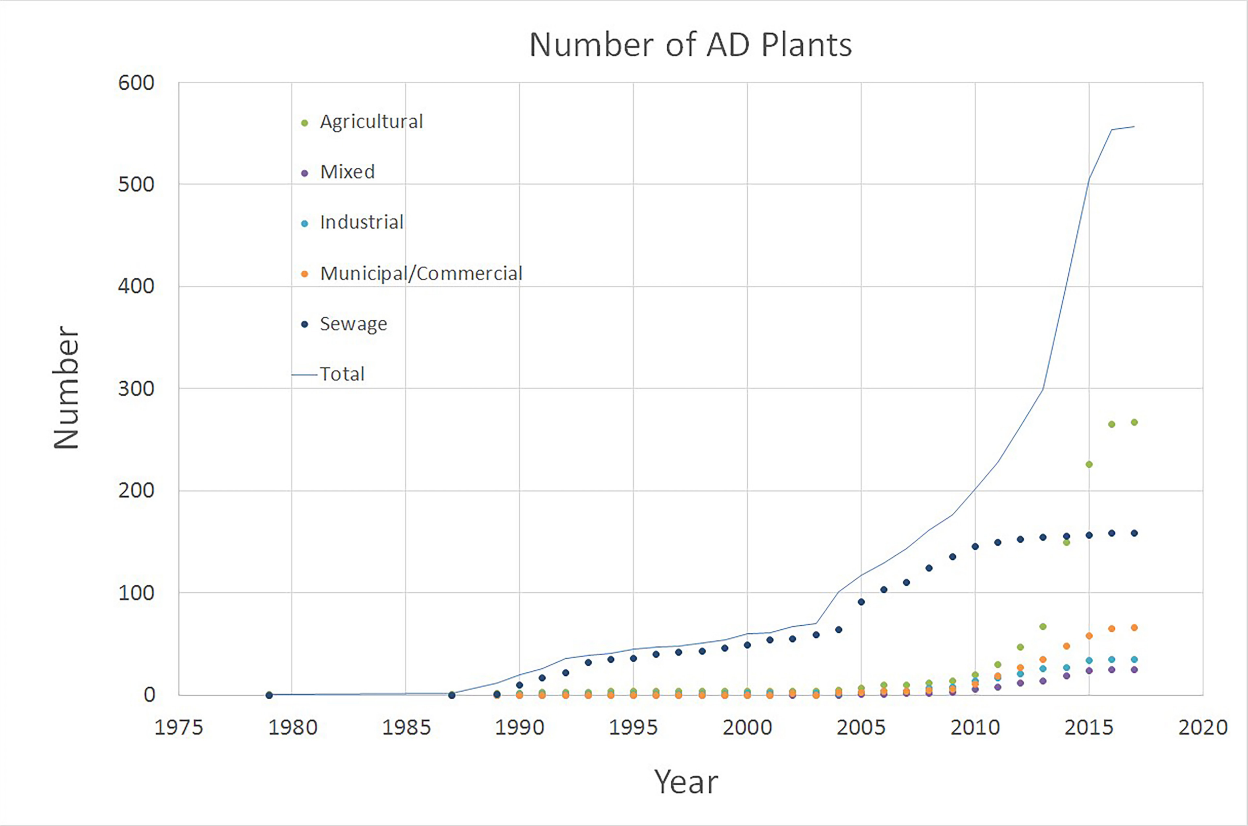
Distribution		**Diffusion Rate**		
		Slow	**Steady**	**Aggressive**
	Decentralised	Alt 1	Alt 2	Alt 3
	Uniform	Alt 4	Alt 5	Alt 6
	Centralised	Alt 7	Alt 8	Alt 9

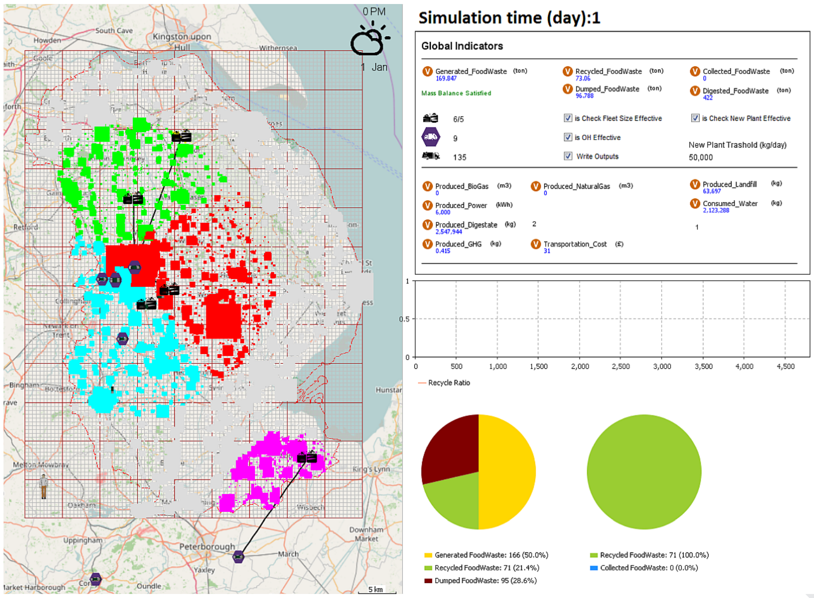
	Objective	ABM Input Parameter/Variable	ABM Output Variables
Environmental	Minimize (fresh) water consumed	AD Type, Technology, Bussiness Model	Type and net amount of water used by AD plants (lt)
	Maximise digestate	AD Type, Technology, Bussiness Model	Produced digestate (lt)
	Minimize food waste to landfill	Recycle rate (kg/kg)	Food waste to landfill (ton)
	Emitted CO_2	CO2 emmision rate of transport vehicles (m3/km)	CO2 produced by trucks (m3)
Social	Minimize Visual impact of AD plant	Acceptablity parameter, increased diffusion	Negatively affected people (number)
Economic	Minimize capital costs	AD Type, Technology, Bussiness Model	Investment and operation cost (million £)
	Maximize net biogas produced	AD Type, Technology, Bussiness Model	Net generated biogas (kWhr)
	Minimize operating costs	Recycle rate (kg/kg)	Food waste to landfill (ton)
	Minimize transport costs	CO2 emmision rate of transport vehicles (m3/km)	CO2 produced by trucks (m3)

Decision No	Decision Making Driver	Dumped Food Waste (M ton)	Consumed Water (M ton)	Produced Biogas (M m3)	Produced Digestate (M ton)	Emitted CO2 (M ton)	Trans. Cost (K £)	Cap. Cost (M £)	Opr. Cost (M £)	Dist. Index
1	None	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111
2	Economy	0.017	0.017	0.017	0.017	0.017	0.300	0.300	0.300	0.017
3	Energy	0.013	0.013	0.900	0.013	0.013	0.013	0.013	0.013	0.013
4	Waste	0.900	0.0125	0.0125	0.0125	0.0125	0.0125	0.0125	0.0125	0.0125
5	Transport	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000
6	Social	0.0125	0.0125	0.0125	0.0125	0.0125	0.0125	0.0125	0.0125	0.900
7	Carbon	0.013	0.013	0.013	0.013	0.900	0.013	0.013	0.013	0.013

Table 3 Weights explored based on different decision-making preferences and drivers eg. Economy, energy, waste or low carbon.

Dumped Food Waste (M ton)	Consumed Water (M ton)	Produced Biogas (M m3)	Produced Digestate (M ton)	Emitted CO2 (M ton)	Trans. Cost (K £)	Cap. Cost (M £)	Opr. Cost (M £)	Dist. Index
3.616	7.74	149.43	7.89	6.89	7778	16.0	92.3	17410
3.774	7.65	154.44	7.89	11.07	10104	19.5	95.0	29908
3.284	7.65	167.75	7.98	13.24	14564	27.1	98.5	58123
3.604	7.86	177.38	8.07	49.63	60442	26.6	98.0	12298
3.227	7.91	185.11	8.15	64.95	81347	37.2	104.7	20798
2.802	7.96	200.92	8.21	62.46	91110	29.6	113.1	31567
3.772	7.87	153.74	8.07	41.12	49936	18.6	94.7	8436
3.808	7.74	158.18	8.03	37.90	46428	21.2	93.5	11653
2.614	7.97	201.98	8.23	80.38	97428	23.9	110.1	15831


Number of AD Plants
Number
Year
0
100
200
300
400
500
600
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
Agricultural
Mixed
Industrial
Municipal/Commercial
Sewage
Total



Simulation time (day):1

Global Indicators

Generated_FoodWaste (ton) 169.847

Recycled_FoodWaste (ton) 73.06

Collected_FoodWaste (ton) 0

Dumped_FoodWaste (ton) 96.788

Digested_FoodWaste (ton) 422

Mass Balance Satisfied

6/5

9

135

☑ is Check Fleet Size Effective

☑ is OH Effective

☑ Write Outputs

☑ is Check New Plant Effective

New Plant Trashold (kg/day)
50,000

Produced_BioGas (m3) 0

Produced_NaturalGas (m3) 0

Produced_Landfill (kg) 63,697

Produced_Power (kWh) 6,000

Consumed_Water (kg) 2,123,288

Produced_Digestate (kg) 2,547,944

2

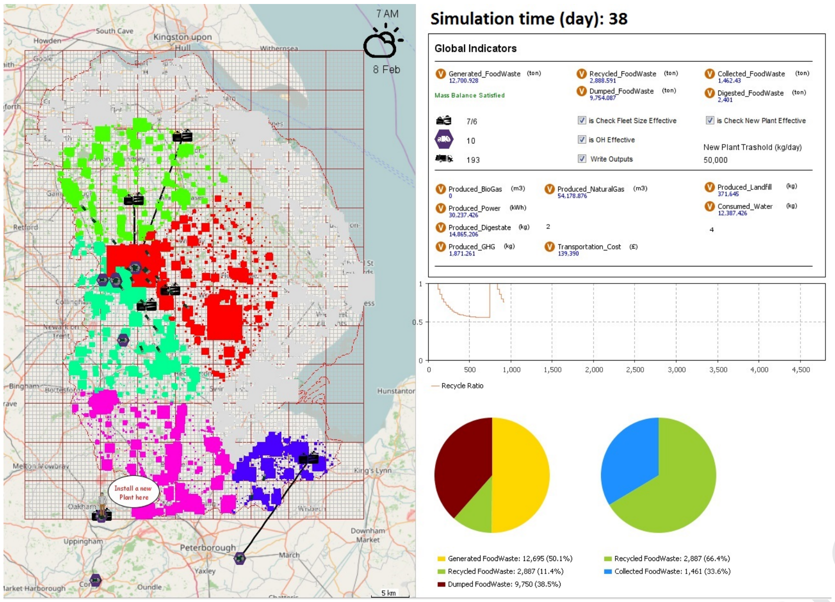
1

Produced_GHG (kg) 0.415

Transportation_Cost (£) 31

- 🟨 Generated FoodWaste: 166 (50.0%)
- 🟩 Recycled FoodWaste: 71 (21.4%)
- 🟥 Dumped FoodWaste: 95 (28.6%)

- 🟩 Recycled FoodWaste: 71 (100.0%)
- 🟦 Collected FoodWaste: 0 (0.0%)



Simulation time (day): 38

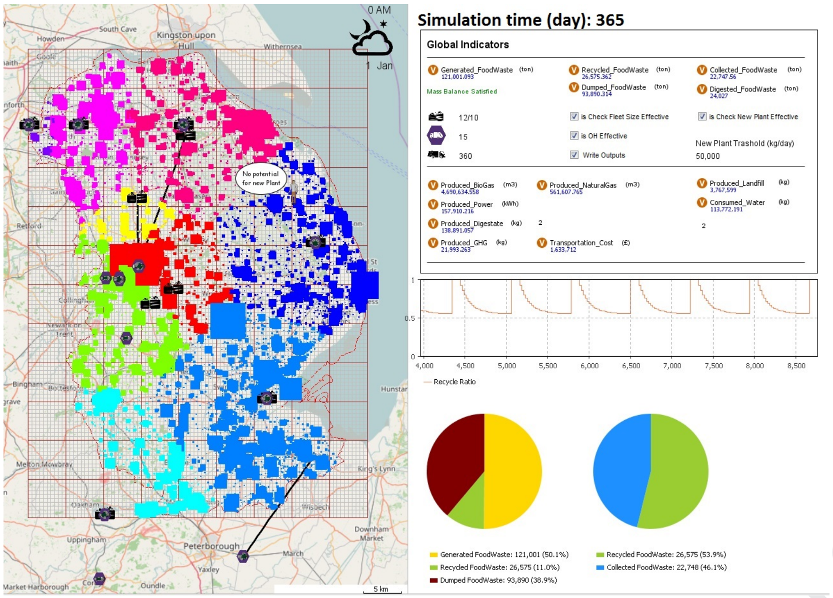
Global Indicators

Generated_FoodWaste (ton) 12,700.928
Recycled_FoodWaste (ton) 2,888.591
Collected_FoodWaste (ton) 1,462.43
Mass Balance Satisfied
Dumped_FoodWaste (ton) 9,754.087
Digested_FoodWaste (ton) 2,401

7/6
10
193
☑ is Check Fleet Size Effective
☑ is OH Effective
☑ Write Outputs
☑ is Check New Plant Effective
New Plant Trashold (kg/day) 50,000

Produced_BioGas (m3) 0
Produced_NaturalGas (m3) 54,178.876
Produced_Landfill (kg) 371,645
Produced_Power (kWh) 30,237.426
Consumed_Water (kg) 12,387,426
Produced_Digestate (kg) 14,865,206
2
4
Produced_GHG (kg) 1,871.261
Transportation_Cost (£) 139,390

Generated FoodWaste: 12,695 (50.1%)
Recycled FoodWaste: 2,887 (11.4%)
Dumped FoodWaste: 9,750 (38.5%)
Recycled FoodWaste: 2,887 (66.4%)
Collected FoodWaste: 1,461 (33.6%)



Simulation time (day): 365

Global Indicators

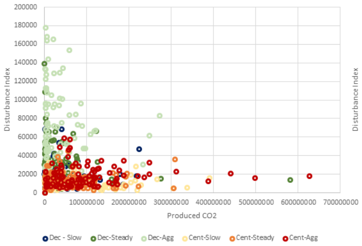
Generated_FoodWaste (ton) 121,001.093
Mass Balance Satisfied
Recycled_FoodWaste (ton) 26,575.362
Dumped_FoodWaste (ton) 93,890.314
Collected_FoodWaste (ton) 22,747.56
Digested_FoodWaste (ton) 24,027

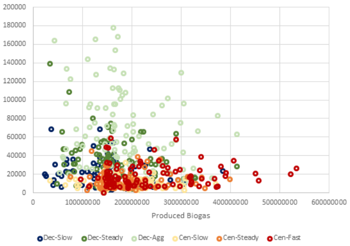
12/10
15
360
☑ is Check Fleet Size Effective
☑ is OH Effective
☑ Write Outputs
☑ is Check New Plant Effective
New Plant Trashold (kg/day) 50,000

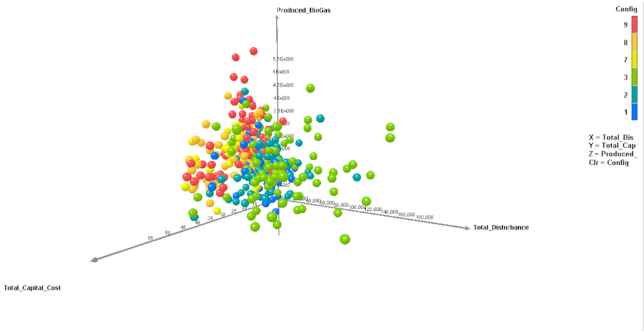
Produced_BioGas (m3) 4,690,634.558
Produced_Power (kWh) 157,910.216
Produced_Digestate (kg) 138,891,057
Produced_GHG (kg) 21,993.263
Produced_NaturalGas (m3) 561,607.765
Transportation_Cost (£) 1,633,712
Produced_Landfill (kg) 3,767,599
Consumed_Water (kg) 113,772,191
2
2

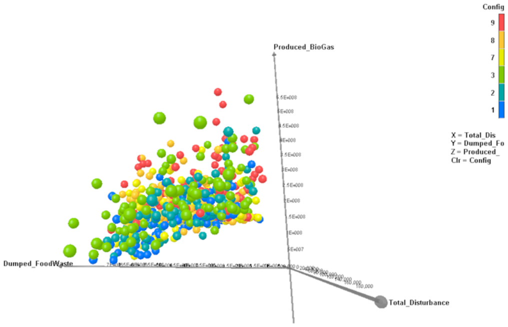
🟨 Generated FoodWaste: 121,001 (50.1%)
🟩 Recycled FoodWaste: 26,575 (11.0%)
🟥 Dumped FoodWaste: 93,890 (38.9%)

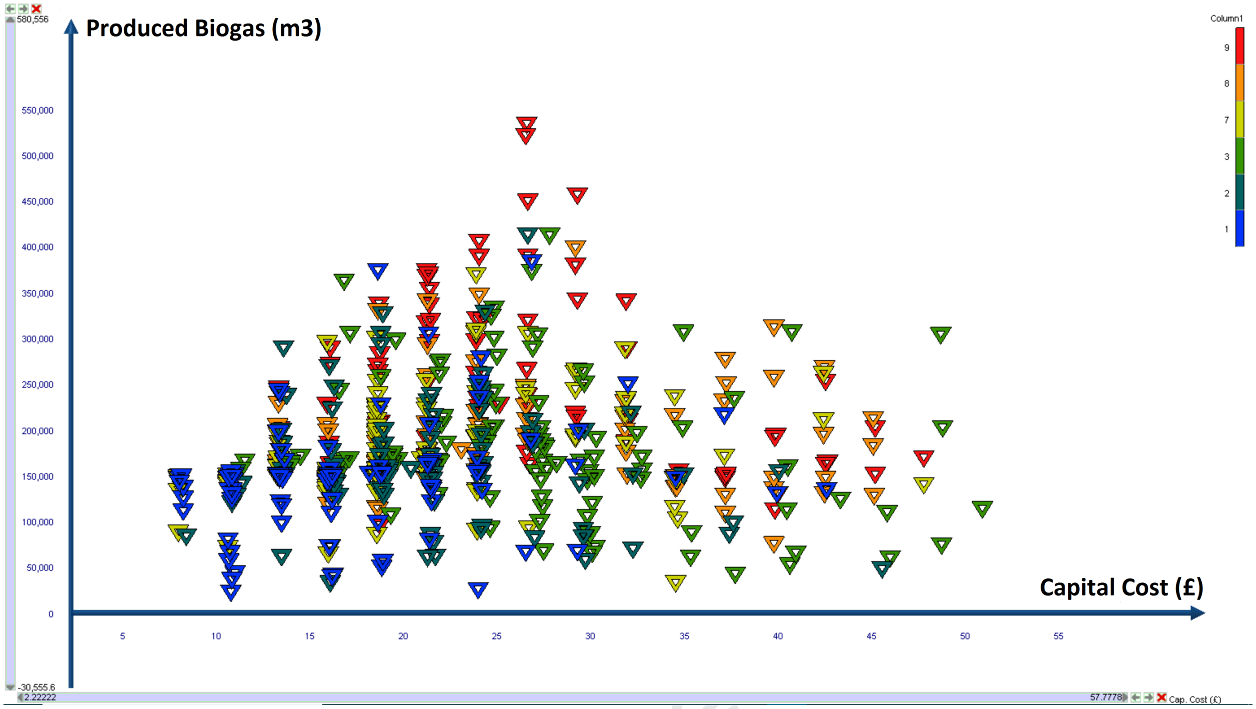
🟩 Recycled FoodWaste: 26,575 (53.9%)
🟦 Collected FoodWaste: 22,748 (46.1%)

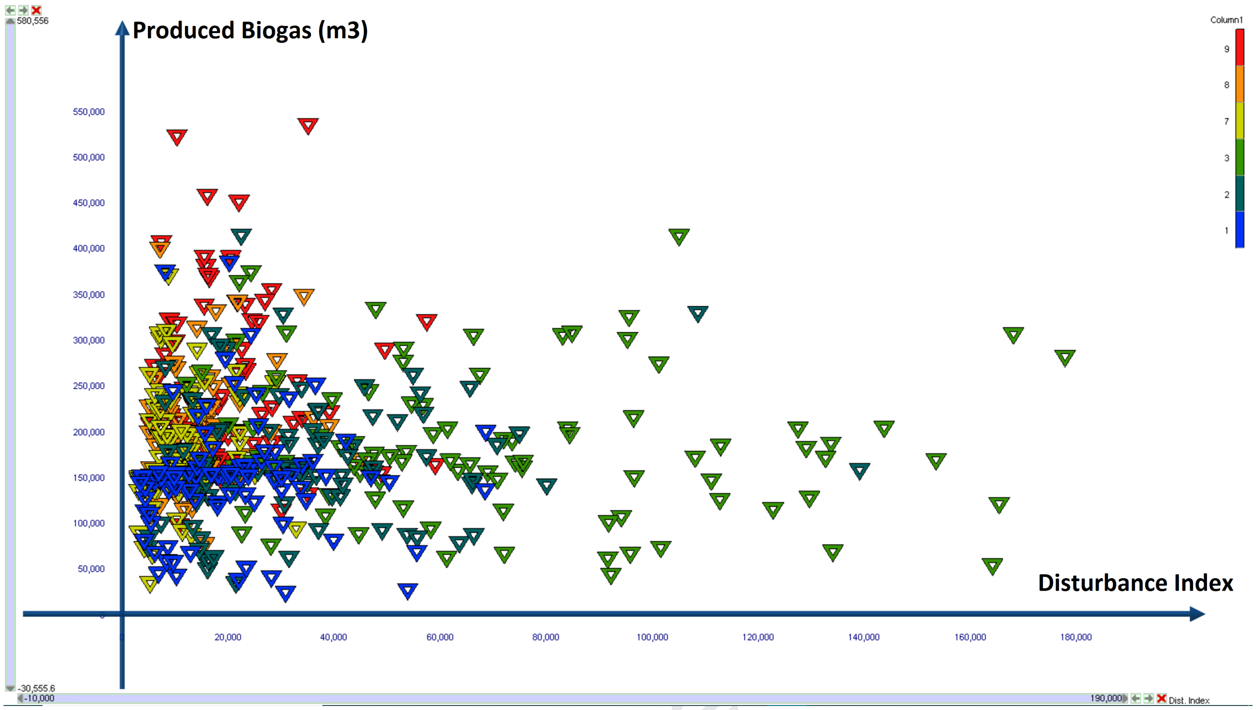

200000
180000
160000
140000
120000
100000
80000
60000
40000
20000
0
Disturbance Index
0
100000000
200000000
300000000
400000000
500000000
600000000
700000000
Produced CO2
Dec - Slow
Dec-Steady
Dec-Agg
Cent-Slow
Cent-Steady
Cent-Agg

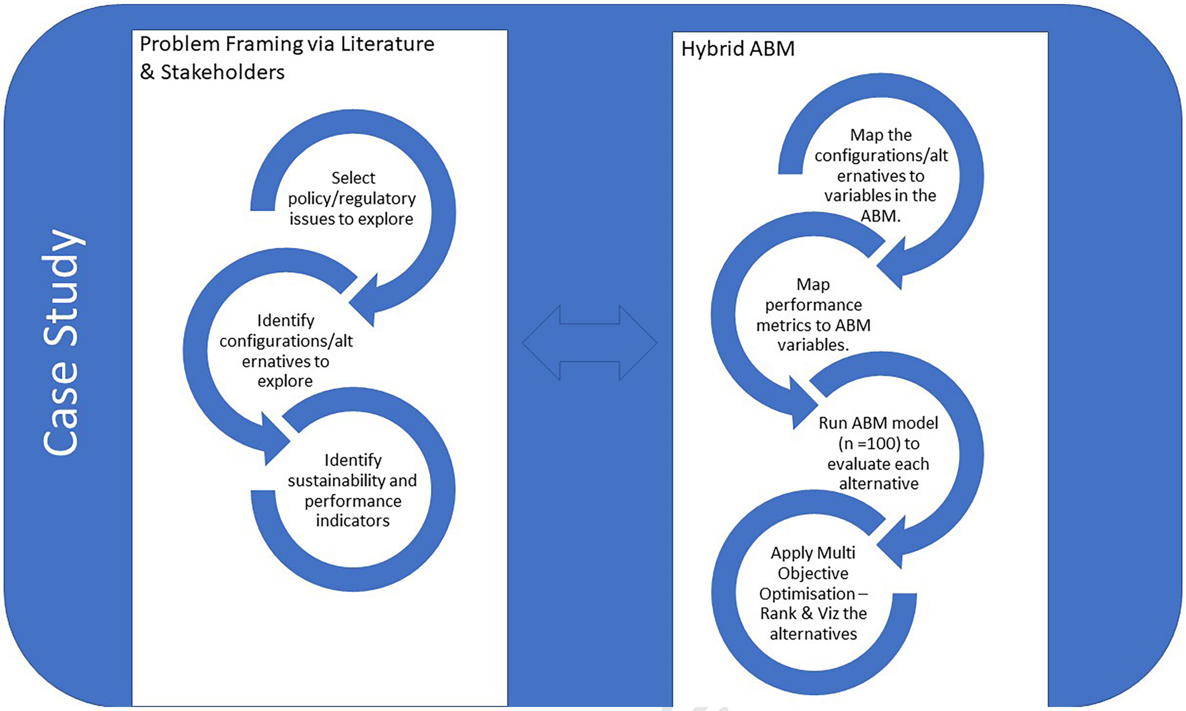

200000
180000
160000
140000
120000
100000
80000
60000
40000
20000
0
Disturbance Index
0
100000000
200000000
300000000
400000000
500000000
600000000
Produced Biogas
Dec-Slow
Dec-Steady
Dec-Agg
Cen-Slow
Cen-Steady
Cen-Fast

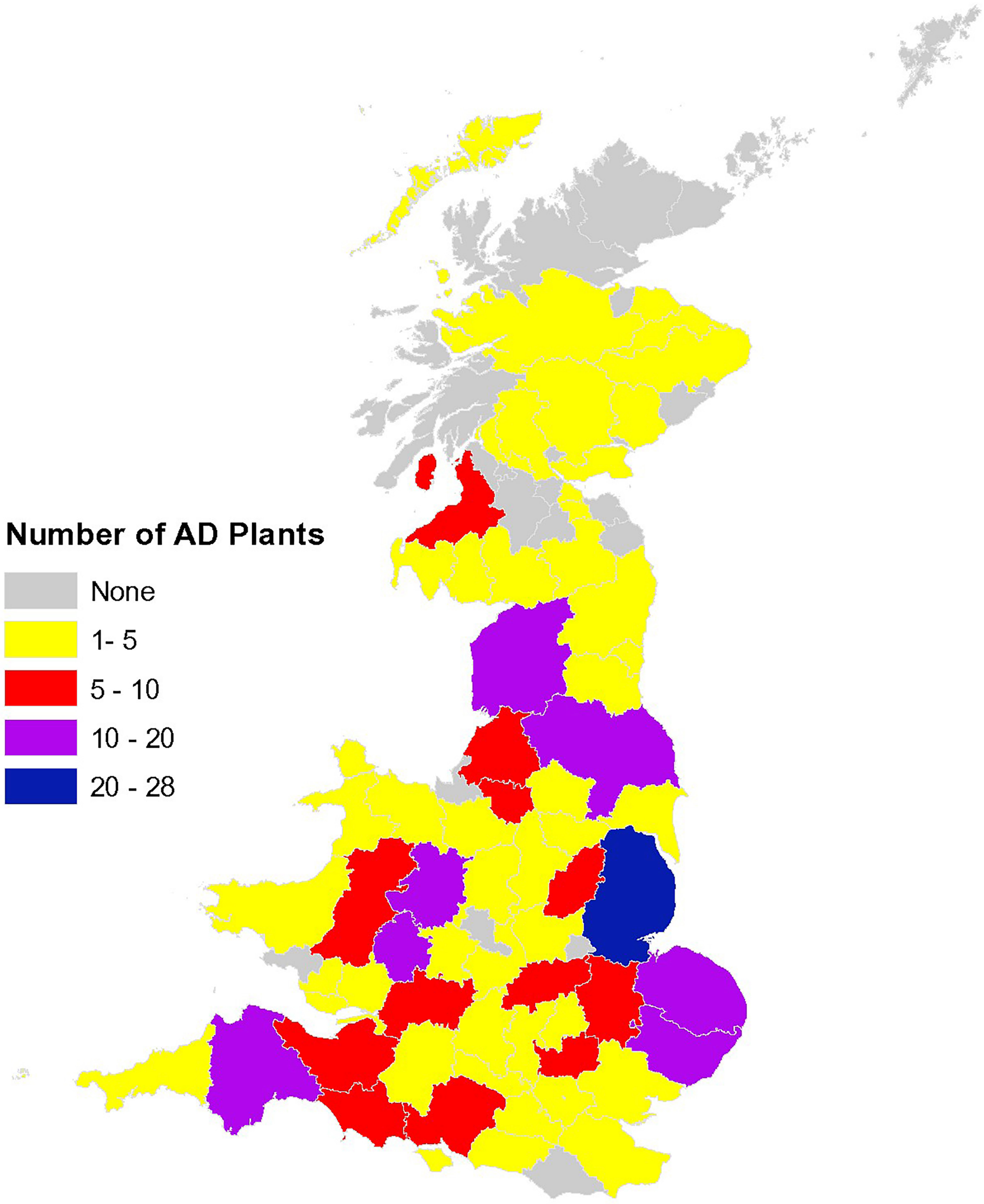

Produced_BioGas
5.5E+008
5E+008
4.5E+008
4E+008
3.5E+008
Total_Disturbance
40,000
60,000
80,000
100,000
120,000
140,000
160,000
180,000
Total_Capital_Cost
55
50
45
40
35
30
25
20
15
Config
9
8
7
3
2
1
X = Total_Dis
Y = Total_Cap
Z = Produced_
Clr = Config

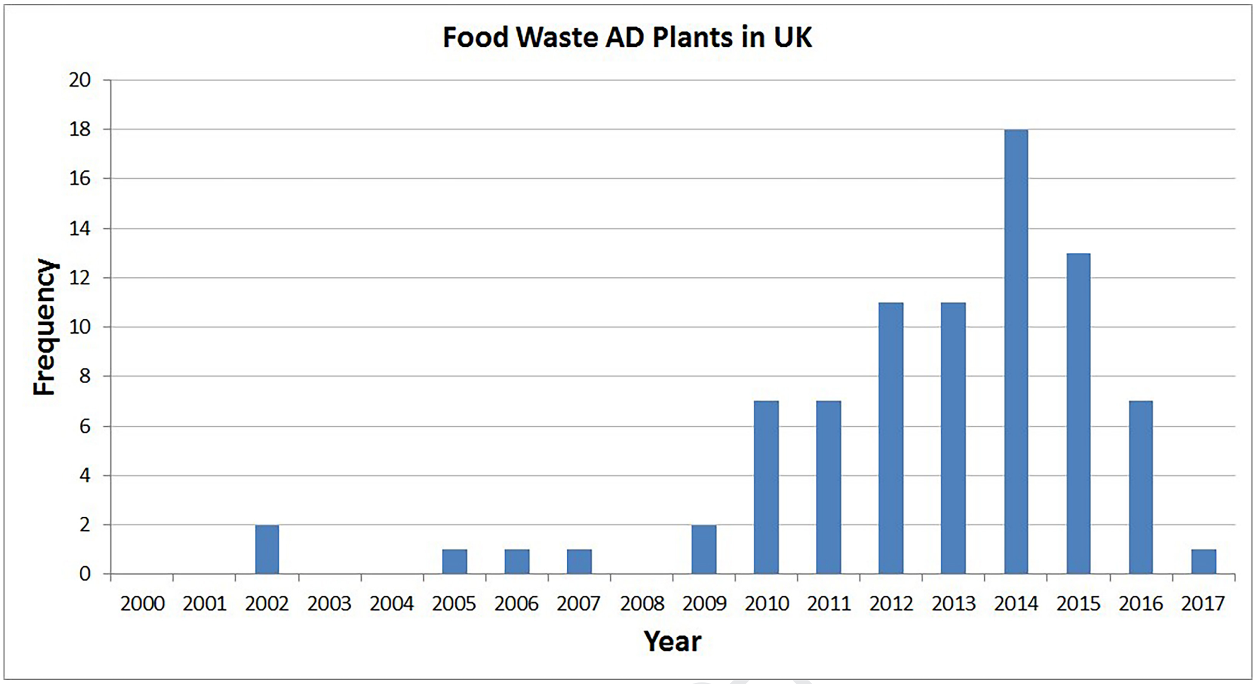

Config
9
8
7
3
2
1
Produced_BioGas
5.5E+008
5E+008
4.5E+008
4E+008
3.5E+008
3E+008
2.5E+008
2E+008
1.5E+008
1E+008
5E+007
Dumped_FoodWaste
Total_Disturbance
140,000
160,000
180,000
X = Total_Dis
Y = Dumped_Fo
Z = Produced_
Clr = Config

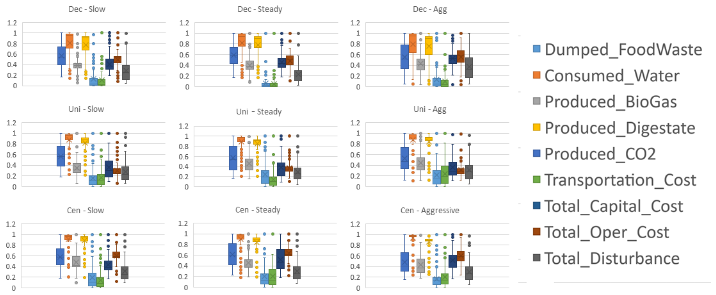

Produced Biogas (m3)
Capital Cost (£)
580,556
550,000
500,000
450,000
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
-30,555.6
5
10
15
20
25
30
35
40
45
50
55
2.22222
57.7778
Cap. Cost (£)
Column1
9
8
7
3
2
1


580,556
Produced Biogas (m3)
550,000
500,000
450,000
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
-30,555.6
Column1
9
8
7
3
2
1
Disturbance Index
0
20,000
40,000
60,000
80,000
100,000
120,000
140,000
160,000
180,000
-10,000
190,000
Dist. Index

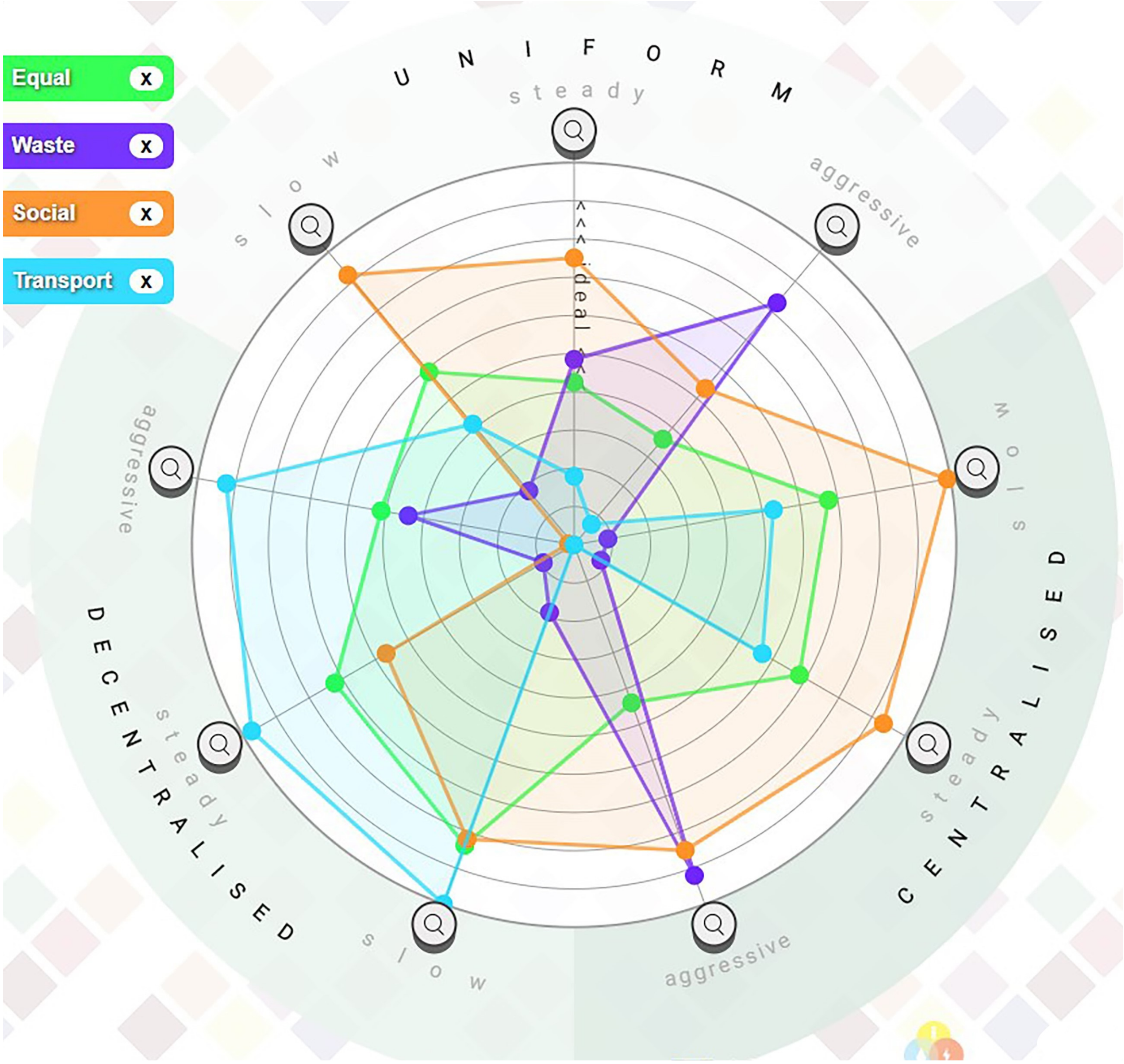

Case Study
Problem Framing via Literature & Stakeholders
Select policy/regulatory issues to explore
Identify configurations/alternatives to explore
Identify sustainability and performance indicators
Hybrid ABM
Map the configurations/alternatives to variables in the ABM.
Map performance metrics to ABM variables.
Run ABM model (n =100) to evaluate each alternative
Apply Multi Objective Optimisation – Rank & Viz the alternatives

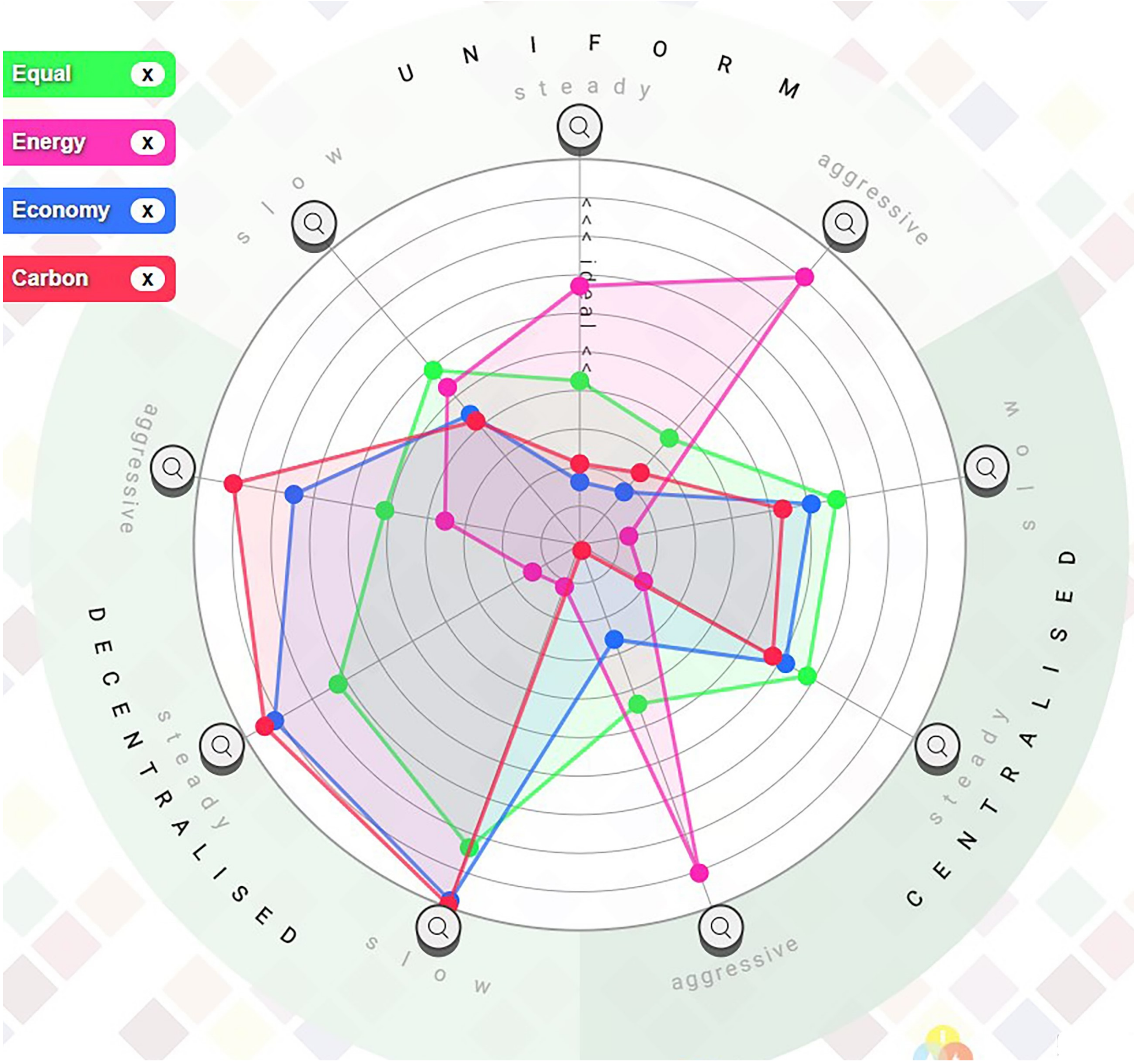

Number of AD Plants
None
1- 5
5 - 10
10 - 20
20 - 28

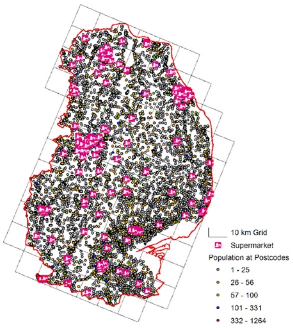

Food Waste AD Plants in UK
Frequency
20
18
16
14
12
10
8
6
4
2
0
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Year

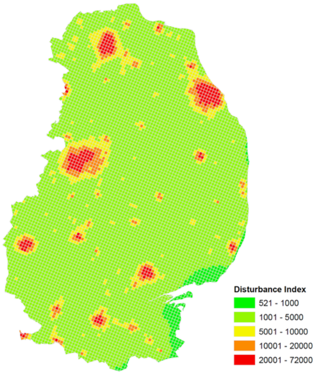

Dec - Slow
Dec - Steady
Dec - Agg
Uni - Slow
Uni - Steady
Uni - Agg
Cen - Slow
Cen - Steady
Cen - Aggressive
1.2
1
0.8
0.6
0.4
0.2
0
Dumped_FoodWaste
Consumed_Water
Produced_BioGas
Produced_Digestate
Produced_CO2
Transportation_Cost
Total_Capital_Cost
Total_Oper_Cost
Total_Disturbance

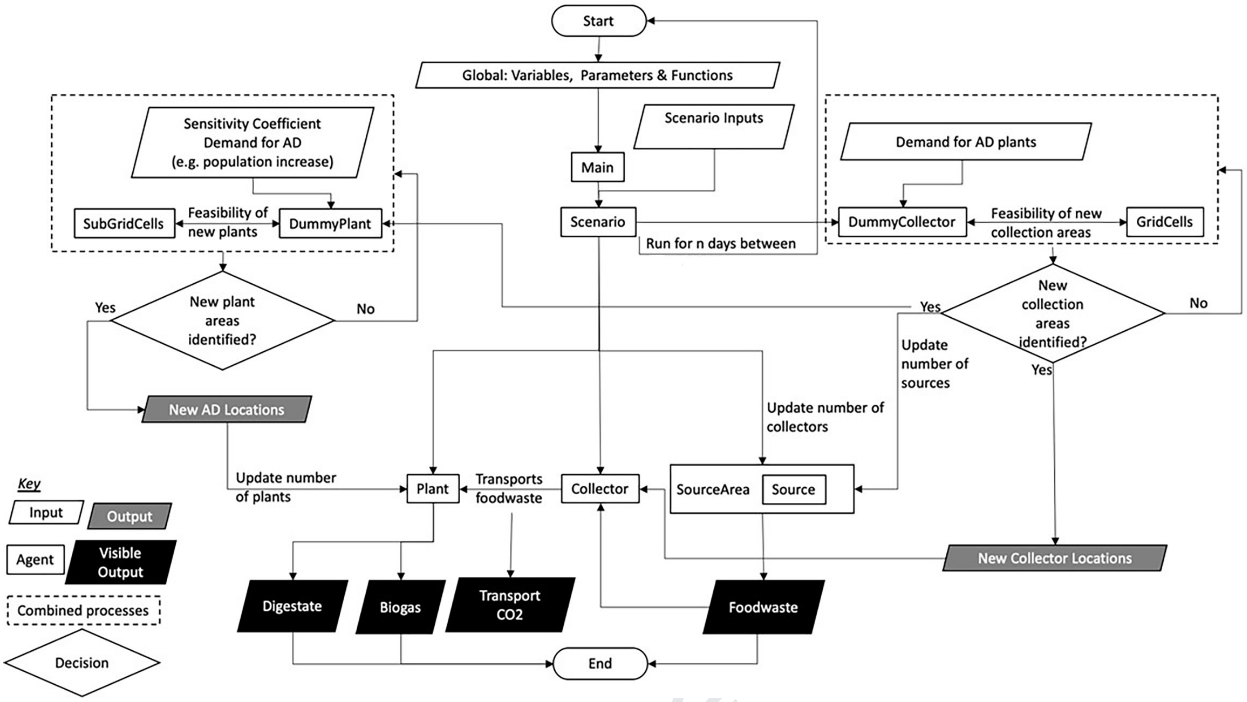

Dumped Food Waste (M ton)
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Consumed Water (M ton)
8.00
7.90
7.80
7.70
7.60
7.50
7.40
Produced Biogas (M m3)
250.00
200.00
150.00
100.00
50.00
0.00
Produced Digestate (M ton)
8.30
8.20
8.10
8.00
7.90
7.80
7.70
Emitted CO2 (M ton)
100.00
80.00
60.00
40.00
20.00
0.00
Trans. Cost (K £)
120000
100000
80000
60000
40000
20000
0
Cap. Cost (M £)
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
Opr. Cost (M £)
120.0
100.0
80.0
60.0
40.0
20.0
0.0
Dist. Index
70000
60000
50000
40000
30000
20000
10000
0
Dec-Slow
Dec-Steady
Dec-Agg.
Uni-Slow
Uni-Steady
Uni-Agg.
Cent-Slow
Cen-Steady
Cen-Agg

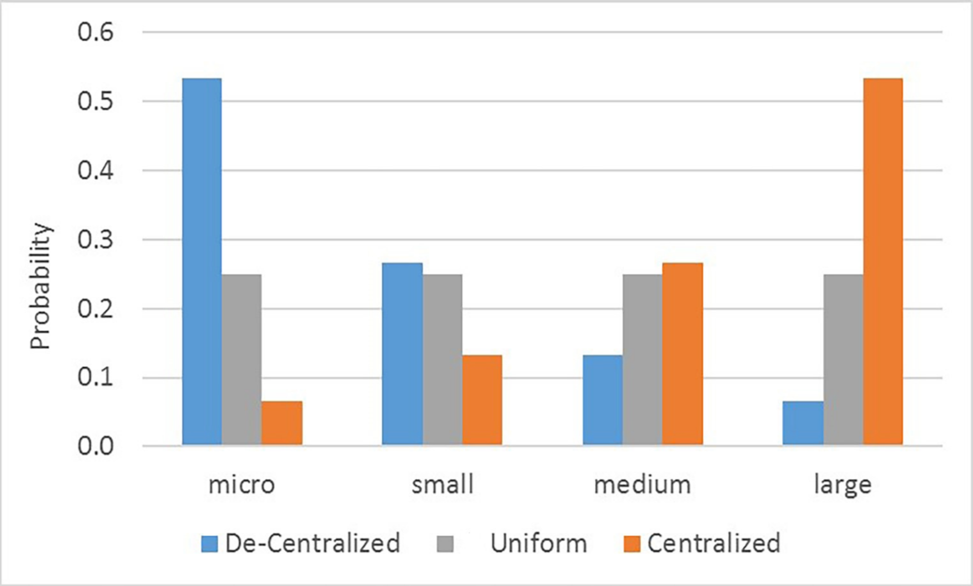

Equal X
Waste X
Social X
Transport X
UNIFORM
CENTRALISED
DECENTRALISED
steady
aggressive
slow
steady
aggressive
slow
steady
aggressive
slow
<<< ideal


Equal x
Energy x
Economy x
Carbon x
UNIFORM
steady
aggressive
slow
CENTRALISED
steady
aggressive
slow
DECENTRALISED
steady
aggressive
slow
<<< ideal <<<


10 km Grid
Supermarket
Population at Postcodes
1 - 25
26 - 56
57 - 100
101 - 331
332 - 1264


Disturbance Index
521 - 1000
1001 - 5000
5001 - 10000
10001 - 20000
20001 - 72000


Start
Global: Variables, Parameters & Functions
Scenario Inputs
Main
Scenario
Run for n days between
Sensitivity Coefficient
Demand for AD
(e.g. population increase)
SubGridCells
Feasibility of new plants
DummyPlant
New plant areas identified?
Yes
No
New AD Locations
Update number of plants
Demand for AD plants
DummyCollector
Feasibility of new collection areas
GridCells
New collection areas identified?
Yes
No
Yes
Update number of sources
Update number of collectors
New Collector Locations
Plant
Transports foodwaste
Collector
SourceArea
Source
Digestate
Biogas
Transport CO2
Foodwaste
End
Key
Input
Output
Agent
Visible Output
Combined processes
Decision


0.6
0.5
0.4
0.3
0.2
0.1
0.0
Probability
micro
small
medium
large
De-Centralized
Uniform
Centralized

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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