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WASTE BIOMASS BASED ENERGY SUPPLY CHAIN NETWORK DESIGN

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Abstract:
Reducing dependence on fossil fuels, alleviating environmental impacts and ensuring sustainable economic growth are among the most promising aspects of utilizing renewable energy resources. Biomass is a major renewable energy resource that has the potential for creating sustainable energy systems that are critical in terms of social welfare. Utilization of biomass for bioenergy production is an efficient alternative for meeting rising energy demands, reducing greenhouse gas emissions and thus alleviating climate change. A supply chain for such an energy source is crucial for assisting deliverance of a competitive end product to end-user markets. Considering the existing constraints, a mixed integer linear programming (MILP) model for waste biomass based supply chain was proposed in this study for economic performance optimization. Performance of the proposed modelling approach was demonstrated with a real life application study realized in İstanbul. Moreover, sensitivity analyses were conducted which would serve as a foresight for efficient management of the supply chain as a whole

Keywords:
Biomass supply chain, biomass, biogas, anaerobic digestion, supply chain network design

1. Introduction
Increasing concerns on climate change and energy security nowadays encourage world countries utilize natural resources more effectively. International Energy Agency (IEA) data foresees that the global energy demand for the year 2040 would be one thirds higher than the energy demand for the year 2015 (IEA, 2014). Fossil fuels such as oil, coal and natural gas that are termed to be non-renewable energy resources supply a great portion of global energy demand at a level of 88% (Othman et al. 2017). Nevertheless, a trust issue with respect to these energy resources emerged after the Oil Crisis of 1973. Despite the petroleum embargo being a short-term event, some of its consequences manifested themselves in the long run. Industrialized countries gravitated towards alternative energy resources after this crisis. This quest was pushed on as well because of the rising fossil fuel (oil, natural gas) prices, dependency on the energy imported from a limited number of countries and the intensive generation of greenhouse gases by fossil fuels. Renewable energy resources started to become of importance throughout this period (Nematollahi et al. 2016). It is expected that the utilization of renewable energy resources would increase from the recent 13.5% levels to 30% in year 2040; in order to meet the increasing energy demands, to comply with the national regulations for greenhouse gas emissions and to restrict utilization of fossil fuels (IEA, 2014).
Biomass is termed as a potential renewable energy resource to be utilized through a variety of biomass conversion technologies for the production of biofuels, bioenergy, biochemical and other bioproducts that are highly valuable (Ng et al. 2015). Bioenergy generated from renewable raw material resources has the potential to enhance economic growth, energy security and resource sustainability. Despite all these advantages, a long-term multi-period strategical planning should be established in order for bioenergy being able to compete with energy production from fossil fuels. Researchers mostly focused on technologies that convert biomasses to bioenergy, however, a sustainable and reliable biomass supply chain network should be developed in order to provide an end product that is highly competitive and that would increase customer satisfaction. The best strategy for planning the biomass supply chain would be having full information on the parameters (Awudu and Zhang, 2012), however the main challenge with this

respect stems from the presence of numerous uncertainties. These uncertainties include, but not limited to unforeseen weather conditions, transport and storage of biomass, demand for biofuels, raw material and product prices, production technologies, and biofuel related policies (Bairamzadeh et al. 2018).

Bioenergy which is a clean energy resource cannot be utilized on commercial levels despite its numerous advantages, due to the presence of various challenges related to biomass supply chain management and general deficiencies (Sansaniwal et al. 2017). Considering all these facts and in order for sustainably meeting the growing demand for energy, a decision model was developed for the waste biomass based energy supply chain that is dependent on real-life assumptions and restrictions to cope with problems related to fossil fuel consumption in Turkey, which possesses highly rich resources with respect to biomass energy. Main objective of this study is providing the most convenient supply chain configuration that maximizes profitability all through the related processes for designing the optimal planning for bioenergy production. A mixed integer linear programming model (MILP) that allows decision-making in anaerobic digestion based bioenergy conversion procedure by determining the biomass and end product flow rate between the nodes of the network designed to contain the number of storage facilities and plants, their capacities and locations was proposed for this purpose. Contribution of this study is based on the development of a mathematical programming model that combines all elements of waste biomass based energy supply chain under a single framework in order to optimize decision-making for strategic supply chain decisions. Execution of this research contributes to making use of waste in energy production and as compost, instead of having them idly stored in an environmentally detrimental manner; to meet the current energy deficit in our country, to alleviate our dependence on foreign countries for fertilizer needs and to enhance local economy.

The remainder of this article is organized as follows: Literature review is presented in the 2nd section. The problem is defined and the proposed mathematical method is explained in the methodology section, namely the 3rd section. A case study based on a real life problem is demonstrated along the 4th section. Results and verification of the proposed model is provided in the 5th section. Finally, research is thoroughly summarized and recommendations for certain future research topics to be investigated is provided in the 6th section.

2. Literature Review

Researchers lately focused on development of mathematical models for the design of biomass supply chain. Literature review revealed that numerous studies were conducted with respect to development of biomass supply chain models, and some of these research will be reviewed herein.

Uncertainties play a major role in decision-making for biomass supply chains, as was stated along the introduction chapter. Some of the developed models created different scenarios by taking efficiency, demand and price uncertainties into consideration. Ekşioğlu et al. (2009), proposed a biomass based biorefinery supply chain model that utilized corn and ligneous waste to produce ethanol. They formulized a multi-period MILP model that predicted material flows along with the network design. Moreover, a scenario analysis was conducted taking existing biomass options into consideration. An et al. (2011), developed a mathematical model for maximizing total profit in lignocellulosic biomass based biofuel supply chain that is planned to generate ethanol as the end-product. Effects of uncertainty sources such as biomass cost, biomass efficiency, ethanol prices and ethanol demands on biomass supply chain performance was investigated. Zhang and Hu (2013), constructed two distinct MILP models that minimized the cost of supply chain and optimized the number, capacity and locations of biorefinery plants by using corn waste. They considered these models on an annual and periodical (monthly) basis. Sensitivity of biofuel demand was considered in this periodical based model. Paulo et al. (2015) developed a MILP model for bioenergy supply chain design and planning for bioenergy production by utilizing forestry waste as the biomass supply.

They conducted sensitivity analysis on biomass availability, logistics, production and investment costs for determining their corresponding effects on supply chain network. Duarte et al. (2016), proposed a MILP model that aimed at providing the maximum benefit for the supply chain design of the sustainable biofuel produced from the agricultural residue known as Coffee Cut Stem (Coffee-CS). They evaluated the effect of CO2 price by conducting sensitivity analysis. By taking forest biomass as the raw material, Zhang et al. (2017) focused on formulizing a MILP model for designing a supply chain network that minimized total system cost. In their proposed study, they determined the plant locations by Geographical Information System (GIS) beforehand and used these data as the input for optimization modelling method. They investigated sensitivities of the uncertainties such as ethanol demand and biomass availability.

During the corresponding literature review, it was observed that MILP model was the most commonly used method among all mathematical programming techniques for the assessment of biomass supply chain. Still, unlike most researchers, Marufuzzaman and Ekşioğlu (2017), proposed the mixed integer non-linear programming model (MINLP) that eliminated the deadlock in biomass supply chain of lignocellulosic biomass due to seasonality by dynamic transportation routing and utilization of multi-mode facilities, while minimizing total cost. They solved a linear approach of their proposed model by using hybrid Benders-based rolling horizon algorithm. Rentizelas et al. (2009), developed a MINLP model that maximized the net present value (NPV) of the investment on bioenergy conversion systems for trigeneration (electricity, heating and cooling) that used agricultural waste as the raw material for biomass. They utilized genetic algorithm (GA) and quadratic programming (SQP) as their optimization methods. By using a simulation model for biomass supply chain, Zhang et al. (2012), developed a supply chain model by using Arena simulation software that determined potential plant locations based on GIS, and that took biomass raw material cost, energy consumption and greenhouse emissions into account. Windisch et al. (2013) predicted the time spent for each organizational and managerial activity regarding forest biomass supply chain of two different countries by using mutually exclusive event simulation. They utilized business process mapping methodology for the comparison of the business processes and shareholders that take place in each supply chain.
Summing up, as the related literature was reviewed, it was observed that most of the studies focused on biofuel conversion by similar biomass raw materials having various sources of uncertainty. Selection of animal waste as the raw material to be used in this study with respect to food and feed safety, along with the application of the supply chain model designed for utilization of wholesale vegetable and fruit market waste in energy production contributes to the current literature in terms of enhancing renewable energy resources.

3. Methodology

This study proposes the MILP model for the design and management of waste biomass based energy supply chain that takes economic performance into consideration. This supply chain at hand consists of raw material suppliers, biomass storage facilities, biogas plants and points of demand. Figure 1 demonstrates an overview of the supply chain network used for the model.

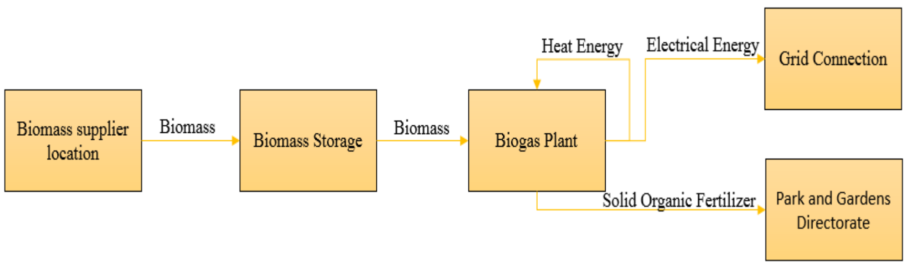

Figure 1. General structure of biomass based energy supply chain network

3.1. Problem Definition

Waste biomass based energy supply chain covers the processes commencing from suppliers and extending to points of demand. Model inputs are cattle manure, hen manure and broiler manure for the supply chain in question. Waste collected from farms and wholesale markets for vegetable and fruit are transported from biomass storage facilities to biogas plants, where they are fed to a digester that produces biogas and high organic content fertilizer through anaerobic digestion process. Collective anaerobic digestion of waste enhances biogas efficiency, which in turn provides important advantages such as an increase in energy sales, savings in organic waste management and decrease in greenhouse gases related to fertilizer and fossil fuel consumption. Produced biogas is then converted into heat and electrical energy within the biogas cogeneration (CHP) plant. Electrical energy is fed to the national electricity grid. Waste heat on the other hand, is utilized as process heat for the plant. Fertilizer that is the effluent of digestion process is sent to the separator where it is converted into solid and liquid organic fertilizer. Solid organic fertilizer is put into use through sales of the material to municipalities to be used in parks and gardens. Digestion effluent liquid organic fertilizer is used for partial fulfilling of water need in the digester. Waste biomass based energy supply chain represents an interconnecting integral system by providing organic waste treatment, renewable energy generation and recycling simultaneously. The model that is to optimize the supply chain in question is constructed so as to determine the relevant system configuration which maximizes profit all through the supply chain. The model aims to make decisions that correspond to below listed items:

1. Supply of biomass resources,
2. Biomass amount transported to plants and storage facilities,
3. Number of plants, their capacities and locations,
4. Number of storage facilities, their capacities and locations,
5. Amount of biogas and electricity produced by each plant,
6. Water quantity to be added to the digester,
7. Amount of fertilizer transported to the point of demand.

3.2. Model Formulation

In this section, the basic mathematical model used in the design of the network is described. The following notations (Table 1) are used for indices, input parameters, and decision variables in the integrated model. Variables are depicted in lowercase letters, whereas the parameters are depicted in uppercase letters.

Table 1. Notation of mathematical modeling

INDICES	
t	plant locations
d	storage facility locations
r	supplier locations
b	waste biomass types
k	plant capacity
c	storage capacity
i	points of demand

PARAMETERS	
$TBKap_{tk}$	biomass processing capacity for k capacity for the plant located at t (ton)
$TEKap_{tk}$	electricity generation capacity for k capacity t located plant (kWe)
$DBKap_{dc}$	biomass storage capacity for c capacity storage facility located at d (ton)
AB_{rb}	available b waste biomass in supplier location of r (ton)
BDO_{b}	biogas conversion potential of waste biomass b (m^3/ ton VS)
MO	methane ratio of biogas (%)
BMI	energy content of biogas in terms of methane (kWh/m^3)
BEV	efficiency of biogas conversion to electricity in cogeneration unit (%)
GDO_{b}	fertilizer conversion rate of waste biomass b (%)
TK_{b}	solid matter ratio of waste biomass b (%)
UKM_{b}	volatile solids content of waste biomass b (%)
Ma_{rd}	distance between storage facility located at d and supplier located at r (km)
Mb_{dt}	distance between storage facility located at d and plant located at t (km)
Me_{ti}	distance between plant located at t and point of demand located at i (km)
$YMal_{tk}$	investment cost of k capacity level plant located at t (€/kwh)
$DYMal_{dc}$	investment cost of c capacity level storage facility located at d (€/ton)
$BTMal_{b}$	unit transportation rate of waste biomass b (€/ton-km)
GTMal	unit transportation rate of digestion effluent solid organic fertilizer (€/ton-km)
EF	cost of electricity (€/kWh)
GF	price of solid organic fertilizer (€/ton)
SF	price of water (€/m^3)
$BMal_{b}$	purchase cost of waste biomass b (€)
IO	predetermined investment cost rate for operating costs (%)
Df	discounting factor (%)

SKO	solid organic fertilizer conversion ratio in separator (%)
SSO	liquid organic fertilizer conversion ratio in separator (%)
MaxTK	maximum total solid content of biomass slurry in the digester (%)
MinTK	minimum total solid content of biomass slurry in the digester (%)

DECISION VARIABLES	
y_{tk}	the value is 1, if a capacity plant of k will be established in plant location t; otherwise the value is 0
x_{dc}	the value is 1, if a storage facility of c will be established in storage location d; otherwise the value is 0
bt_{rdb}	biomass amount b transported from supplier region r to the storage location d (ton)
bd_{dtb}	biomass amount b transported from storage location d to the plant location t (ton)
g_{ti}	amount of solid organic fertilizer transported from the plant location t to the demand point i (ton)
$atik_t$	digestion effluent liquid organic fertilizer amount in the plant located at t (ton)
$urbiyo_t$	biogas generated in the plant located at t (m^3)
$urelk_t$	electricity generated in the plant located at t (kWh)
s_t	amount of water used in the plant located at t (ton)

3.2.1 Objective Function

The model's objective is maximizing the total profit of supply chain network. Profit is calculated by subtracting the total supply chain costs from the total supply chain revenue generated by sales of end products. The economic objective function comprises of five components. The equation given below demonstrates these five components.

Maximum Total Profit = Total Revenue - (Total Investment Cost + Total Operating Cost + Total Transportation Cost + Biomass Purchasing Cost)

Equation (1) Total revenue consists of two elements, namely the sales of produced electrical energy to national network and the sales of solid organic fertilizer to municipalities.

$$\text{Total Income} = EF \cdot \sum_t urelk_t + GF \cdot \sum_t \sum_i g_{ti} \qquad (1)$$

Equation (2) Total investment cost consists of two elements, namely the investment cost of plants and storage facilities.

$$\text{Total Investment Cost} = Df \cdot \sum_d \sum_c DYMal_{dc} \cdot x_{dc} + Df \cdot \sum_t \sum_k YMal_{tk} \cdot y_{tk} \qquad (2)$$

Equation (3) Total operating cost consists of the operating costs of storage facilities, operating costs of plants, and cost of water. Operating costs were taken as a predetermined percentage of the investment cost.

$$\text{Total Operating Cost} = IO \cdot \sum_d \sum_c DYMal_{dc} \cdot x_{dc} + IO \cdot \sum_t \sum_k YMal_{tk} \cdot y_{tk} + \sum_t s_t \cdot SF \qquad (3)$$

Equation (4) Total cost of transportation consists of three elements that is; biomass sources transported to storage facilities, biomass transported from storage facilities to plants and the transportation cost of solid organic fertilizer from the plants to the point of demand.

$$\text{Total Transportation Cost} = \sum_b BTMal_b \cdot \left(\left(\sum_r \sum_d bt_{rdb} \cdot Ma_{rd} \right) + \left(\sum_d \sum_t bd_{dtb} \cdot Mb_{dt} \right) \right) + \left(\sum_t \sum_i g_{ti} \cdot GTMal \cdot Me_{ti} \right) \qquad (4)$$

Equation (5) Biomass purchasing cost is calculated by the cost of waste biomass purchased from supplier locations

$$\text{Biomass Purchasing Cost} = \sum_r \sum_d \sum_b BMal_b \cdot bt_{rdb} \qquad (3)$$

3.2.2. Model Constraints

Equations (6) - (19) represent the constraints of the model.

3.2.2.1. Biomass Supply Restrictions
Equation (6) ensures that the biomass quantity supplied from a supplier location does not exceed the existing biomass quantity.

$$\sum_{d} bt_{rdb} \leq AB_{rb} \quad \forall r, \forall b \tag{4}$$

3.2.2.2. Flow Protection Constraint
Equation (7) represents the constraint that ensures the amount of biomass transported from biomass supplier locations to storage facilities will be equal to the biomass amount transported from storage facilities to plants.

$$\sum_{r} bt_{rdb} = \sum_{t} bd_{dtb} \quad \forall b, \forall d \tag{5}$$

3.2.2.3. Capacity Constraints
Equation (8) ensures that the biomass quantity transported from the biomass supplier locations to storage facilities will not exceed total capacity of storage facilities.

$$\sum_{r}\sum_{b} bt_{rdb} \leq \sum_{c} DBKap_{dc} \cdot x_{dc} \quad \forall d \tag{6}$$

Equation (9) ensures that the biomass quantity transported from storage facilities to plants will not exceed total plant capacity.

$$\sum_{d}\sum_{b} bd_{dtb} \leq \sum_{k} TBKap_{tk} \cdot y_{tk} \quad \forall t \tag{7}$$

3.2.2.4. Production Constraints
Equation (10) calculates the amount of biogas produced in the plants, whereas Equation (11) calculates the conversion rate of produced biogas to electricity.

$$\sum_{d}\sum_{b} bd_{dtb} \cdot BDO_{b} \cdot UKM_{b} \cdot TK_{b} = urbiyo_{t} \quad \forall t \tag{8}$$

$$urbiyo_{t} \cdot BMI \cdot BEV \cdot MO = urelk_{t} \quad \forall t \tag{9}$$

Equation (12) ensures that the electricity produced in the plants will not exceed plants' technical capacity limit for electrical energy production.

$$urelk_{t} \leq \sum_{k} TEKap_{tk} \cdot y_{tk} \quad \forall t \tag{10}$$

3.2.2.5 Fertilizer Distribution Constraints
Equation (13) calculates the amount of solid organic fertilizer produced in plants. Equation (14) calculates the amount of liquid organic fertilizer produced in plants.

$$SKO \cdot \sum_{d}\sum_{b} bd_{dtb} \cdot GDO_{b} = \sum_{i} g_{ti} \quad \forall t \tag{11}$$

$$SSO \cdot \sum_{d}\sum_{b} bd_{dtb} \cdot GDO_{b} = atik_{t} \quad \forall t \tag{14}$$

3.2.2.6. Digester Solid Content
Equation (15) demonstrates the formula for mixing solutions. Here m_n is the mass of the solute and $\%_n$ is the mass concentration. If the pure solvent (water) is added to a solution, the $\%_n$ is taken to 0%. Using this formula, equations (16) and (17) that ensure total solid content will be within technical limits for wet fermentation process of biomass slurry in the digesters, are derived. Moreover, both constraints calculate the water quantity added to the digester.

$$\left(m_1 \cdot \%_1\right)+\left(m_2 \cdot \%_2\right)+\left(m_n \cdot \%_n\right)=\%_{son}\left(m_1+m_2+m_n\right) \quad (12)$$

$$\left(\sum_d \sum_b TK_b \cdot bd_{dtb}\right)+\left(0\% \cdot s_t\right) \leq MaxTK \cdot \left(\sum_d \sum_b bd_{dtb}+s_t\right) \quad \forall t \quad (13)$$

$$\left(\sum_d \sum_b TK_b \cdot bd_{dtb}\right)+\left(0\% \cdot s_t\right) \geq MinTK \cdot \left(\sum_d \sum_b bd_{dtb}+s_t\right) \quad \forall t \quad (14)$$

3.2.2.7. Decision Variable Restrictions

Equation (18) shows the binary decision variables, whereas equation (19) shows integer decision variables.

$$y_{tk}, x_{dc} \in \{0,1\} \quad \forall d, \forall t, \forall k, \forall c \quad (15)$$

$$bt_{rdb}, bd_{dtb}, g_{ti}, urbiyo_t, urelk_t, s_t, atik_t \geq 0 \quad \forall r, \forall d, \forall b, \forall d, \forall t, \forall i \quad (16)$$

4. Application

It was aimed to conduct a case study regarding waste biomass based supply chain network design in the country's most populated city of Istanbul which dominates surrounding settlements in terms of both economic and societal development, in order to evaluate the performance of proposed model.

The ever increasing food demand hand in hand with the population growth during recent years led to an increase in waste generation. Uncontrolled and wild dump sites deteriorate the natural resources and generate greenhouse gases which in turn causes problems that threaten both human and environmental health. These wastes which have highly adverse environmental effects can be utilized as biomass sources for energy production in bioenergy plants, instead of being dumped. Istanbul has an important potential for organic wastes such as animal waste and waste from wholesale vegetable and fruit market. With the utilization of waste as biomass source, both energy production and organic fertilizer production as the anaerobic digestion effluent would be possible. Model was applied to certain districts of Istanbul. Predetermined districts of Istanbul were regarded as potential regions for supply of biomass, biomass storage facilities, biogas plants and points of demand within this model. Corresponding map of the related study is given in Figure 2.

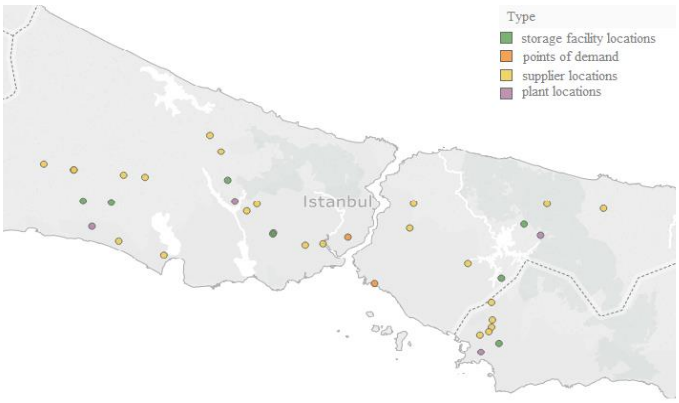

Figure 2. Application locations map

4.1. Biomass Resources

Four types of biomass were regarded as raw material to be utilized in biogas facilities in this study, which are the cattle manure, hen manure, broiler manure and waste from wholesale vegetable and fruit market. For attaining high biogas efficiencies, animal manure and waste from wholesale vegetable and fruit market were processed together in anaerobic digestion process. Data related to waste biomass potential of districts was obtained from the Ministry of Food, Agriculture and Livestock. Waste amount per animal was calculated by taking 34 kg/day (Sözer and Yaldiz, 2011) for cattle, and 0.16 kg/day (Hart, 1960) as basis. Data concerning the waste from wholesale fruit and vegetable market was obtained from Istanbul Metropolitan Municipality's Directorate of Wholesale Vegetable and Fruit Markets. Characteristics of waste biomass that was investigated in the study is provided in Table 2.

Table 2. Characteristics of waste biomass

Biomass Resources	Total Solid (%)	Reference	Volatile Solid (%)	Reference	Biogas Yield (m^3/ton VS)	Reference
Cattle Manure	16.3	(Zhang et al. 2013)	81	(Avcioğlu and Türker, 2012)	340	(Avcioğlu and Türker, 2012)
Hen Manure	24.5	(Keskin et al. 2018)	75	(Avcioğluand Türker, 2012)	450	(Avcioğlu and Türker, 2012)
Broiler Manure	50	(Avcioğlu and Türker, 2012)	65	(Avcioğlu and Türker, 2012)	550	(Avcioğlu and Türker, 2012)
Waste From Wholesale Vegetable And Fruit Market	12.7	(Ganesh at al. 2015)	84.9	(Scano et al. 2014)	450	(Ganesh et al. 2015)

4.2 Transportation

National transportation infrastructure is suitable for road transport that is selected as the transportation mode for biomass and fertilizer. Data utilized in this article were given in terms of district levels, and the district coordinates were used for calculating the distances between locations. Among the biomass types; cattle manure was transported at a cost of 0.05 €/ton, whereas waste from wholesale fruit and vegetable market was transported at a cost of 0.03 €/ton (Poeschl, 2010). It is assumed that the hen manure and the broiler manure were transported at the same cost as the cattle manure.

4.3 Biomass Storage Facilities and Biogas Plants

Potential locations of biomass storage facilities and biogas plants were selected as close as was possible to biogas supplier locations in order for decreasing transportation costs. Biogas produced as the result of anaerobic digestion in biogas plants was only utilized for electrical and heat energy production in this study. Electrical energy produced by the cogeneration system was assumed to be totally distributed to national electrical energy by associating the electrical energy production with the demand. Whereas the heat energy produced by the plant was assumed to be utilized for fulfilling various heat demands of plants. Three capacity levels, such as 4000 ton/month, 6000 ton/month and 14000 ton/month were considered for biogas plants. Installed capacities of electric energy production in cogeneration systems corresponding to each capacity level for were 1000 kWe, 2000 kWe and 3000 kWe. Cogeneration systems' electrical and heat energy efficiencies were taken as 41% and 44% respectively (Lijó et al. 2017). Total solid content of biomass slurry in the digester is limited to be between minimum 8% and maximum 13%.

4.4. Economic Parameters

The electrical energy generated by biogas plants was fed to the national grid at a price of 0.133 €/kWh. Electricity price defined in 5346 number Law for Utilization of Renewable Energy Resources for Electrical Energy Production was taken as the corresponding electricity price used in the model. Anaerobic digestion effluent solid organic fertilizer was sold to points of demand for 8.4 €/ton. The discounting factor was taken as 0.0824 and plants' service life were assumed to be 20 years.

Since the investment costs mostly did not differ for different plant sizes, the relationship between investment costs and corresponding plant capacities could be expressed by Equation 20 (Amigun and Von Blottnitz, 2010). Corresponding investment cost for a 1000 kWe capacity level plant was predicted by taking the information present in literature regarding costs of different capacity plants as the basis (Kremljak, 2017). Annual operating costs of plants and storage facilities were considered to be 10% of investment costs.

$$\frac{C_1}{C_2} = \left(\frac{Q_1}{Q_2}\right)^n \tag{17}$$

In this sense, Q2 and C2 stood for the capacity of reference plant and its corresponding investment cost respectively; whereas Q1 and C1 stood for the capacity of a new plant and its corresponding investment cost. The exponent n stood for the cost factor.

5. Results

Results of the applied model are provided in this section. Recommended MILP model for waste biomass based energy supply chain design and optimization in Istanbul was applied in GAMS optimization program, version 25.0.3 and was solved using the CPLEX Solver version 12.8. Solution trials for MILP models were realized on a Windows 8.1 Pro 64 operating system, 16 GB RAM and Intel Core i7 6700HQ 2.60 GHz processor. Model consisted of 849 continuous variables and 29 discrete variables. Solution of the model took 0.063 seconds. Results of the strategic and tactical decisions taken in the proposed model are presented in Table 3. Biomass storage facilities and biogas plants were established in some selected districts. Results revealed that the model tended to decide for second level of capacity (14000 ton/month) for biomass storage facilities, and third level of capacity (3000 kWe) for biogas plants. Waste biomass and fertilizer flow between certain districts could not be provided due to high transportation costs.

Table 3. Results of the proposed model

Maximum profit (€/year)	
Objective	2308910.103
Storage capacity and location decisions	
x_{dc}	$x_{2,2}$=1, $x_{3,2}$=1, $x_{5,2}$=1, $x_{6,2}$=1 and all other x_{dc} =0
Plant capacity and location decisions	
y_{tk}	$y_{2,3}$=1, $y_{3,3}$=1, $y_{5,3}$=1 and all other y_{tk}=0
Waste biomass flow amounts from biomass supplier locations to storages (ton/year)	
bt_{rdb}	$B_{3,2,1}$= 109477.294, $B_{5,3,1}$= 75241.830, $B_{6,3,1}$= 59426.493, $B_{8,5,1}$= 17882.810, $B_{10,5,1}$= 49652.410, $B_{11,5,1}$= 36237.200, $B_{12,6,2}$= 56624.056, $B_{13,2,2}$= 613.200, $B_{14,2,2}$= 67.160, $B_{15,3,2}$= 175.200, $B_{16,3,2}$= 122.056, $B_{17,5,2}$= 642.400, $B_{18,5,2}$= 905.200, $B_{19,5,2}$= 6599.200, $B_{20,6,3}$= 39057.102, $B_{21,5,3}$= 2645.520, $B_{22,3,4}$= 10139.000, $B_{23,5,4}$= 15208.000 and all other bt_{dtp}=0
Waste biomass flow amounts from storages to plants (ton/year)	
bd_{dtb}	$B_{2,2,1}$= 109477.294, $B_{2,2,2}$= 67.160, $B_{3,3,1}$= 134668.323, $B_{3,3,4}$= 10139.000, $B_{3,5,2}$= 910.456, $B_{5,5,1}$= 103772.420, $B_{5,5,2}$= 8146.800, $B_{5,5,3}$= 2645.520, $B_{5,5,4}$= 15208.000, $B_{6,2,2}$= 14136.673, $B_{6,2,3}$= 39057.102, $B_{6,3,2}$= 23192.677 $B_{6,5,2}$= 19294.706 and all other bt_{dtp}=0
Solid organic fertilizer flow amounts from plants to points of demand (ton/year)	
g_{ti}	$g_{5,1}$= 39116.591, $g_{2,2}$= 43140.408, $g_{3,2}$= 44403.770 and all other g_{ti}=0

5.1. Sensitivity Analysis

Effects of an important input factor with respect to decisions to be taken in waste biomass based supply chain were investigated in this section. Biomass availability is one of the main uncertainty types that affect supply chain activities. A sensitivity analysis was conducted for examining the effect of only the biomass availability that is presumed to have the highest effect on the performance of waste biomass based energy supply chain, in this study.

Table 4. Results of the sensitivity analysis

Biomass Availability (%)	Biogas Plant	Biomass Storage	Total Profit (€/year)
%10	$x_{2,1}$	$x_{2,1}$	40045.603
%20	$x_{2,3}$	$x_{2,2}$	427860.348
%30	$x_{3,3}$	$x_{2,1}$, $x_{3,1}$, $x_{6,1}$	740800.894
%40	$x_{2,3}$, $x_{3,3}$	$x_{6,1}$, $x_{2,2}$, $x_{3,2}$	885754.501
%50	$x_{2,3}$, $x_{3,3}$	$x_{2,2}$, $x_{3,2}$	1195092.331
%60	$x_{2,3}$, $x_{3,3}$	$x_{2,2}$, $x_{3,2}$	1508287.595
%70	$x_{2,3}$, $x_{3,3}$, $x_{5,3}$	$x_{6,1}$, $x_{2,2}$, $x_{3,2}$, $x_{5,2}$	1675668.871
%80	$x_{2,3}$, $x_{3,3}$, $x_{5,3}$	$x_{2,2}$, $x_{3,2}$, $x_{5,2}$	1950839.025
%90	$x_{2,3}$, $x_{3,3}$, $x_{5,3}$	$x_{2,2}$, $x_{3,2}$, $x_{5,2}$, $x_{6,2}$	2221587.382

Results of the applied model are summarized in Table 4. Herein depicts the effects of the +10% range of parameter change. Biomass availability affects plant capacities and installation decisions. Accordingly, higher biomass availability reduced the unit cost of bioenergy and thus increased the system profitability by increasing bioenergy production. According to these results and as it can be seen from Figure 3, it was observed that the supply chain design decisions were highly affected by biomass availability.

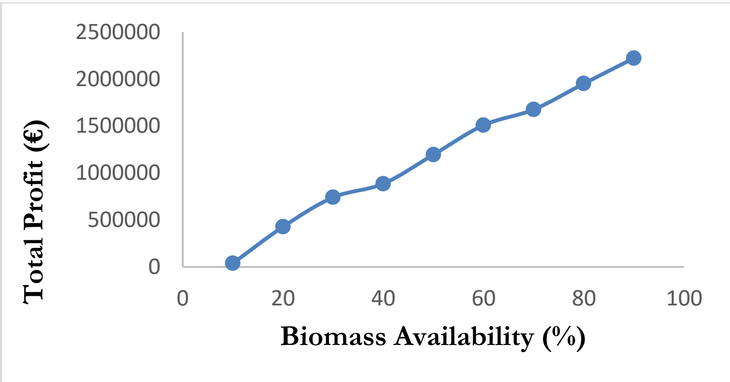

Figure 3. Effect of biomass availability on total profit

6. Results and Recommendations

This study presented a research effort regarding the design and management of a waste biomass based energy supply chain. A mathematical model that can be utilized for designing and managing such a supply chain was developed. The model covered the supply chain network as a whole, starting from biomass supply to bioenergy production. The objective of proposed model was maximizing the total profit of supply chain network. Results attained revealed the importance of waste biomass based energy for supporting energy demands in Istanbul. While providing a real life application of waste biomass based supply chain for the literature, this study also revealed an important role of supply chain management in the field of renewable energies.

Further research might extend this study in various ways. Firstly, models that include the concept of sustainability for achieving better optimization levels in waste biomass based energy supply chain management could be developed. Decisions regarding the design of waste biomass based energy supply chain network directly affect social and environmental performances of the supply chain. Hence, a robust supply chain design might be established by developing models that include social and environmental aspects of sustainability. The trigeneration system might be considered for enhancing the efficiency of the supply chain. Government interventions encouraging bioenergy production could be a smart opening strategy for the purpose of reducing total greenhouse gas emissions and dependence on fossil fuels. Sensitivity analysis might be extended for identifying important interactions occurring in parameters. Moreover, uncertainties could be addressed by utilizing stochastic programming models. A model that covers a larger geographical area might be considered as an alternative for a model that covered only a single city. Last but not least, a multi-period model that considers developments in infrastructure through time in the planning horizon, instead of a single-period model might be designed.

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