ASSESSING COSTS AND ENVIRONMENTAL IMPACTS OF MUNICIPAL
FOOD WASTE TREATMENT OPTIONS IN COLUMBIA, MISSOURI: A
DECISION SUPPORT TOOL INTEGRATING LIFE CYCLE ANALYSIS AND
ROBUST OPTIMIZATION

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FOOD WASTE TREATMENT OPTIONS IN COLUMBIA, MISSOURI: A
DECISION SUPPORT TOOL INTEGRATING LIFE CYCLE ANALYSIS AND
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Abstract

Many municipal governments currently have goals in place to align with global efforts and policy to reduce greenhouse gas (GHGs) emissions and take advantage of waste as a resource for renewable energy and nutrients. To meet specified goals and targets, decisionmakers need data-driven analysis to understand both the costs and environmental impacts of their plans. This study develops a decision support tool applied in Columbia, Missouri, USA, with aims to model the economic and environmental tradeoffs in solid waste management decisions for the collection and treatment of food waste in the municipal solid waste stream while considering existing infrastructure and uncertainty in environmental impact data. The tool uses life cycle analysis environmental impact data from literature and cost data from case-studies to simulate both a FW collection route and the processing of FW through various potential and existing treatment options (anaerobic digestion, anaerobic co-digestion with sewage sludge, composting, landfilling, dry animal feed production, wet animal feed production). The model calculates the cost and greenhouse gas emissions of the transportation and treatment processes in each simulation. The tool can choose the best FW management scenario for the objective of minimizing cost or minimizing GHG emissions. Robust optimization incorporates uncertainty into the model by allowing environmental impacts for any FW treatment option to assume a maximum or minimum of a range of values from literature, representing the worst- and best-case values for environmental performance, respectively. Average case results indicate that a minimum cost scenario uses a combination of landfilling and composting FW that results in net positive GHG emissions. To minimize environmental impact, the average case results favor anaerobic digestion, a scenario which results in net negative GHG emissions. Compared to the minimum cost scenario, the transportation costs in the minimum impact scenario are similar, while the costs to treat the FW are nearly nine times higher. Robust results focus on variability in environmental impacts. In the model results, anaerobic digestion is favored when assuming its minimum environmental impact value but is outperformed by other options when anaerobic digestion assumes the maximum of its possible range. All considered options outperform landfilling, but the rankings among landfilling alternatives depend highly on assumptions regarding offsets estimated

in life cycle assessment. Without any offsets, wet animal feed production is the best FW treatment solution. Environmental impact of transportation in this model is not influential. The results demonstrate the importance of model assumptions, uncertainty in life cycle GHG estimates, and consideration of existing infrastructure in determining the optimal scenarios.

1. Introduction

Every year in the United States, an estimated 31% of food produced for human consumption is not eaten (Buzby, Farah-Wells, & Hyman, 2014). Food waste (FW) amounts to nearly \$162 billion in retail value each year, in addition to wasted labor, water, energy, and agricultural chemicals used in production (U.S. Environmental Protection Agency, 2020a). The economic value of this food does not even begin to capture the negative externalities when food is wasted, like air pollution from farm machinery and transportation, water pollution from pesticides and fertilizer, and soil damage resulting from farm practices (Buzby et al., 2014).

A significant portion of FW in the U.S. occurs at the residential and commercial level. Excluding manufacturing and processing wastes, American households and businesses contribute to 88% of the nation's municipal FW every year (U.S. Environmental Protection Agency, 2020a). FW at this level occurs for a number of reasons, including confusion over expiration dates, lack of knowledge about food, over-stocking, cosmetic marketing standards, and seasonal factors (Buzby & Hyman, 2012). Meanwhile, it is estimated that one in ten Americans is food insecure (U.S. Department of Agriculture, 2020). Clearly, the issue of FW is complex and has economic, social, and environmental dimensions.

Most FW in the U.S. is landfilled (Figure 1-1), where its embodied value is unutilized and its degradation forms greenhouse gases (GHG). Landfills contribute about 3% of the total GHG emissions in the U.S. but are the third-largest source of the potent GHG, methane (CH₄), behind natural gas systems and livestock (U.S. Environmental Protection Agency, 2021b). These emissions are attributable to the organic fraction of waste, which is mostly FW (U.S. Environmental Protection Agency, 2020a).

Figure 1-1: Fate of FW In the U.S. For Residential and Commercial Sources. Data From U.S. Environmental Protection Agency (2020a).

National and international efforts are underway to tackle the problem of FW. Project Drawdown, an effort to model global impacts of a wide range of climate change solutions, named “Reduced Food Waste” as one of their top solutions that prevents both upstream GHG emissions from agricultural production and downstream emissions to prevent CH₄ generation in landfills (Project Drawdown, 2021b). In 2015, the United States Environmental Protection Agency (EPA) announced a goal to reduce food waste by 50% by the year 2030 and has partnered with the United States Department of Agriculture (USDA) and major companies to reduce FW, track progress, and demonstrate the environmental benefits of their actions (U.S. Environmental Protection Agency, 2021d). This goal aligns with international sustainability goals like the United Nations’ Sustainable Development Goal 12.3 (United Nations, 2021). While each of these efforts prioritizes solutions like prevention and supply chain strategies for reducing FW at the point of generation, downstream efforts at managing FW are also an important part of the picture. The Environmental Protection Agency’s (EPA) Food Recovery Hierarchy (Figure 1-2) makes feeding people and animals a top priority because that “creates the most benefits for the environment, society, and the economy” (U.S. Environmental Protection Agency, 2020e). If FW is unfit for those uses, though, there are other beneficial options like anaerobic digestion and composting.

Figure 1-2: EPA's Food Recovery Hierarchy with Most Preferred Options at The Top and The Least Preferred Options at The Bottom. Reference: U.S. Environmental Protection Agency (2020e).

Waste management has developed over time out of concern for public health (Tchobanoglous, Theisen, & Vigil, 1993). With the establishment of the EPA amidst growing environmental concerns, waste management priorities shifted to prevention of harm to the environment and conservation of natural resources (McDougall, White, Franke, & Hindle, 2008). Recently, the impacts of climate change have become of utmost urgency in waste management, especially as Earth's atmosphere approaches levels of carbon that have catastrophic climate implications (Intergovernmental Panel on Climate Change, 2021). This has led to scores of work in the last ten years on assessing the environmental impacts of waste management systems.

One of the most well-established methods of environmental assessment is life cycle analysis (LCA), which aims to compile the "inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (International Standards Organization, 2016). When applied to waste management, it can account for the impacts of various processes in waste management systems, like collection, transportation, treatment, and final disposal (Clift, Doig, & Finnveden, 2000). A key aspect of deciding on waste management decision-making lies with the assumptions about "offsets" in waste management; when waste treatment processes produce useful byproducts like electricity or compost, a life cycle estimate of environmental impacts can consider that the production system used to create those products from raw materials was

displaced. Essentially, this displaces the environmental impact of producing some amount of that product from raw materials (Finnveden, 1999). Though research on greenhouse gas emissions from waste management systems is extensive, determining which waste management method is the best is hardly a universal evaluation. The best option depends on a number of uncertain factors with regards to both environmental impacts and offsets, especially assumptions about energy sources and soil amendments (Bernstad & la Cour Jansen, 2012; Bernstad Saraiva Schott, Wenzel, & la Cour Jansen, 2016; Bisinella et al., 2017; Clavreul, Guyonnet, & Christensen, 2012; Morris, Brown, Cotton, & Matthews, 2017). Uncertainty is an important issue in LCA of any system beyond waste management (Huijbregts, 1998), and is usually examined using sensitivity analyses.

Decisions about waste management are typically made at the state or municipal level, where budgetary constraints are key. Given the complexity of waste management system processes and constraints, a number of mathematical models have been developed to optimize the cost of waste management systems (Aghajani Mir et al., 2016; Antmann, Shi, Celik, & Dai, 2013; Cai, Huang, Nie, Li, & Tan, 2007; N.-B. Chang, Qi, Islam, & Hossain, 2012; P. Li, Li, Huang, & Zhang, 2015; Minoglou & Komilis, 2013; Munster, Ravn, Hedegaard, Juul, & Ljunggren Soderman, 2015; Roberts et al., 2018; Xu, Huang, Qin, Cao, & Sun, 2010). These models typically determine the most cost-effective way to allocate waste from generation points to waste treatment facilities with considerations of a specified geographic context and constraints on capacity and budget. Sometimes these models incorporate consideration of environmental impacts with waste management but are lacking full transparency of environmental impact methods and full consideration of those methods when discussing decisions based on those models.

This study focuses on municipal FW management and develops a model that optimizes the waste management system to choose FW treatment options that will minimize either costs or environmental impacts in the form of GHG emissions. This study will incorporate both optimization and uncertainty methods. Optimization will help decision-makers to select the best FW treatment methods as well as the tradeoffs between objectives that will contribute to reliable decisions. The uncertainty methods will focus on environmental impacts to discuss specific

conditions under which certain treatment options are considered better than others, especially in the context of uncertainty resulting from LCA modeling of GHG estimates.

In Chapter 2, a literature review covers a series of topics integral to building an effective model for FW management optimization. First, a range of common FW treatment technologies are presented along with their advantages and disadvantages. These include the most common forms of FW treatment in place in the United States: landfilling and composting. Discussion also expands on emerging treatment options like anaerobic digestion, animal feed production, combustion/waste-to-energy, and production of bio-based chemicals. Then, an introduction to environmental assessment methods of waste management systems compares common methods and narrows the focus to the well-established method of life cycle analysis. This discussion has a special emphasis on limitations and uncertainty in life cycle analysis. The final sections of the literature review examine a selected set of waste management models based on a) optimization methods and b) life cycle assessment methods. This discussion pays special attention to solution methods, impact methods, and uncertainty methods. The objective is to determine how these models support decisions, which types of decisions they can support, and the robustness of their decision support in the face of uncertainty. This review demonstrates there is a lack of synthesis between optimization, environmental impacts, and uncertainty for waste management systems. More research needs to be done to find the “best” waste management system under a range of conditions.

In Chapter 3, the study area of Columbia, Missouri, is introduced. This discussion provides context for the existing FW situation in Columbia including the magnitude of FW generation and management options. This context is important for establishing a representative model in Chapter 4. Columbia's Climate Action Plan is also briefly discussed to outline the city's climate change goals and any FW management efforts underway.

The study's methodology is covered in Chapter 4. This section covers the development of the FW management model, which optimizes FW collection, transportation, and treatment activities among six potential FW treatment options. The model is capable of prioritizing environmental or economic objectives. Development of model geography explains important

assumptions for the collection and transportation activities. A detailed section on environmental impact estimates for the included FW treatment options establishes exactly what environmental impacts are included in FW management systems, underlying assumptions for the greenhouse gas impact estimates, and how literature values are adjusted for consistency and representativeness for use in the model. The optimization model formulation is presented, including the parameters, objective functions, and constraints in both algebraic notation and plain text. Finally, the solution approach is described for both average case model environmental impact data followed by the robust model which develops results using environmental impact estimates at their best and worst-case values.

Chapter 5 is split into three main sections. In Average Case Results, the model is solved both to minimize cost and minimize environmental impacts. The tradeoffs between environmental impact and cost priorities are discussed. In Robust Results, the model is solved to minimize environmental impacts while incorporating uncertainty in the environmental impact parameter. The discussion revolves around the conditions under which certain FW treatment options are preferable to others in Columbia, especially with regards to the offsets of environmental impacts. The section concludes with

Additional Runs, where questions regarding specific concerns for each treatment option are addressed and modeled.

The study ends with a discussion on the conclusions and future work, outlining the work that can build upon the conclusions here and fill in other research gaps regarding sustainability of waste management.

2. Literature Review

Municipal solid waste (MSW) management is concerned with controlling the various processes of generation, storage, collection, transfer, transport, processing, and disposal of solid wastes from residences and businesses (Tchobanoglous et al., 1993). Management developed out of public health and safety issues as unmanaged waste caused diseases to spread and attracted pests (Tchobanoglous et al., 1993). In the last fifty years, the focus with MSW management turned to environmental impacts as the United States created the Environmental Protection Agency and implemented legislation like the Resource Conservation and Recovery Act and Clean Air Act which aimed to control the emission of pollutants from landfills to the air and surrounding water ("Resource Conservation and Recovery Act," 1991; U.S. Environmental Protection Agency, 2020i). Regulations led MSW management systems to become more controlled but also increasingly complex, employing engineered systems like sanitary landfills. As a municipal service, decision-making in MSW management must balance the needs of a range of stakeholders while prioritizing economic efficiency (Allesch & Brunner, 2014; Babalola, 2015; Y. J. Chang & Lin, 2013; El Hanandeh & El-Zein, 2010).

Growing concerns for environmental problems by stakeholders have broadened the focus from preventing environmental pollution at landfills to other environmental goals. Many cities have implemented programs to divert waste from landfills and reprocess valuable materials like aluminum and paper into new products (Waste360 Staff, 2018), conserving resources but also further complicating the system regarding collection and waste treatment facilities. Cities are also beginning to implement policies that mandate diversion of organic waste from landfills in an effort to reduce the impacts of landfills on climate change (Sandson, Broad Leib, Macaluso, & Mansell, 2019). As a result, decision-makers are faced with even more complexity as they change their MSW management systems aimed at achieving environmental sustainability goals but maintaining economic viability. What should be done with organic waste that is diverted from landfills? Are landfilling alternatives actually reducing climate change impacts and by how much? What are the economic and environmental tradeoffs of these alternatives?

In this literature review, first a set of common organic waste management technologies are briefly reviewed for context both in the literature review and in the remainder of the paper. Second, a discussion on environmental assessments will cover the needs and methods for quantitative environmental sustainability analysis to answer the question, “What is sustainable?” In the third section, mathematical models for decision support in MSW management systems are extensively reviewed. This section focuses on optimization models as well as assessment tools that incorporate environmental sustainability analysis methods.

2.1 Organic Waste Management Technologies

Several technologies have been developed to manage FW and to create value by transforming FW into useful byproducts. This section will review common FW management technologies: landfilling, composting, anaerobic digestion, feeding animals, and others. Each section will discuss the general process, technical features, benefits, and challenges that affect these technologies in practice.

2.1.1 Landfilling

Landfilling is the most common practice of managing FW and other wastes, in which waste is buried in an engineered hole in the ground. Active MSW landfills have been mandated by the Resource Conservation and Recovery Act Subtitle D to have protections in place to prevent contaminants from migrating into soil and water, like a liner to prevent mercury and arsenic from leaching into a watershed ("Resource Conservation and Recovery Act," 1991). When organic matter is landfilled, it decomposes into gaseous compounds. In the initial placement of a landfill, aerobic microbes decompose organic matter into carbon dioxide (CO_2). As more waste is placed, anaerobic conditions are created, where microbes transform organic matter into CH_4 (Figure 2-1) (U.S. Environmental Protection Agency, 2021a). During this methanogenic phase a portion of landfill gas, 20% for active landfills with gas collection and 10% for those without, is oxidized into CO_2 (U.S. Environmental Protection Agency, 2020f).

Figure 2-1: Dynamics of Greenhouse Gas Emissions from Landfills. Reference: U.S. Environmental Protection Agency (2021a).

Because CH₄ is a potent greenhouse gas, landfills often have some sort of landfill gas collection system. Most commonly, landfill gas is combusted for electricity at the grid, treated as a direct source of fuel, or upgraded to the equivalent of natural gas (U.S. Environmental Protection Agency, 2020g). Gas collection systems are placed as sections of the landfill are completed, increasing collection efficiency over time and contributing further to dynamic landfill gas emissions (City of Columbia, 2017). The collection efficiency increases as more collection systems are placed during the active filling phase and peaks once the final cover and collection system is in place (Broun & Sattler, 2016). In bioreactor landfills, liquid is injected in the landfill to create anaerobic conditions that accelerate the decomposition and stabilization rate. This reduces risk and increases the landfill density, which also reduces costs for landfill space as well as the post-closure process (City of Columbia, 2017).

Landfilling is common practice because it is a relatively cheap and technically simple method for disposing of MSW. In landfills with gas collection systems, benefits of energy production can be realized either as electricity or fuel. As mentioned previously, though, landfilling contributes a relatively large amount of greenhouse gases when managing FW. Though landfilling is the most

common method of waste disposal in the world, there is an increasing emphasis on alternatives for MSW management to tackle climate change, create value of materials and resources at the end of their life, and save space in landfills (DSM Environmental Services Inc., 2017; Kim & Kim, 2010; Morelli et al., 2020; Yoshida, Gable, & Park, 2012).

2.1.2 Composting

Composting is the decomposition of organic matter by microbes in the presence of oxygen which results in a stabilized material that resembles humus and can be applied to soils. In general, the process involves mixing organic matter in a pile and letting it cure while providing air to maintain aerobic conditions. Greenhouse emissions from composting depend on the feedstock, which can consist of FW among others: yard trimmings, paper, and municipal biosolids (Brown & Subler, 2007). Compost piles will produce CO₂ as aerobic microbes decompose the material, but anaerobic conditions may occur and cause anaerobic microbes to produce CH₄ and nitrous oxide (N₂O), which are much more potent greenhouse gases (Hobson, Frederickson, & Dise, 2005). Careful management methods, like sufficient aeration (Brown & Subler, 2007) and balancing feedstocks to maintain a proper carbon-to-nitrogen ratio for more rapid stabilization (Ayilara, Olanrewaju, Babalola, & Odeyemi, 2020).

Technological configurations of composting range in level of technical complexity and cost. Compared to home composting sites, industrial sites are much larger and optimized, making them able to break down compostable plastics, tough fibers, and animal-based products without attracting vermin (Goldstein & Coker, 2021). Most commonly, composting occurs by windrow composting, in which the composting process is done in large, long piles outdoors. Periodically, the rows are turned and watered to maintain favorable conditions for aerobic microbes. Generally, this is the cheapest configuration of windrow composting but can be difficult to control while generating undesirable odors (van Haaren, Themelis, & Barlaz, 2010). Other forms of composting are more expensive but allow greater control over the process. Aerated static piles are laid on a concrete foundation and covered with a Gore-Tex cloth that contains odorous vapors and moisture while exchanging greenhouse gases and oxygen with the surrounding air. Sensors are used to monitor the oxygen and temperature for controlled aeration using tubes from underneath

(W. L. Gore & Associates GmbH, 2012). This process requires a front-end loader to pre-mix and move materials as well as screens to filter out large particles or contaminants (van Haaren et al., 2010). In-vessel composting is another highly controlled method of composting in which the compost is added to a rotary drum equipped with a controlled aeration system. Active composting in the drum is followed by a curing stage in windrows (van Haaren et al., 2010). The more controlled methods may take as little as one to three months, but windrow composting can take up to six months depending on management methods and regional climate (van Haaren et al., 2010). Other forms of composting include vermicomposting, sheet composting, Indian Indore composting, Berkley rapid composting, and Indian Bangalore composting (Ayilara et al., 2020).

Composting is touted as a simple, scalable, and flexible form of managing FW that reduces greenhouse gas emissions by as much as 40% compared to landfilling (Project Drawdown, 2021a). Using compost as a soil amendment has other benefits as well – it adds organic matter to soil that increases water retention, feeds beneficial microbes at the base of the ecosystem, suppresses pests and disease, enhances resistance to soil erosion, and fortifies soil with nutrients (U.S. Environmental Protection Agency, 2021c). All of these soil improvements can contribute to yield increases without or with a reduced dependence on fertilizer (Morris, 2014).

Although relatively simple, compost is not without its challenges. Composting can take a long time compared to other FW management technologies and may be extended due to uncontrollable factors like feedstock composition and climatic conditions (Ayilara et al., 2020). While compost can add nutrients to soil, the nutrient type in the compost can be unpredictable or in the incorrect form for plant uptake (Morris, 2014). There are also concerns that compost, particularly from supermarkets and households, is contaminated with heavy metals or microplastics, which may introduce toxins to the food chain for both humans and wildlife (Pathan et al., 2020). In addition to these concerns, demand for municipal compost from western agricultural users lags behind the supply because of the time period over which benefits can be realized, which may be multiple growing seasons during which compost is applied (Hills, Brady, Yorgey, & Collins, 2019).

2.1.3 Anaerobic Digestion

Anaerobic digestion is the decomposition of an organic substance by microbes in the absence of oxygen to produce biogas, composed of 50-70% CH₄ (U.S. Environmental Protection Agency, 2020f). Anaerobic digestion takes place inside of a reactor that maintains anaerobic conditions and has some sort of gas collection system for beneficial uses, like energy production. The stabilized, digested solids are also useful as a soil amendment similar to compost. The process is capable as a management option for a variety of feedstocks, including food, human or animal manures, yard waste, and food energy crops (Morris, 2014; U.S. Environmental Protection Agency, 2020f).

Anaerobic digestion technology configuration is based on a few main operating parameters: operating temperature, moisture level, batch style, and number of stages. Digesters can operate at one of two temperature ranges to optimize particular groups of microbes: thermophilic and mesophilic (Moriarty, 2013). Thermophilic digestion occurs at high temperature ranges (125°F-140°F) to digest waste relatively quickly (14 days) and produce more energy. At lower temperatures (95°F-105°F), mesophilic digesters produce less energy and take a bit more time (15-30 days) but are generally favored for easier control and lower capital costs compared with thermophilic (Moriarty, 2013). Anaerobic digesters all handle feedstocks with high moisture content (>70%), but their design can be optimized for dry (<85% moisture) or wet (90-97% moisture) digestion (Moriarty, 2013). For this reason, dry digesters are typically chosen for handling FW alone while wet digesters are in use at wastewater treatment plants. Wet digesters are typically operating at the mesophilic range while dry digesters are usually thermophilic (Moriarty, 2013).

Anaerobic digesters can also be classified by the way in which feedstock is fed into the digester. Continuous digesters are common and suitable for wet and dry digestion. In this type of digester, feedstock is added periodically to the process. Batch processing is less common and is only applied to dry digestion. Batch digestion is characterized by adding a large amount of feedstock to the digester at once and keeping the process sealed for the duration of digestion. Sometimes, a composting process may be added onto batch digestion processes to complete the

stabilization of solids (Moriarty, 2013). Furthermore, digesters can be single-stage, in which one reactor operates at one temperature, or two-stage. In two-stage, or temperature-phased, anaerobic digestion, feedstock goes through two separate reactors operating at different temperature ranges for different phases of digestion. Though temperature-phased digestion optimizes biogas production, it has much higher capital costs than single-stage (Moriarty, 2013).

As mentioned above, anaerobic digestion produces biogas which can be used for energy in a few ways. Biogas can be combusted in an engine for conversion to mechanical, heat, or electric power, which includes combined heat and power systems (U.S. Environmental Protection Agency, 2020b). It can also be distributed in natural gas pipelines or upgraded for use as an alternative vehicle fuel (Moriarty, 2013; U.S. Environmental Protection Agency, 2020b). For all of these uses, biogas must be cleaned of contaminants like hydrogen sulfide, CO₂, and water vapor (Moriarty, 2013). Beyond biogas benefits, the solids remaining at the end of digestion, or digestate, can be applied to soils similarly to compost. Like compost, digestate can add carbon, plant nutrients (nitrogen, phosphorus, potassium), water retention, disease and pest resistance, and improved soil structure (Morris, 2014). Morris (2014) notes that digestate has more concentrated nutrients than compost, even though most available research on digestate has been on products of wastewater digestion instead of food-only digestion. Digestate can also be applied to landfills as an alternative daily cover (City of Columbia, 2020).

Moriarty (2013) highlights that the major barrier to adoption of anaerobic digestion is high capital and operation costs. Often, owners of waste facilities recuperate costs by way of selling beneficial byproducts or tipping fees, where waste haulers pay per unit weight of waste dumped at the facility. Biogas prices are low and high gate fees as a consequence may make anaerobic digestion unattractive in comparison to cheaper landfilling and composting (Moriarty, 2013). Digestate can also be sold, but often is not valued highly enough to generate significant revenues. Several of the same concerns about composting quality, contamination, and predictability also exist for digestate (Morris, 2014).

2.1.4 Animal Feed

FW can be directly fed to animals in some cases, but processing FW before feeding animals can help control both the safety and quality of the end product. Producing animal feed from FW typically involves screening contaminants out of FW, shredding the FW, and heating the FW to kill pathogens. There are generally two types: wet feed and dry feed. Dry feed typically has less than 20% moisture by weight, whereas wet feed is anything exceeding 20% but can contain around 80% moisture (Kim & Kim, 2010; Westendorf & Myer, 2004). While both require some heat energy to sterilize the FW, dry feed requires considerably higher energy inputs to dehydrate FW, typically around 70% moisture (Bisinella et al., 2017), to 20% moisture or less. The lower moisture content, however, makes dry feed cheaper to transport than wet feed. Wet feed's low energy inputs make it attractive from a climate change point of view, but transportation of high-moisture product across long distances can yield significant environmental impacts and high costs (Westendorf & Myer, 2004). Westendorf and Myer (2004) also notes that FW from households has high variability in nutrients and high moisture content, which may limit nutrient intake for swine. In some cases, additives may be incorporated into the FW in the process to optimize the feed's nutrient content. For a more detailed review on processing FW into animal feed, see (M. Hall, 2016).

Feeding un-processed FW to animals would pose a risk to public health. If fed FW containing animal protein, ruminants like cattle and goats can be vulnerable to bovine spongiform encephalopathy (Harvard Food Law and Policy Clinic, 2016). The Ruminant Feed Ban Rule of 1997 outlawed the inclusion of animal proteins in feed for ruminants (Harvard Food Law and Policy Clinic, 2016). Swine are also vulnerable to un-processed FW because of disease-causing bacteria (Westendorf & Myer, 2004). The Swine Health Protection Act of 1980 mandates that FW must be heat-treated at 212° F for 30 minutes before feeding it to swine ("Swine Health Protection Act," 2019). Missouri's state regulations are consistent with the Swine Health Protection Act and go further by requiring licensure to feed treated FW to swine (Harvard Food Law and Policy Clinic, 2016).

2.1.5 Other Treatment Methods

Thermal waste treatment methods – incineration, gasification, and pyrolysis – are also available to treat MSW. Incineration employs combustion of waste to heat a boiler that produces steam which is then converted to electricity (Dong et al., 2018). Gasification and pyrolysis are more efficient methods of converting waste synthetic gas that could produce energy more efficiently (Dong et al., 2018). Thermal treatments are able to produce energy and reduce the total volume of MSW but may not be suitable for food and organic waste because of their low heat content and high moisture content (Pham, Kaushik, Parshetti, Mahmood, & Balasubramanian, 2015). In 2005, the EIA reported that mixed MSW had a heat content of 11.73 MMBtu/ton waste (waste was heat treated, whereas in Sweden and Denmark the method was applied to 30-50% of their total waste generated (Larsen, Petersen, & Christensen, 2012).

Table 2-1). This is comparable to individual components like textiles and wood but only one third to one half the heat content of various plastics and bituminous coal. FW, by comparison, is less than half the value of MSW and about one eighth the value of polypropylene. Yard waste has a heat content comparable to FW.

Low energy potential of organic waste may be partially resolved by methods like refuse-derived fuel (RDF), in which waste is shredded and dried to improve its combustibility (Sadeef et al., 2016). However, other issues are associated with heat treating organic waste that make other options more attractive. The process could result in persistent organic pollutants in the air (e.g., dioxins), produces a byproduct fly ash that must be properly disposed, and requires higher capital costs than landfilling and composting (Matsakas, Gao, Jansson, Rova, & Christakopoulos, 2017). Furthermore, heat treating organics misses the opportunity to extract valuable compounds, like nutrients, from organic materials (Matsakas et al., 2017). Heat treatment methods are much more popular in European countries, where tipping fees and land for landfills are expensive. In the USA, about 12% of waste was heat treated, whereas in Sweden and Denmark the method was applied to 30-50% of their total waste generated (Larsen, Petersen, & Christensen, 2012).

Table 2-1: Heat Content for Various Materials Found in MSW.

Material	Million Btu / short ton	Source
Bituminous coal	20.1	U.S. Energy Information Administration (2020b)
Polyethylene terephthalate (PET)	20.5	Lariviere (2007)
High density polyethylene (HDPE)	38.0	
Polypropylene (PP)	38.0	
Polystyrene (PS)	35.6	
Low density polyethylene (LDPE)	24.1	
Leather	14.4	
Textiles	13.8	
Wood	10.0	
Newspaper	16.0	
Food	5.2	
Yard trimmings	6.0	

Recently there has been interest in transforming FW into bio-based products like biofuels, bioplastics, fatty acids, proteins, enzymes, colorants, and antioxidants. Some technologies include ultrasound extraction, microwave extraction, enzyme immobilization extraction, and fermentation. Santagata, Ripa, Genovese, and Ulgiati (2021) provides a review on FW conversion pathways with an LCA perspective that highlights similar benefits from the reviewed waste treatment technologies like recovered value of nutrients and reduced environmental impacts. Sharma et al. (2021) covers the disadvantages and advantages of several reviewed valorization technologies, highlighting that they have the potential to generate revenues when used for value-added products in supply chains. Teigiserova, Hamelin, and Thomsen (2019) reviews literature on the conversion of inedible or unavoidable FW and finds that fermentation is a key technology. While these technologies are promising and require further research, this study takes the position that these are opportunities for industry. This study focuses on feasible opportunities for MSW management.

2.2 Environmental Impact Assessment

2.2.1 Environmental Impact Assessment Methods

While conceptual management frameworks (European Commission, 2021; U.S. Environmental Protection Agency, 2020e) are available to guide environmental decision-making, they are criticized as lacking a scientific basis and lacking consideration for local conditions

(Vergara & Tchobanoglous, 2012). Redlingshöfer, Barles, and Weisz (2020) suggest that waste hierarchies work well for greenhouse gas emissions but require adjustments for other impacts like nutrient cycles and air pollution. Quantitative approaches can assist in understanding the degree to which MSW management alternatives impact the environment and can be leveraged to achieve goals. Finnveden, Björklund, Moberg, Ekvall, and Moberg (2007) review some approaches commonly used in assessing the sustainability of MSW management systems, including environmental impact assessment (EIA), environmental auditing in environmental management systems (EMS), risk assessment, and life cycle assessment (LCA). EIA is most appropriate for evaluating the pollution flows – chemical, physical, visual, etc. – of a specific project and for use in site selection (Petts, 2009). EMS and environmental auditing are mostly applied to organizations to assess compliance with environmental regulations; these focus on primarily reducing energy use and waste while prioritizing the competitive advantages an organization gains like marketing (Sayre, 2014; Steger, 2000). Risk assessment of MSW management systems can evaluate a system's risk to human health based on exposure and toxicity of chemicals emitted (Eduljee, 2000). LCA has emerged as a more comprehensive assessment of both the burdens and benefits in a complex system like MSW management that can be applied to compare alternatives and avoid system sub-optimization (Finnveden et al., 2007). For this purpose, this study focuses on LCA and its use in optimized sustainable MSW management.

2.2.2 Life Cycle Analysis

Life cycle analysis (LCA) is a “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (International Standards Organization, 2016). LCA can be applied to MSW management systems to understand quantitatively how different operations in MSW management contribute to potential environmental emissions from the “cradle” of waste generation to the “grave” of final disposal. Clift et al. (2000), McDougall et al. (2008), and Nabavi-Pelesaraei, Kaab, Hosseini-Fashami, and Mostashari-Rad (2019) present methodologies for the application of LCA to MSW management systems. LCA models of MSW management should include direct impacts from MSW management processes

in the foreground system (including transportation), indirect impacts in the background system (i.e., impacts embedded in the supply chain of materials / energy provided to the MSW management system), and avoided burdens (associated with economic activities displaced by material/energy recovered from the waste) (Clift et al., 2000). Finnveden describes system expansion methods commonly used by LCA practitioners to estimate the avoided burdens in waste management systems Finnveden (1999). Common impact categories for MSW management systems include global warming potential, acidification potential, eutrophication potential, photochemical ozone formation, human toxicity potential, and resource use (Bernstad & la Cour Jansen, 2012; McDougall et al., 2008).

2.2.3 LCA and MSW Management

LCA studies of MSW management can identify the “hotspots” for emissions in individual operations in an existing or potential system, estimate potential benefits in useful waste byproducts, and aid decision makers in selecting an appropriate technology in the MSW management planning process (Chadderton et al., 2017; Edwards, Othman, Crossin, & Burn, 2017; Levis & Barlaz, 2011; McDougall et al., 2008; Morelli et al., 2020; Ogino et al., 2007). Results can show that one technology ranks the best for all considered categories (Levis & Barlaz, 2011; Ogino et al., 2007), but often they show that one technology does not rank the best for all impact categories investigated. For example, Broun and Sattler (2016) compared impacts of conventional landfills with energy recovery to bioreactor landfills; conventional landfills had lower GWP and acidification potential, but bioreactors ranked better for two pollutants that contribute to human health impacts. Colón et al. (2012) compared anaerobic digestion with four different types of composting; anaerobic digestion ranked best for GWP, acidification, eutrophication, and human toxicity but ranked third for photochemical oxidation. Thyberg and Tonjes (2017) also found that anaerobic digestion ranked best for most categories, but it tied with waste-to-energy for GWP, tied with all other technologies for ozone depletion, and ranked second for marine eutrophication. To determine the “best” option, LCA studies sometimes use methods like averaging an option’s rank across multiple impact categories (Thyberg & Tonjes, 2017) or more subjective means like weighted impacts (Blengini, 2008) that are dependent on stakeholder

priorities. LCAs that analyze organic waste management typically include some form of composting and anaerobic digestion, comparing performance to landfilling or waste-to-energy (Andersen, Boldrin, Christensen, & Scheutz, 2012; Blengini, 2008; Levis & Barlaz, 2011; Takata et al., 2012; Thyberg & Tonjes, 2017; Yoshida et al., 2012). LCAs can also be used to examine potential impacts of less common methods like production of animal feed from FW (M. Hall, 2016; Kim & Kim, 2010; Lee, Choi, Osako, & Dong, 2007; Ogino et al., 2007; Takata et al., 2012) or emerging technologies (Brunklaus, Rex, Carlsson, & Berlin, 2018; Elginöz, Khatami, Owusu-Agyeman, & Cetecioglu, 2020).

It is critical that LCAs of MSW management systems analyze the impacts of specific waste materials. First, waste type determines the appropriate treatment method and can even determine which waste types are better for a given treatment method (i.e., which waste fractions have a higher heat content for waste-to-energy technologies (Lariviere, 2007)). Organic waste has a different chemical composition than other MSW fractions, especially moisture and nutrient content (Bisinella et al., 2017). Nutrient content and types of organic compounds even differ among organic fractions (Barlaz, 1998; Bisinella et al., 2017). For example, FW has more nitrogen (3% of total solids) compared to garden waste (1% of total solids) (Bisinella et al., 2017). Chemical composition forms the basis for assumptions about rate of degradation into greenhouse gases in landfills, CH₄ production in anaerobic digesters, ability to replace products like fertilizer, and amount of carbon stored in soils (Barlaz, 1998; Bisinella et al., 2017; Edwards et al., 2017; Levis & Barlaz, 2011; Yoshida et al., 2012). Moisture content also determines energy needs in certain processes. In animal feed production, for instance, more heat is needed to dehydrate FW with a higher moisture content, which increases the greenhouse gas impacts per functional unit of output when based on wet FW as an input (M. Hall, 2016).

2.2.4 Limitations of LCA

LCA is subject to some limitations in its applicability to MSW management decision support: LCA is relatively static and cannot assess the effects of changing waste quantities or waste prevention, is unable to handle spatial information for pollutants, and models waste systems using linear relationships when actual relationships between emissions and ecological health

depend on concentration and duration of exposure (Ekvall, Assefa, Bjorklund, Eriksson, & Finnveden, 2007). Despite the wide range of impact categories that have been developed for LCA, the method is still incapable of quantifying certain types of impacts, like the full range of benefits to ecosystems from the application of soil amendments like compost (Morris, 2014). Another wide criticism of LCA is uncertainty, defined by Heijungs and Huijbregts (2004) as the use of data for which there is a) no value, b) inappropriate values, and c) more than one value. Clavreul et al. (2012) presents common sources of uncertainty specific to MSW management LCAs and follows Huijbregts (1998) in categorizing them into model, scenario, and parameter uncertainties. Model uncertainty results from equations used to calculate various relationships in MSW management such as emissions from treatment facilities, impact assessment methods that characterize the impact of emissions on the environment, waste collection assumptions (e.g., road conditions, the number of stops, fuel efficiency), biodegradation, and use of organic waste management byproducts on soil (Clavreul et al., 2012). Scenario uncertainties occur in the process of developing scenarios when a modeler makes choices regarding system boundaries (i.e., which processes are included and which are not), representativity of technologies, time horizons, and allocation of flows (e.g., mass-based or economic) (Clavreul et al., 2012). Parameter uncertainty can arise in each individual parameter in a model and results from inherent variability, data uncertainty, and imprecise measurement (Clavreul et al., 2012).

Uncertainty affects the reliability of decisions made based on LCA results. In a review of FW management system LCAs, Bernstad and la Cour Jansen (2012) found inconsistencies in ranking technologies for their performance with respect to global warming. In their review, seven out of eleven comparative studies ranked anaerobic digestion as the best option, while two out of eleven studies ranked it the worst. Similarly, large-scale composting ranked best in four out of twelve studies and worst in two out of twelve. They concluded the rankings varied largely due to system boundary setting, modeling assumptions, and, to a lesser extent, input data variation. Bisinella et al. (2017) also found that properties of waste composition, especially carbon (non-biogenic), volatile solids, and energy content, dominated the output uncertainty in waste

management modeling. Both of these studies recommend the use of sensitivity analyses to identify key issues and assumptions in LCA.

While some reviewed studies include no uncertainty or sensitivity analysis (Takata et al., 2013; Takata et al., 2012), most reviewed studies include a sensitivity analysis for individual model parameters. Alternatively, Monte-Carlo simulation can be used to evaluate the uncertainty of the overall results (Edwards et al., 2017) or harmonization across many LCAs can produce a single representative value for a technology using statistical methods (Morris et al., 2017). Harmonization may smooth out the variation of the different configurations of a technology and exclude uncommon technologies like animal feed production. For example, the harmonized value for composting may not be representative for both home composting and in-vessel composting.

Authors use sensitivity analyses of FW management system models to investigate the relative influence on model outputs by uncertain parameters. Most reviewed studies of FW systems only investigated the influence of model parameters on GWP, though Edwards et al. (2017) and Andersen et al. (2012) did include other outputs. Sensitivity analyses of FW disposal via landfills and anaerobic digestion focus on CH₄; they show that emissions are most significantly influenced by waste characteristics that drive CH₄ production and, to a lesser extent, operational factors that contribute to reducing fugitive CH₄ while recovering CH₄ for energy production (Broun & Sattler, 2016; Edwards et al., 2017; Levis & Barlaz, 2011; Yoshida et al., 2012). Oxidation of CH₄ into CO₂ through landfill soil cover is less significant (Edwards et al., 2017; Yoshida et al., 2012).

Some models of composting systems (Thyberg & Tonjes, 2017; Yoshida et al., 2012) assumed a well-managed system does not produce CH₄ and that biogenic CO₂ from the degradation of plant matter is 0 GWP as recommended by Christensen et al. (2009), but Levis and Barlaz (2011) found these to be significant drivers of the balance between burdens of carbon emitted and benefits of carbon stored in composting. Significant emissions of CH₄ and N₂O have been measured in both home composting systems and industrial-scale composting systems (Hobson et al., 2005; Martínez-Blanco et al., 2010). Other studies on composting found that

carbon storage and mineral fertilizer offsets were most significant for overall GWP (Andersen et al., 2012; Edwards et al., 2017).

M. Hall (2016) determined that the moisture content of input FW and the energy source used to produce animal feed from FW were significant factors for GWP. M. Hall (2016) and Ogino et al. (2007) found that the transportation distance of FW to the feed production facility and to its end-use destination were significant contributors to GWP, but not as important as heating and cooking the FW. This conclusion is supported by M. Hall (2016)'s sensitivity analysis to estimate the influence of the avoided impact for producing animal feed from virgin material. When using an offset of less magnitude for virgin feed, the subject system in M. Hall (2016) still performed better than similar studies. This demonstrates that the lower impact from direct process emissions contributes to its superior environmental performance more than the avoided feed impact.

FW is often treated as a single waste substance in LCAs, but the actual composition of the FW fraction of MSW can vary and have a large impact on estimated GWP. Assumptions about the types of carbon in FW impact the relative amount of CO₂ and CH₄ formed and their balance with carbon stored in the ground, which in turn drives the balance of net positive emissions and offsets in a system (Edwards et al., 2017; Levis & Barlaz, 2011). Content of nitrogen affects the extent to which a FW byproduct can replace the function of mineral fertilizer or animal feed, affecting the magnitude of offsets (Edwards et al., 2017; M. Hall, 2016; Levis & Barlaz, 2011). Increased moisture content of FW increases GWP significantly for anaerobic digestion, composting, and animal feed production because the functional unit assumes wet weight of FW but offsets are determined by dry weight (M. Hall, 2016; Levis & Barlaz, 2011). Moisture content has the opposite effect on landfilling because of decreased CH₄ generation (Levis & Barlaz, 2011).

Some studies discuss how the outputs of their sensitivity analyses affect the rankings of alternative MSW management systems, particularly when discussing GWP offsets. If incineration of FW displaces biomass-based electricity instead of fossil electricity, it produces more GWP than composting (Andersen et al., 2012). Edwards et al. (2017) found that if biogas production isn't increased when adding FW to an anaerobic digestion system of sewage sludge, though

enhanced biogas production is demonstrated in literature, co-digestion performs better for disposing FW than landfilling. Edwards et al. (2017) also found that not including the benefits from fertilizer and offsets resulted in landfilling FW performing better for GWP than co-digestion. Kim and Kim (2010) estimated GWP if byproducts of FW are not used due to insufficient demand. When landfilled or incinerated, the GWP of dry feed, wet feed, and compost systems increased by a factor of anywhere from two times up to fifteen times. In the case of incineration, wet feed production would be the worst option out of all investigated methods.

In summary, these sensitivity analyses demonstrate high uncertainty associated with GWP emissions and offsets in FW management systems, especially related to sources of electricity, assumptions about FW degradation in compost piles, and the inclusion of offsets from using waste byproducts like animal feed or compost. When modeling the alternatives to landfilling FW, it is important to analyze the impact of uncertain FW composition and use of byproducts. Authors should discuss which factors could affect overall rankings of FW alternatives. Furthermore, sensitivity analyses only analyze the effect of one parameter on model output at a time, when in reality more than one may be uncertain simultaneously.

2.3 Mathematical Models of MSW Management Systems

Due to the complexity of MSW management, mathematical tools have been used as decision support. Discussion of mathematical models is separated into those that focus on optimization and models that focus on environmental assessment.

2.3.1 Optimization Models

According to a review on mathematical models applied in MSW management problems, such models can generally be classified as either simulation models, which aim to predict a scenario outcome based on some input, or optimization models, which aim to find the best solution to an objective based on a given set of constraints (Singh, 2019). Optimization models have been applied to many problems in MSW management, like sizing and locating a network of waste treatment facilities (Ahani, Arjmandi, Hoveidi, Ghodousi, & Miri Lavasani, 2019; Habibi, Asadi, Sadjadi, & Barzinpour, 2017; Tirkolaee, Mahdavi, Esfahani, & Weber, 2020), sizing and

locating a network of waste receptacles (Badran & El-Haggar, 2006; Nikouei Mehr & McGarvey, 2017), deciding how to invest in waste prevention measures (Cristobal, Castellani, Manfredi, & Sala, 2018), and designing waste collection and transportation routes (Das & Bhattacharyya, 2015). Most reviewed models, however, optimize the allocation of waste to potential and existing waste treatment facilities (Aghajani Mir et al., 2016; Antmann et al., 2013; Cai et al., 2007; N.-B. Chang et al., 2012; P. Li et al., 2015; Minoglou & Komilis, 2013; Munster et al., 2015; Roberts et al., 2018; Xu et al., 2010). This work seeks to expand on optimization models of the costs of waste allocation and shift the focus to environmental impacts. Reviewed studies vary by the type of problem solved, mathematical modeling methods, optimization objectives, environmental impacts, and consideration of uncertainty (deciding whether to open a new waste treatment facility and incur a capital cost for doing so, as in this study. Some linear programs represent the decision variables as intervals to represent uncertain parameters (Cai et al., 2007; P. Li et al., 2015; Xu et al., 2010). Others represent parameters using fuzzy sets (Cai et al., 2007; Y. J. Chang & Lin, 2013). In these studies, linear programming has demonstrated its ability to represent relationships between the variables in MSW management problems, like enforcing a mass balance of waste flows from one point to another. Nonlinear methods, however, have been developed (Ahani et al., 2019; Minoglou & Komilis, 2013; Roberts et al., 2018) to represent more complex relationships in MSW management like transformation processes in waste treatment that change the composition of the waste stream and account for spatial and temporal variations.

Table 2-2).

2.3.1.1 Mathematical Methods

Most studies utilized linear programming to solve MSW management system problems (deciding whether to open a new waste treatment facility and incur a capital cost for doing so, as in this study. Some linear programs represent the decision variables as intervals to represent uncertain parameters (Cai et al., 2007; P. Li et al., 2015; Xu et al., 2010). Others represent parameters using fuzzy sets (Cai et al., 2007; Y. J. Chang & Lin, 2013). In these studies, linear programming has demonstrated its ability to represent relationships between the variables in MSW management problems, like enforcing a mass balance of waste flows from one point to

another. Nonlinear methods, however, have been developed (Ahani et al., 2019; Minoglou & Komilis, 2013; Roberts et al., 2018) to represent more complex relationships in MSW management like transformation processes in waste treatment that change the composition of the waste stream and account for spatial and temporal variations.

Table 2-2), which uses linear equations for the objective function and all constraints (Hillier & Lieberman, 2010). Several of these studies used Mixed Integer Linear Programming (MILP) to either solve a single objective at a time (Das & Bhattacharyya, 2015; Munster et al., 2015; Nikouei Mehr & McGarvey, 2017; Tirkolaee et al., 2020) or multiple objectives simultaneously (Badran & El-Haggar, 2006; Cristobal et al., 2018; Habibi et al., 2017). In MILP, decision variables are a mix of continuous and integer variables (Hillier & Lieberman, 2010). These may also involve binary variables, which represent yes/no decisions, such as deciding whether to open a new waste treatment facility and incur a capital cost for doing so, as in this study. Some linear programs represent the decision variables as intervals to represent uncertain parameters (Cai et al., 2007; P. Li et al., 2015; Xu et al., 2010). Others represent parameters using fuzzy sets (Cai et al., 2007; Y. J. Chang & Lin, 2013). In these studies, linear programming has demonstrated its ability to represent relationships between the variables in MSW management problems, like enforcing a mass balance of waste flows from one point to another. Nonlinear methods, however, have been developed (Ahani et al., 2019; Minoglou & Komilis, 2013; Roberts et al., 2018) to represent more complex relationships in MSW management like transformation processes in waste treatment that change the composition of the waste stream and account for spatial and temporal variations.

Table 2-2: Characteristics of Selected Optimization Models of MSW Management Systems and This Study.

Study	Problem	Optimization Method	Objective		Environmental Impact	Uncertainty Method
			Economic	Environmental		
Tirkolaee et al. (2020)	location allocation inventory	Robust Mixed Integer Linear Programming	✓	✓	Cost of uncollected waste Cost of air pollution	Robust Optimization
Habibi et al. (2017)	location allocation inventory	Robust Multi-Objective Mixed Integer Linear Programming	✓	✓	Greenhouse gas emissions	Robust Optimization
Roberts et al. (2018)	allocation inventory	Depth First Search Algorithm + Sequential Evolutionary Genetic Algorithm	✓	✓	Greenhouse gas emissions	n/a
N.-B. Chang et al. (2012)	allocation	Fuzzy Multi-Objective Linear Program +	✓	✓	Greenhouse gas emissions	n/a

		Compromise Programming			
Xu et al. (2010)	allocation	Interval Parameter Stochastic-Robust Programming	✓		Hybrid Stochastic Robust Optimization
P. Li et al. (2015)	allocation	LCA-Interval Parameter Programming	✓	✓	Cost of air pollution Interval-Parameter Programming
Cai et al. (2007)	allocation	Mixed Interval Parameter Fuzzy-Stochastic Robust Programming	✓		n/a Integrated Chance-Constraint, Interval, and Fuzzy Robust Programming
Cristobal et al. (2018)	allocation	Multi-Objective Mixed Integer Linear Programming	✓	✓	Normalized impact factor using ILCD methods, includes greenhouse gas emissions n/a
Minoglou and Komilis (2013)	allocation	Non-Linear Programming	✓	✓	Greenhouse gas emissions n/a
Munster et al. (2015)	allocation	Mixed Integer Linear Programming	✓	✓	Greenhouse gas emissions n/a
Antmann et al. (2013)	allocation	Discrete-Continuous Simulation with Tabu Search, Scatter Search, Neural Networks	✓	✓	Greenhouse gas emissions Frequency Distribution with Random Seed Generation
Y. J. Chang and Lin (2013)	allocation	Fuzzy Multi-Objective Linear Programming	✓	✓	Non-greenhouse-gas air pollutants n/a
Nikouei Mehr and McGarvey (2017)	location allocation inventory	Robust Mixed Integer Linear Programming	✓		n/a Robust Optimization
Ahani et al. (2019)	allocation inventory	Multi-Objective Using Mon-Dominated Sorting Genetic Algorithm and Fuzzy Expert System	✓	✓	Normalized impact factor using fuzzy expert system, includes greenhouse gas emissions Fuzzy Expert System
Badran and El-Haggar (2006)	location inventory	Multi-Objective Mixed Integer Linear Programming	✓	✓	n/a n/a
Das and Bhattacharyya (2015)	location	Mixed Integer Linear Programming	✓		n/a n/a
This study	location allocation	Robust Mixed Integer Linear Programming	✓	✓	Greenhouse gas emissions Robust optimization

“Allocation” refers to allocation of waste from generation points to final disposal points, which differs from the LCA definition of allocation, referring to the methods by which environmental impacts are allocated to products (e.g., economic or mass-based).

2.3.1.2 Optimization Objectives

In the selected studies (deciding whether to open a new waste treatment facility and incur a capital cost for doing so, as in this study. Some linear programs represent the decision variables as intervals to represent uncertain parameters (Cai et al., 2007; P. Li et al., 2015; Xu et al., 2010). Others represent parameters using fuzzy sets (Cai et al., 2007; Y. J. Chang & Lin, 2013). In these studies, linear programming has demonstrated its ability to represent relationships between the variables in MSW management problems, like enforcing a mass balance of waste flows from one point to another. Nonlinear methods, however, have been developed (Ahani et al., 2019; Minoglou & Komilis, 2013; Roberts et al., 2018) to represent more complex relationships in MSW

management like transformation processes in waste treatment that change the composition of the waste stream and account for spatial and temporal variations.

Table 2-2), the most common objective is to minimize the total cost of the MSW management system (Ahani et al., 2019; Antmann et al., 2013; Badran & El-Haggar, 2006; Y. J. Chang & Lin, 2013; Nikouei Mehr & McGarvey, 2017). Many models include objectives that capture the environmental impacts of the system, but they differ in how to represent those impacts mathematically. Environmental impacts can be represented in the objective function as a monetary cost to manage air or water pollutants (Badran & El-Haggar, 2006; P. Li et al., 2015; Tirkolaee et al., 2020) or as a qualitative criterion as determined by a Fuzzy Expert System (Ahani et al., 2019) or LCA methods (Cristobal et al., 2018). Some studies developed an objective function separate from the minimize cost function that minimizes environmental impact to demonstrate tradeoffs between the two objectives (P. Li et al., 2015; Munster et al., 2015; Roberts et al., 2018; Tirkolaee et al., 2020) while others used multi-objective approaches to find a solution that simultaneously minimizes both cost and environmental impacts (N.-B. Chang et al., 2012; Habibi et al., 2017; Minoglou & Komilis, 2013) or minimized environmental impact within a budgetary constraint (Cristobal et al., 2018). If objectives conflict with each other, multi-objective optimization may return a set of alternatives with tradeoffs called Pareto-optimal solutions that require further analysis computationally or by a decision-maker to arrive at a desired solution (Branke, Branke, Deb, Miettinen, & Slowiński, 2008); however, single-objective optimization is useful in understanding a best possible value for the solution within the constraints. In the case of minimizing some objective function, the best possible value is a lower bound; when maximizing, it is an upper bound.

2.3.1.3 Environmental Impact Methods

The environmental impacts most commonly evaluated in the selected waste system optimization models are GHG emissions (N.-B. Chang et al., 2012; Cristobal et al., 2018; Habibi et al., 2017; Minoglou & Komilis, 2013; Munster et al., 2015; Roberts et al., 2018), but sometimes modeling prioritized minimizing air pollutants that damage human health (Y. J. Chang & Lin, 2013; Habibi et al., 2017) or maximizing the waste recycling rate (Antmann et al., 2013). For

studies that prioritized GHG emissions, though, only a few extensively discussed the assumptions regarding methods and data sources related to the emissions (N.-B. Chang et al., 2012; Cristobal et al., 2018; Roberts et al., 2018), which is critical in validating the comparability between options in a model. For example, it is unclear whether the GHG emissions in Minoglou and Komilis (2013) or P. Li et al. (2015) include any offsets for byproducts of MSW management systems like electricity produced at a landfill, which would reduce the environmental impacts of those options using system expansion methods in LCA. Studies that were more transparent about assumptions regarding environmental impacts used LCA methods for estimating environmental impacts. Clearly, there is a need for transparency about modeling assumptions related to the environmental impacts of MSW management in optimization models.

2.3.1.4 MSW Management Processes

Models that determined optimal allocation of waste to treatment facilities usually included transportation as well, but a few did not (Ahani et al., 2019; Cristobal et al., 2018). Modeling both collection/transportation and treatment is important for capturing the full cost and environmental implications of the system, especially when considering separate collection of different waste fractions that require specific treatment. The treatment options included in these models most commonly considered landfilling, followed by incineration, composting, and a tie between recycling and anaerobic digestion (**Error! Not a valid bookmark self-reference.**). Two studies included production of refuse-derived fuel (Munster et al., 2015), and one study included direct feeding to animals and processing FW into animal feed as MSW management options (Cristobal et al., 2018). However, these studies note that their optimization frameworks can be expanded to include more treatment options. All of these models assume some composition for mixed MSW, typically divided into fractions like inorganic recyclables, organics, and others; some include sub-fractions within these categories. One exception is Cristobal et al. (2018), which analyzes flows of FW from the food supply chain and households.

Table 2-3: Treatment Facilities Included in MSW Management Optimization Models and In This Study.

REFERENCE	LF	COM	AD	WTE	MRF	OTHER
TIRKOLAE ET AL. (2020)	✓					
HABIBI ET AL. (2017)	✓				✓	
ROBERTS ET AL. (2018)	✓	✓	✓		✓	
N.-B. CHANG ET AL. (2012)	✓				✓	
XU ET AL. (2010)	✓			✓		
P. LI ET AL. (2015)	✓	✓		✓		
CAI ET AL. (2007)	✓			✓		
CRISTOBAL ET AL. (2018)		✓	✓			Direct feeding animals, AFP
MINOGLU AND KOMILIS (2013)	✓	✓	✓	✓		
MUNSTER ET AL. (2015)			✓	✓		RDF
ANTMANN ET AL. (2013)	✓			✓		
Y. J. CHANG AND LIN (2013)	✓	✓		✓		
BADRAN AND EL-HAGGAR (2006)	✓	✓				
AGHAJANI MIR ET AL. (2016)	✓	✓	✓	✓	✓	RDF
THIS STUDY	✓	✓	✓			AFP

LF = landfill, COM = composting, AD = anaerobic digestion, WTE = incineration for waste to energy, MRF = material recovery/recycling, RDF = refuse-derived fuel, AFP = animal feed production.

2.3.1.5 Uncertainty Methods

Several of the reviewed studies incorporated some consideration of uncertainty in their optimization models (deciding whether to open a new waste treatment facility and incur a capital cost for doing so, as in this study. Some linear programs represent the decision variables as intervals to represent uncertain parameters (Cai et al., 2007; P. Li et al., 2015; Xu et al., 2010). Others represent parameters using fuzzy sets (Cai et al., 2007; Y. J. Chang & Lin, 2013). In these studies, linear programming has demonstrated its ability to represent relationships between the variables in MSW management problems, like enforcing a mass balance of waste flows from one point to another. Nonlinear methods, however, have been developed (Ahani et al., 2019; Minoglou & Komilis, 2013; Roberts et al., 2018) to represent more complex relationships in MSW management like transformation processes in waste treatment that change the composition of the waste stream and account for spatial and temporal variations.

Table 2-2). Most often, costs are considered an uncertain parameter, including one or some combination of the following: transportation costs, operation costs, and revenues (Ahani et al., 2019; Antmann et al., 2013; Cai et al., 2007; P. Li et al., 2015; Xu et al., 2010). Other common uncertain parameters are waste generation rate (Antmann et al., 2013; Cai et al., 2007; Tirkolae et al., 2020; Xu et al., 2010), waste composition (Antmann et al., 2013; Habibi et al., 2017; P. Li et al., 2015), facility capacity (Antmann et al., 2013; Cai et al., 2007; Xu et al., 2010) and

environmental impacts (Ahani et al., 2019; Antmann et al., 2013; P. Li et al., 2015). Some sources also considered uncertainty in safety factors for waste treatment facilities (Cai et al., 2007), processing times for MSW management activities (Antmann et al., 2013), and volume at which a waste receptacle is serviced (Nikouei Mehr & McGarvey, 2017).

To handle uncertainty in these MSW management optimization models, several methods were used, such as stochastic programming, interval-parameter programming, fuzzy programming, frequency distributions using random seed generation, robust optimization, and hybrid approaches (deciding whether to open a new waste treatment facility and incur a capital cost for doing so, as in this study. Some linear programs represent the decision variables as intervals to represent uncertain parameters (Cai et al., 2007; P. Li et al., 2015; Xu et al., 2010). Others represent parameters using fuzzy sets (Cai et al., 2007; Y. J. Chang & Lin, 2013). In these studies, linear programming has demonstrated its ability to represent relationships between the variables in MSW management problems, like enforcing a mass balance of waste flows from one point to another. Nonlinear methods, however, have been developed (Ahani et al., 2019; Minoglou & Komilis, 2013; Roberts et al., 2018) to represent more complex relationships in MSW management like transformation processes in waste treatment that change the composition of the waste stream and account for spatial and temporal variations.

Table 2-2). In stochastic programming, model parameters are represented using probability distributions and random variables (Bertsimas, Brown, & Caramanis, 2011; Birge & Louveaux, 2011). Because the probability distribution for a parameter may be unknown, methods have been developed to represent uncertain parameters in models of complex systems. Fuzzy programming represents uncertain parameters using fuzzy membership functions based on fuzzy set theory (Inuiguchi & Ramik, 2000; Zadeh, 1965). Interval-parameter programming and some methods of robust optimization represent uncertain model parameters as a range with a known upper and lower bound (Ben-Tal & Nemirovski, 2000; Cai et al., 2007; P. Li et al., 2015; Xu et al., 2010). Other forms of robust optimization are more computationally complex and use a protection level to balance the tradeoff between solution robustness and model performance (Bertsimas et al., 2011).

Linear programs, like those used for optimizing MSW management, can be susceptible to producing infeasible or suboptimal results even given small uncertainties in model parameters (Ben-Tal & Nemirovski, 2000). Robust optimization was developed to find solutions to optimization problems that are robust against perturbations in the parameters while the model remains tractable and efficient (Bertsimas et al., 2011). According to M. Li, Gabriel, Shim, and Azarm (2011), “a solution is said to be robust if given any combination of possible uncertain factors, it is still feasible and the variation in its objective function value is still acceptable.” Robust results enable decision-makers to make decisions based on the worst-case rather than mean point estimates (Tirkolaee et al., 2020). In the literature, robust optimization has been demonstrated to be appropriate for large-scale problems like MSW management (Habibi et al., 2017; Nikouei Mehr & McGarvey, 2017; Tirkolaee et al., 2020; Xu et al., 2010) and infrastructure (M. Li et al., 2011). Robust optimization has not been applied to life cycle estimates of environmental parameters in MSW management systems.

2.3.2 Life Cycle-Based Models

There also exist mathematical models that use LCA methods to support decision-making in MSW management that place a greater focus on environmental impacts. In a review of decision support tools for MSW management, Blikra Veia, Martinez-Sanchez, and Thomsen (2018) determined that there are eight tools that are able to assess sustainability of the organic fraction of MSW based on documentation transparency, use of at least one environmental performance criteria, inclusion of MSW, use of LCA, ability to model co-products (offsets), and inclusion of at least one biological treatment option (e.g., composting). One tool Blikra Veia et al. (2018) reviewed, Valorisation des Matieres Residuelles (VMR), was excluded from this literature review due to unavailable documentation at the time of the study. Thus, seven of these tools are reviewed further alongside four other tools to compare methods used in the models, with a special focus on optimization, uncertainty, and environmental impact methods (Den Boer, Den Boer, and Jager (2007) selected a set of impact categories after testing best- and worst-case scenarios with their tool to determine critical impacts with their system. Presenting a number of impact categories provides the opportunity to assess tradeoffs between different types of impacts;

for example, in organic waste management systems, there may be a tradeoff between minimizing greenhouse gases and minimizing eutrophication impacts. Though GHG emissions have been the subject of extensive study, this study only explores GHG emissions because of the availability of data on GHGs compared to other impacts in addition to the study's simultaneous focus on optimization methods.

All tools were clear on which flows of emissions were modeled from the MSW management system to the environment they modeled. Various methods were used across the tools, but not all tools were clear on which methods they used to characterize the flows into impact categories (**Error! Not a valid bookmark self-reference.**). Transparency regarding this assumption is critical, because some methods may employ different characterization factors on certain flows and affect ultimate decisions. There is no single best method, but it is important to be clear about which methods are used. This study uses IPCC GWP₁₀₀ characterization factors to characterize flows of greenhouse gas emissions to the single indicator of CO₂ equivalents, or CO₂e (Intergovernmental Panel on Climate Change, 2014).

2.3.2.1 Waste Fractions

All of the above tools except for P. Li et al. (2015) are capable of assessing the impacts and costs of managing organic waste as a separated fraction (Table 2-4). This sets the LCA-based models apart from the optimization-focused models, several of which do not address separated organic waste fractions. As described in section 2.2.2, the type of waste determines which treatment methods are appropriate as well as the estimate of environmental impacts resulting from a treatment method. This study uses available LCA literature environmental impacts of treating FW through various waste treatment technologies when available but uses organic waste LCA literature for a proxy when necessary.

Table 2-4). Further discussion will highlight MSW management treatment options (

Table 2-5) and greenhouse gas emissions offsets (

Table 2-6). These studies will be referred to as “tool” in this section to avoid confusion on addressing the overall assessment tool and underlying LCA models that operate within the tools.

2.3.2.2 Optimization

About half of the reviewed tools are used to assess and compare MSW management system scenarios based on environmental performance but do not optimize the performance of the system (Den Boer, Den Boer, and Jager (2007) selected a set of impact categories after testing best- and worst-case scenarios with their tool to determine critical impacts with their system. Presenting a number of impact categories provides the opportunity to assess tradeoffs between different types of impacts; for example, in organic waste management systems, there may be a tradeoff between minimizing greenhouse gases and minimizing eutrophication impacts. Though GHG emissions have been the subject of extensive study, this study only explores GHG emissions because of the availability of data on GHGs compared to other impacts in addition to the study’s simultaneous focus on optimization methods.

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Table 2-4). Five of these tools can also use optimization methods to determine the “best” MSW management scenario based on minimum cost or minimum impact priorities; P. Li et al. (2015), however, incorporates the environmental impact into the objective function as a cost for managing air pollution in the MSW management system and is capable of assessing but not optimizing the system for environmental impacts. Both S-WOLF and MSW-DST note that either the cost or environmental impact (e.g., emissions, recycling rates) of a management system can be formulated as an objective as well as a constraint. For example, one can put a limit on the budget while optimizing for environmental performance, or find the minimum cost solution at a target recycling rate (Levis, Barlaz, DeCarolis, & Ranjithan, 2013; Thorneloe, Weitz, & Jambeck, 2007). Such constraints can be easily integrated into this study’s model framework.

2.3.2.4 Environmental Impacts

Every reviewed tool considers the impact of greenhouse gas emissions in the MSW management system evaluation (Den Boer, Den Boer, and Jager (2007) selected a set of impact categories after testing best- and worst-case scenarios with their tool to determine critical impacts with their system. Presenting a number of impact categories provides the opportunity to assess tradeoffs between different types of impacts; for example, in organic waste management systems, there may be a tradeoff between minimizing greenhouse gases and minimizing eutrophication impacts. Though GHG emissions have been the subject of extensive study, this study only explores GHG emissions because of the availability of data on GHGs compared to other impacts in addition to the study’s simultaneous focus on optimization methods.

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All of the above tools except for P. Li et al. (2015) are capable of assessing the impacts and costs of managing organic waste as a separated fraction (**Error! Not a valid bookmark self-reference.**). This sets the LCA-based models apart from the optimization-focused models, several of which do not address separated organic waste fractions. As described in section 2.2.3, the type of waste determines which treatment methods are appropriate as well as the estimate of environmental impacts resulting from a treatment method. This study uses available LCA literature environmental impacts of treating FW through various waste treatment technologies when available but uses organic waste LCA literature for a proxy when necessary.

Table 2-4). A few tools are able to incorporate any environmental impacts into their structure, which provides the flexibility for decision-makers to prioritize the impacts that are most important to their particular set of stakeholders. Selecting impact categories is an important component of the early phases of any LCA project (McDougall et al., 2008) and thus is implied to be important for LCA tools. Den Boer, Den Boer, and Jager (2007) selected a set of impact categories after testing best- and worst-case scenarios with their tool to determine critical impacts with their system. Presenting a number of impact categories provides the opportunity to assess tradeoffs between different types of impacts; for example, in organic waste management systems, there may be a tradeoff between minimizing greenhouse gases and minimizing eutrophication impacts. Though GHG emissions have been the subject of extensive study, this study only explores GHG emissions because of the availability of data on GHGs compared to other impacts in addition to the study's simultaneous focus on optimization methods.

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Table 2-4: Characteristics of Selected Life-Cycle-Based Decision Support Models and This Study.

Model	Reference	Optimization	Economic Assessment	Environmental Impacts	Assessment Method	Uncertainty
WARM v. 15	U.S. Environmental Protection Agency (2020f)		✓	global warming energy	IPCC GWP ₁₀₀	
S-WOLF	Levis et al. (2013); Levis, Barlaz, DeCarolus, and Ranjithan (2014); Sardarmehni (2021)	✓	✓	any	Contains a library of several impact assessment methods	✓
EASETECH	Boldrin et al. (2011); Clavreul, Baumeister, Christensen, and		✓	any	EDIP97	

Damgaard (2014)						
LCA-IWM	Den Boer et al. (2007)		✓	global warming depletion of abiotic resources human toxicity photo-oxidant formation acidification eutrophication	CML 2001	
MSW-DST	Thorneloe et al. (2007)	✓	✓	global warming	TRACI	
ORWARE	Eriksson et al. (2002)		✓	global warming volatile organic compounds acidification eutrophication heavy metals	unclear	
WRATE	D. Hall et al. (2017)			global warming depletion of abiotic resources human toxicity freshwater toxicity acidification eutrophication	CML 2001	
Opti-Waste	Munster et al. (2015)	✓	✓	any	unclear	
SWIMS	Roberts et al. (2018)	✓	✓	any	IPCC GWP ₁₀₀	
	P. Li et al. (2015)	✓	✓	global warming acidification respiratory air pollutants	unclear	✓
SIWMS	Hanandeh and El-Zein (2010)		✓	global warming respiratory air pollutants acidification heavy metals energy	unclear	✓
This Study		✓	✓	global warming	IPCC GWP ₁₀₀	✓

GHG = greenhouse gas emissions, any = any impacts can be incorporated to the framework.

2.3.2.7 Uncertainty

Only three of the reviewed LCA-based tools explicitly incorporated uncertainty into the model framework to account for uncertain parameters. Some make no mention of uncertainty in the referenced documents (Boldrin et al., 2011; Den Boer et al., 2007; Munster et al., 2015; U.S. Environmental Protection Agency, 2020f). The remaining tools that do not include uncertainty analysis do recommend the use of tools like sensitivity analysis or stochastic methods. For tools that do include uncertainty in the framework, two use Monte-Carlo simulations. In a series of 10,000 simulations, system parameters – population, waste characteristics, LCA model parameters – are varied using some distribution information and predicting the environmental

impact with some level of probability (Hanandeh & El-Zein, 2010; Sardarmehni, 2021). As mentioned before, distribution may be unknown for several parameters. As noted by Roberts et al. (2018), stochastic methods require a lot of data. As discussed in a previous section, P. Li et al. (2015) uses interval-parameter methods to account for uncertainty but does not apply them to optimization of environmental impacts. This model uses a high and low range of impacts from literature and examines best- and worst-case scenarios for environmental impacts when optimizing for an MSW management system.

Table 2-5: Waste Treatment Options Included in Selected Life-Cycle-Based Tools and This Study.

Model	Reference	LF	COM	AD	WTE	MRF	RDF	AFP	COD	Others
WARM v. 15	U.S. Environmental Protection Agency (2020f)	✓	✓	✓		✓				source reduction
S-WOLF	Levis et al. (2013); Levis et al. (2014); Sardamehni (2021))	✓	✓	✓	✓	✓				gasification
EASETECH	Boldrin et al. (2011); Clavreul et al. (2014)	✓	✓	✓			✓			
LCA-IWM	Den Boer et al. (2007)	✓	✓	✓	✓	✓	✓			
MSW-DST	Thorneloe et al. (2007)	✓	✓		✓	✓	✓			
ORWARE	Eriksson et al. (2002)	✓	✓	✓	✓	✓				Gasification sewage treatment
WRATE	D. Hall et al. (2017)	✓	✓	✓	✓	✓	✓			mechanical biological treatment
Opti-Waste	Munster et al. (2015)	✓		✓	✓					
SWIMS	Roberts et al. (2018)	✓	✓	✓	✓	✓	✓			mechanical biological treatment mechanical heat treatment
	P. Li et al. (2015)	✓	✓		✓					
SIWMS	Hanandeh and El-Zein (2010)	✓	✓			✓				
This Study		✓	✓	✓				✓	✓	

LF = landfill, COM = composting, AD = anaerobic digestion, WTE = incineration for waste to energy, MRF = material recovery/recycling, RDF = refuse-derived fuel, AFP = animal feed production, COD = anaerobic co-digestion at wastewater treatment plant.

2.3.2.8 MSW Management Options

The sets of waste treatment options for the FW fraction in LCA-based models most often included landfill, composting, anaerobic digestion (

Table 2-5). These are some of the most common options for FW treatment in the world and have data readily available for LCA modeling. Materials recycling, waste-to-energy, and refuse-derived fuel were provided as options often, but not typically as an option for the organic fraction. Across the available LCA models embedded in these tools, the particular treatment option's technological configuration may affect its environmental impacts. For example, most models of anaerobic digestion produce electricity at the grid while only a couple models of anaerobic digestion have upgrading equipment installed to produce biogas for vehicle transportation (Munster et al., 2015; Roberts et al., 2018). Two models included mechanical biological treatment and mechanical heat treatment, which pre-treats wastes for RDF and landfilling (Den Boer et al., 2007; D. Hall et al., 2017). WARM is the only model to include source reduction of wastes, which demonstrates the benefits of reducing waste; however, this is often considered out of scope for waste treatment studies. This study's model is the only one that includes separate wet and dry animal feed production and anaerobic co-digestion with sewage sludge at a wastewater treatment plant as options for an MSW management system. However, S-WOLF has been updated with an open-source framework in Python in which the creators claim that users can develop any kind of MSW management process module to incorporate into the tool (Sardarmehni, 2021).

Table 2-6: Climate Change Impacts Offsets in Selected Lifecycle-Based Tools and This Study.

Model	Reference	Recycling	Electricity	Fertilizer	Carbon Storage	Thermal Energy	Vehicle Fuel	Animal Feed
WARM v. 15	U.S. Environmental Protection Agency (2020f)	✓	✓	✓	✓			
S-WOLF	Levis et al. (2013); Levis et al. (2014)	✓	✓	✓	✓			
EASETECH	Boldrin et al. (2011); Clavreul et al. (2014)	✓	✓	✓	✓	✓		
LCA-IWM	Den Boer et al. (2007)	✓	✓	✓	✓	✓		
MSW-DST	Thorneloe et al. (2007)		✓				✓	
ORWARE	Eriksson et al. (2002)	✓	✓	✓		✓	✓	
WRATE	D. Hall et al. (2017)	✓	✓	✓		✓		
Opti-Waste	Munster et al. (2015)		✓	✓		✓	✓	
SWIMS	Roberts et al. (2018)	✓	✓	✓		✓		

equipment to upgrade, and is excluded (Moriarty, 2013). Offsets are also included for the avoidance of animal feed production.

Based on the literature, LCA embodies considerable uncertainty that results in conflicting answers on what the best management option is for municipal FW. Optimization models of MSW management have mostly been applied to find the most cost-efficient solutions. Studies have explored optimal MSW management from an environmental perspective, but few are transparent about methods used for the environmental emissions that enable comparison of equivalent options. Robust optimization provides a framework to find the optimal FW management system under uncertainty of such emissions estimates. This study will integrate life cycle estimates of FW management options into a robust optimization framework to model the climate impacts of waste collection, transportation, and treatment in Columbia, MO, to understand the conditions under which certain options perform better than others. This will be the first optimization model to integrate animal feed production. Furthermore, results will demonstrate the degree to which FW management can contribute to greenhouse gas emissions reductions in Columbia, MO. The results can be used by MSW management professionals to make FW management decisions based on uncertain conditions, as is the case in MSW management.

3. Background

3.1 Introduction to Columbia, MO

The study area of Columbia, Missouri, located in Boone County, lies in the middle of the state with a population of 123,195 in 2019 (U.S. Census Bureau, 2019). The city's MSW data reports that about 60,000 mt of MSW were generated in 2017, 53% generated by residents and the remaining 47% by commercial sources (Ben Kreitner, personal communication, 10 October 2019). In data provided by the city, waste from roll-off trucks and from the University of Missouri are provided as separate categories from residential and commercial waste and are excluded from this total. For reference, MSW makes up about 1/3 of the total mass landfilled. A Waste Composition Study in from 2016-2017 found that FW composes 17.8% of the total waste stream (Missouri Department of Natural Resources, 2018). Thus, the implied FW generated as a part of MSW in a year is about 10,600 mt.

3.2 Current Food Waste Management Options

The City of Columbia has two main disposal options for FW: bioreactor landfill and windrow composting. These are both located at the sanitary landfill in the northeast corner of Columbia. Additionally, on the western edge of Columbia, the City's wastewater treatment plant (WWTP) operates an anaerobic digester that co-digests sewage sludge and some FW from in-sink garbage disposals. At this time, the City does not currently offer separated FW collection for residents, but they do provide collection of separated organic waste from a number of participating businesses to be composted. In current practice, Columbia residents dispose of their FW in a mix with all other MSW to the municipal landfill via curbside pickup of trash bags at single-family homes and dumpsters at multi-family buildings.

3.2.1 Current Disposal Options – Landfill

The Columbia Sanitary Landfill is a bioreactor landfill with an energy collection system. A bioreactor landfill is an engineered and controlled landfill (Figure 3-1). The active cell of the bioreactor landfill is injected with liquid to increase rates of decomposition and stabilization. This

increased decomposition rate leads to increased production of landfill gas made primarily of CH₄, which is recovered for energy production by three turbines to produce electricity for the grid (City of Columbia, 2017). According to a report by Columbia Power and Light, the electricity produced from the landfill gas has accounted for up to 1.5% of Columbia's total electric load (City of Columbia Power and Light, 2019).

Figure 3-1: Columbia Bioreactor Landfill. Reference: City of Columbia (2021c)

3.2.2 Current Disposal Options – Compost

The windrow composting site at the Columbia Landfill (Figure 3-2) accepts FW from businesses and organizations that choose to participate. Some of these organizations include local restaurants, grocers, and schools. In the composting operation, FW is combined with yard waste from residents. In accordance with the Columbia Climate Action and Adaptation Plan goals to increase diversion of material from the landfill and to increase public education on how to reduce waste (City of Columbia, 2019), the city also offers scheduled composting workshops to teach residents how to compost their organic waste into a soil amendment they can use for applications like at-home gardening.

Figure 3-2: Columbia Windrow Composting. Reference: City of Columbia (2021e)

3.2.3 Current Disposal Options – Anaerobic Digestion

Some municipal FW is disposed of via in-sink garbage disposals. This FW flows through sewers to the city's WWTP and is co-digested with sewage sludge in an anaerobic digester (Figure 3-3 a). CH_4 is collected for use as fuel in a boiler to produce heat and waste heat is collected to warm the digester and enhance the digestion process (Figure 3-3 b) (City of Columbia, 2020). The mass of FW disposed via in-sink garbage disposals is assumed to be a negligible fraction of the total MSW stream because the city does not track the amount of FW entering the digester (Kori Thompson, personal communication, December 2019). The stabilized sludge that exits the digester, called biosolids (Figure 3-3 c), is applied to public and private property as a soil amendment and to the municipal landfill as cover.

Figure 3-3: A. Anaerobic Digester Building (City of Columbia, 2021a), B. Methane Combustion Engine (City of Columbia, 2021b), C. Biosolids (City of Columbia, 2021d)

3.3 Columbia Climate Action and Adaptation Plan

Columbia's city council released a Climate Action and Adaptation Plan in 2019 as a commitment to a comprehensive plan to reduce GHG emissions generated by the city (City of Columbia, 2019). The plan recognizes the human role in climate change, especially through the use of fossil fuels, and outlines goals for GHG reductions as well as corresponding actions and potential funding sources to meet the targets set. The plan addresses GHG emissions sources and actions by specific sectors, such as transportation, energy, and buildings. The city keeps a GHG inventory and tracks emissions via the GHG Protocol (World Resources Institute, C40 Cities, & ICLEI, 2014). According to the inventory, 88% of the 2.4 million mt CO₂e emissions in 2015 are from commercial energy, residential energy, and transportation, while solid waste only yields 2% of the total emissions. The highest-impact actions identified by the plan are to use renewable energy sources, increase energy efficiency in buildings, prioritize pedestrian transit (e.g., walking, biking), and boost public transportation.

When only accounting for municipal operations in direct control of the city, about 164,000 mt CO₂e, solid waste (excluding wastewater treatment) accounts for 28% of total GHG emissions. This is about 45,000 mt CO₂e. It is assumed this excludes transportation for solid waste activities. The report highlights that these emissions are due to the disposal of organic waste, including FW. Goals identified by the city to reduce the impacts of solid waste are reducing waste generation, increasing diversion, and improving the waste management system. Actions identified include educational workshops, city programs for reuse and recycling, and upgrading technologies for sorting at the materials recovery facility and for CH₄ collection at the landfill. According to reports from the sanitary landfill to the EPA (U.S. Environmental Protection Agency, 2015), the majority of the landfill emissions come from the industrial landfill activity in comparison to the MSW landfill.

4. Methods

4.1 Overview of Study

This work utilizes life cycle estimates to represent seven options (small composting, large composting, anaerobic digestion, anaerobic co-digestion, wet animal feed, dry animal feed) to treat FW, Table 4-15. These life cycle data are incorporated into an optimization modeling framework that represents Columbia, MO. This model captures the collection and transportation activities between geographical locations of FW collection points and FW treatment options. The model is utilized to determine optimal outcomes based on minimizing total costs or GHG emissions. First, the model is solved when the treatment options assume average values for GHG emissions. Robust optimization determines optimal outcomes when treatment options are at their best- or worst-case GHG emissions, providing insights for the conditions when certain treatment options perform better than others.

4.2 Problem Definition

For cities with GHG reduction goals, municipal FW management can contribute to the effort to meet GHG emission reduction targets. In order to achieve their goals feasibly, decisionmakers must approach municipal FW management considering the tradeoffs between economic costs and the potential environmental impacts of their decisions. LCA is a useful tool for understanding environmental impacts of a FW management option, but it contains considerable uncertainty and does not provide optimal results. Optimization modeling is a useful tool for understanding the degree to which certain options can meet an objective and the tradeoffs in the system to get there. This research incorporates LCA and robust optimization applied to FW management in Columbia, MO, to uncover insights about the degree to which FW management can reduce GHG emissions while incorporating uncertainty into the LCA GHG estimates that provide robustness to a solution.

4.3 Model Structure, Data, and Assumptions

In this study, a week of FW collection is modeled to account for service to all customers included in Columbia's solid waste utility service area (

Figure 4-1). Each year about 10,600 mt of FW is generated, implying an average of 204 mt of FW is collected from residences and businesses each week (Ben Kreitner, personal communication, 10 October 2019). The model maps the movement of a single FW collection truck (section 4.3.6.1) that drives from collection point to collection point to collect FW until it reaches capacity. When full, the truck drives to a treatment facility to unload FW for processing. At all facilities, some valuable byproduct is produced. For a given objective, the optimization model determines 1) whether to open treatment facilities and 2) how to allocate collected FW to existing and potential treatment facilities. To do this, it calculates the costs of transportation, fixed costs of treatment facilities, and treatment operation costs. It also calculates the potential emissions associated with the movement of collection trucks and the processing of FW at the treatment facilities. Model assumptions are as follows:

1. Columbia, MO, has an existing FW collection system that is owned and operated by the city. The cost of purchasing a fleet of FW collection trucks is not included in the model's cost estimation and optimization.
2. FW collection service occurs weekly and serves all customers over the course of a five-day schedule.
3. The collected FW is perfectly sorted FW and contains no contaminants.
4. Calculations for cost and emissions are estimated for a week of collection and assumed to be constant over time.
5. Each facility has a known, fixed capacity and location. Capacity assumptions are based on literature and case studies. Weekly capacity assumptions about the existing composting facility are based on Columbia's actual composting operations.
6. Environmental emissions are assumed to scale linearly with mass of FW treated at a facility and does not vary with total mass of FW or time.
7. Each resident in Columbia generates the same amount of FW.

4.3.1 Food Waste Treatment Facility Assumptions

Assumptions regarding the seven FW treatment options in the model are discussed below. For life cycle estimates of the GHG emissions associated with each facility, see Section 4.3.3.

4.3.1.1 Composting Assumptions

The windrow composting system assumptions are based on literature (Levis & Barlaz, 2011; Takata et al., 2012; Yoshida et al., 2012) and personal communications with Columbia MSW staff. It is assumed FW is mixed with fibrous yard waste in a volumetric ratio of 1:3 (Ben Kreitner, personal communication, July 2018). As a waste product, it is assumed that yard waste has no environmental impact as an input, consistent with literature (Clift et al., 2000). The yard waste is shredded in a diesel- (Levis & Barlaz, 2011) or electric-powered (Takata et al., 2012) grinder, piled with FW in rows, and turned periodically using a windrow turner powered by diesel as well (Levis & Barlaz, 2011; Takata et al., 2012; Yoshida et al., 2012). It is assumed some fugitive emissions of CH₄ and N₂O occur (Hobson et al., 2005). The final compost is to be used as a soil amendment that can displace synthetic fertilizers and to add to long-term biogenic carbon storage in soils (Levis & Barlaz, 2011; Yoshida et al., 2012). In this model, there are two options for identical composting facilities that only differ in their capacity and fixed cost. The smaller-capacity option represents the existing composting system in Columbia, and the larger option represents an expansion that requires additional capital investment.

4.3.1.2 Anaerobic Digestion Assumptions

The anaerobic digestion system assumptions are based on LCA literature (Levis & Barlaz, 2011; Takata et al., 2013; Yoshida et al., 2012). This system is assumed to be a dry, batch-fed system operating at the thermophilic range. The feedstock is assumed to be FW only, though one source assumes some paper and plastic is mixed in with the FW (Takata et al., 2013). These systems require energy to load FW and mainly depend on electricity to remove contaminants, keep the reactor warm, and to recirculate liquids that contain microbes (Levis & Barlaz, 2011; Takata et al., 2013; Yoshida et al., 2012). Furthermore, the reactor experiences some CH₄ leaks to the atmosphere (Levis & Barlaz, 2011; Yoshida et al., 2012). Electricity generated by CH₄ is assumed to be sold to the grid to displace the Missouri reference fuel mix (U.S. Environmental Protection Agency, 2020h). Digestate is applied as a soil amendment that can displace synthetic fertilizer and contribute to long-term biogenic carbon storage.

4.3.1.3 Anaerobic Co-Digestion Assumptions

The anaerobic co-digestion system assumptions are based on LCA literature (Edwards et al., 2017; Yoshida et al., 2012). This system is assumed to be a wet, continuous, mesophilic system that co-digests FW with sewage sludge at a wastewater treatment plant (WWTP) based on LCA studies (Edwards et al., 2017; Yoshida et al., 2012). The assumed ratio of FW to sludge is 1:6 (Edwards et al., 2017). The system requires energy inputs for mixing, heating, and pumping the substrate (Edwards et al., 2017; Yoshida et al., 2012). Electricity generated by CH₄ is assumed to be sold to the grid to displace the Missouri reference fuel mix (U.S. Environmental Protection Agency, 2020h). Digestate is applied as a soil amendment to add nutrients N and P and contributes to long-term biogenic carbon storage.

4.3.1.4 Landfill Assumptions

The landfill is assumed to be a bioreactor landfill with energy recovery as described in section 2.1.1. The process requires energy for front-end loaders to move FW and clay cover (Levis & Barlaz, 2011; Yoshida et al., 2012). The main emissions in the process are fugitive CH₄ from decomposing FW. CH₄ collected in buried pipes is either flared to produce CO₂ or combusted to produce electricity. The CO₂ produced by flaring is assumed to be biogenic CO₂ and not contributing to climate impacts. Electricity generated by CH₄ is assumed to be sold to the grid to displace the Missouri reference fuel mix (U.S. Environmental Protection Agency, 2020h).

4.3.1.5 Dry Animal Feed Production Assumptions

The dry feed system assumptions are based on LCA literature (Kim & Kim, 2010; Ogino et al., 2007; Takata et al., 2012). Dry feed production systems produce animal feed from FW that contains 5-20% moisture (Kim & Kim, 2010; Ogino et al., 2007; Takata et al., 2012). In this process, electricity is required to shred FW and then mix it while some fuel source heats and dehydrates the FW (Kim & Kim, 2010; Ogino et al., 2007; Takata et al., 2012). The reviewed LCAs include energy use estimates from steam heating and frying methods.

4.3.1.6 Wet Animal Feed Production Assumptions

The wet feed system assumptions are based on LCA literature (Kim & Kim, 2010; Ogino et al., 2007; Takata et al., 2012). This system produces animal feed from FW that contains 70-88% moisture (Kim & Kim, 2010; Ogino et al., 2007; Takata et al., 2012). In this process, electricity is required to shred FW and then mix it while some fuel source heats but does not dehydrate the FW (Kim & Kim, 2010; Ogino et al., 2007; Takata et al., 2012).

It is assumed dry feed and wet animal feed are intended for feeding swine. Missouri is in the top ten states for production of cattle, goats, turkey, swine, and broiler chickens (Missouri Department of Agriculture, 2021).

4.3.2 Model Geography

4.3.2.1 Collection Point Aggregation

It is estimated that the city of Columbia landfilled 10,600 mt of FW collected from residences and businesses in 2017, or 204 mt FW each week (see section 3.1). To model FW collection by a vehicle, the geographic distribution of FW generation is estimated. Assuming each person in Columbia generates the same amount of FW each week, geographic distribution of the population can be used to estimate the geographic distribution of FW generation. This estimate uses data on population at the census block level using 2010 census blocks that are within the Columbia solid waste utility service area map (City of Columbia, 2016; U.S. Census Bureau, 2011). The distribution of the 2010 census population is assumed to be representative for 2017. The relative population of each census block to all census blocks in the Columbia solid waste utility service area is used to determine the percent contribution to weekly FW generation. This percent contribution is multiplied by the total weekly FW generation in 2017 to determine a weekly FW generation rate for each census block, to be aggregated in development of model collection points. For example, Columbia's Census Tract 2001 Block 1003 had a population of 20 in 2010, or 0.018% of the population of all census blocks in the solid waste utility service area. This block is thus assumed to contribute to 0.018% to the total 204 mt of FW generated each week, or 37 kg per week in 2017 (Table 4-1).

Table 4-1: Data and Example Estimate for Weekly FW Generation of a Census Block in Columbia, MO

Location	Population 2010	Weekly FW Generation 2017
Columbia, MO	107,249	204,000 kg
Census Tract 2001 Block 1003	20	37 kg

Census blocks and corresponding FW generation rates are aggregated into clusters of adjacent blocks to create collection points that generate a maximum of 1.9 mt FW in a week. This value was chosen as the upper limit in order to ensure that the model could accommodate simulation of collection by some of the smaller FW collection trucks (Goldstein, 2014; U.S. Environmental Protection Agency, 2016b). For reference, a typical waste collection vehicle in Columbia is 25 cubic yards, which can hold about 15.5 mt FW (U.S. Environmental Protection Agency, 2016b). This yields a set of 110 collection points (

Figure 4-1).

4.3.2.2 Driving Distance Between Collection Points

A matrix is used to represent the distance between each and every pair of collection points. This data was generated using Google Distance Matrix API (Google, 2020) using the geographic coordinates of the centroid for each of the 110 collection points. The Distance Matrix API uses the coordinates for origins and destinations as input and produces an output the driving distance between each origin and destination as determined by Google Maps. This process was used to obtain the driving distance between each pair of collection points and from each collection point to each facility. It is assumed that collection point areas that share a border have no driving distance between them.

Figure 4-1: Centroids of Collection Points of Columbia, MO, In Shaded Areas Outlined in Black and FW Treatment Facility Locations.

Treatment facility locations A: windrow composting (existing), B: windrow composting (potential), C: standalone anaerobic digestion, D: anaerobic co-digestion at WWTP, E: landfill, F: dry animal feed processing, G: wet animal feed processing. Map adapted from City of Columbia (2016).

4.3.2.3 Driving Distance Within Collection Point Areas

In addition to the distance *between* collection points, the model also captures total length of roads driven *within* each collection point area. Columbia's Geospatial Information Services Office provided data for the full length of road within each the area representing a single collection point. Assuming there are households and businesses on both sides of each road, the total road length

within each collection point area was doubled to account for the truck driving to collect FW from every residence and business.

Since all existing and potential FW treatment facilities are assumed to be in the city limits of Columbia, the total distance traveled by trucks on each trip to offload collected FW will not vary significantly depending on the facility used. Facility location is expected to influence the distance traveled to a facility offload waste from a full truck more than it would influence the distance traveled between individual collection points. For some municipalities, waste management facilities are located far outside of the areas they serve and require a transfer station (Habibi et al., 2017; Hanandeh & El-Zein, 2010; P. Li et al., 2015). Facilities can sometimes be conveniently located closer to end-users of waste byproducts, like a feed processing facility or anaerobic digester on a farm (Kim & Kim, 2010; Persson, Bartlett, Branding, & Regan, 2016). Changes in assumptions about distance may have an impact on the best FW management choices.

4.3.2.4 Food Waste Treatment Facility Locations

The small composting, large composting, and landfilling options (A, B, E in

Figure 4-1) are located at the northeast corner of Columbia at the current sanitary landfill site. The small composting facility that already exists is already in this location, so it is assumed a large composting facility will be the result of expansion on the existing facility in the same location. The proposed location for anaerobic digestion (C) is also here. The proposed location for anaerobic co-digestion (D) is at the existing Columbia Regional WWTP because it is an existing source of sewage sludge. Finally, the locations for the wet and dry feed facilities (F, G) are proposed to be at an existing industrial area of Columbia. There is at least one food manufacturing company's facility located in this area at the time of the study.

In this model, the average distance to a treatment facility is defined as the average distance over all collection point locations to a given treatment facility location (

Table 4-2).

Table 4-2: Assumed Average Distance from Collection Point to Treatment Facility in FW Treatment Options and This Study's Model.

	COMPOSTING	ANAEROBIC DIGESTION	CO- DIGESTION	LANDFILL	WET FEED	DRY FEED
THIS MODEL	16	16	11	16	9	9
BLENGINI (2008)	25					
LEVIS AND BARLAZ (2011)		24		32		
YOSHIDA ET AL. (2012)	50	50	50	24		
KIM AND KIM (2010)	63	5	4		30	58
OGINO ET AL. (2007)						22
					150	100
					33	99

Ogino et al. (2007) studied two wet feed systems and three dry feed systems in their LCA.

When compared with this model (

Table 4-2), the reviewed LCAs assumed a greater average distance traveled by a waste collection vehicle to a treatment facility. There are two exceptions in Kim and Kim (2010) in which the anaerobic digestion and co-digestion facilities are closer to their collection points. Full route distances including transportation distance between collection points can only be determined once model results are generated.

4.3.3 Environmental Impact Estimates

This study uses life cycle estimates from LCA literature but makes adjustments to these estimates for FW treatment options to ensure consistent boundaries and enable comparison of environmental impacts. First, the boundary is defined for which FW treatment processes are and are not included in the GHG estimates. The assumptions for the included processes of the FW treatment options and their emissions estimates are discussed and any adjustments to the estimates are explained in detail throughout section 4.3.3. The reported emissions for each process in each FW management option are expressed as the average of all studies on the system. Emissions from FW collection and transportation are also discussed.

Studies used for life cycle estimates were chosen based on the following criteria:

- Evaluate GHG as impact category
- Model disposal of FW and/or organic waste
- Transparent LCI of FW treatment system inputs

4.3.3.1 Selection of Environmental Impact Category

Global warming is the selected impact category evaluated by this model. Climate change is identified as an important indicator for Columbia in the Columbia Climate Action and Adaptation Plan (City of Columbia, 2019). It is also by far the most common impact category in LCAs on FW management (Bernstad & la Cour Jansen, 2012; Edwards et al., 2017; Kim & Kim, 2010; Levis & Barlaz, 2011; Ogino et al., 2007; Takata et al., 2013; Takata et al., 2012; Yoshida et al., 2012). This study uses the indicator global warming potential (GWP), which characterizes flows of GHG emissions into a single indicator in units of CO₂ equivalents, or CO₂e. Characterization for CO₂e

will use the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) GWP₁₀₀ in values relative to CO₂ for a 100-year time horizon (

Table 4-3).

Table 4-3: IPCC GWP₁₀₀ Characterization Factors To Convert GHG Emissions To Climate Change Indicator In CO₂e. Reference: Intergovernmental Panel on Climate Change (2014).

Common Gas Name	Chemical Formula	GWP
Carbon Dioxide	CO ₂	1
Methane	CH ₄	28
Nitrous Oxide	N ₂ O	265

These values are used in the following sections to adjust life cycle estimates from literature. Biogenic CO₂ emissions are assumed to have a GWP of zero and soil carbon has negative GWP, consistent with Christensen et al. (2009).

4.3.3.2 Life Cycle Boundary

To compare FW treatment options on an equivalent basis, the life cycle estimate of GHG emissions for each option is based on a consistent boundary around the FW management system. The boundary for each life cycle estimate includes provision and combustion of fossil fuels for process equipment and heating, combustion of fossil fuels for process electricity, and fugitive emissions of CH₄ and N₂O from decaying organic matter. The GHG estimates also include the avoided impacts, or offsets, for products substituted by byproducts of FW treatment methods (e.g., compost displacing fertilizer).

Emissions associated with producing goods that eventually become FW (e.g., agricultural activities) are not included in the boundary of the GHG estimates, also called the zero burdens assumption (Clift et al., 2000). The following waste system processes are also excluded due to a lack of consistency in reviewed LCAs: wastewater treatment, production or disposal of trash bags or containers, and disposal of material rejected or screened out during process. Furthermore, the estimates do not include construction of facilities and production of facility equipment and vehicles because this is not included in the GHG estimates in reviewed LCAs. Takata et al. (2013) justifies exclusion: “treatment facilities have a long service life and emissions at the construction phase are assumed negligible.” Any transportation emissions in the reviewed

LCA literature is excluded and handled separately by the model. Transportation emission assumptions are discussed in section 4.3.5.

For all FW treatment options that produce a useful byproduct (composting, anaerobic digestion, anaerobic co-digestion, dry feed, wet feed), there is high uncertainty about the end user of the byproduct. Thus, the model does not capture emissions due to transporting the final product from the FW treatment facility to end users. The model also excludes any emissions that may occur from use, like N₂O emissions when compost or digestate is applied (Shen et al., 2018).

4.3.3.3 Impact Estimate for Food Waste Treatment Energy Inputs

To ensure consistent assumptions regarding energy inputs that contribute to GHG emissions, the life cycle inventory for each study is reconstructed to be consistent and representative of Columbia, MO. Since each study used different data sources to estimate GHG emissions as a result of using system energy inputs, the GHG emissions from fuel combustion for each study were recalculated using input flows of fuel derived from the reviewed literature and GHG emission factors from Takata et al. (2012) and Yoshida et al. (2012) (Table 4-4). The GHG emissions of electricity use are also recalculated to represent the emissions from producing electricity with the fuel mix in Missouri. The calculation uses the input electricity flows from reviewed literature multiplied by the GHG emission factor provided by EPA's eGRID data for the SERC Midwest (SRMW) region that contains Missouri (U.S. Environmental Protection Agency, 2020d). Missouri's fuel mix consists of 70% coal, 9% gas, 15% nuclear, and about 6% others (U.S. Environmental Protection Agency, 2020h) (Table 4-4). These GHG emissions are converted to the climate change indicator global warming potential (GWP) in CO₂e using IPCC's AR5 GWP₁₀₀ values (Intergovernmental Panel on Climate Change, 2014). Note that EPA's estimate of electricity impacts are only from fuel combustion and do not include fuel provision.

Table 4-4: GHG Emissions for Energy Inputs in kg CO₂e / Unit.

Energy Source	GHG Emission Factor	Unit	Reference
Electricity (SRMW)	0.76	kg CO ₂ e / kWh	U.S. Environmental Protection Agency (2020d)
Diesel	2.74	kg CO ₂ e / L	Takata et al. (2012)

Heavy oil	2.83	kg CO ₂ e / L	Takata et al. (2012)
Kerosene	2.60	kg CO ₂ e / kg	Takata et al. (2012)
Propane	6.00	kg CO ₂ e / L	Takata et al. (2012)
Natural Gas	5.31	kg CO ₂ e / L	Yoshida et al. (2012)

The GHG emissions of each treatment option are recalculated using the emission factor (Table 4-4) and the flows of energy inputs to the FW treatment system provided in literature (see references below (Table 4-5). These emissions are presented as an average across the studies that include the treatment option (Table 4-5). Similarly, the contributions of electricity use are calculated using inventory of electricity inputs and presented as an average for each FW treatment option (Table 4-5).

Table 4-5: Average Contribution of Fuel and Electricity Inputs to Environmental Impacts Per Mt FW For Each Treatment Option.

Option	Composting ^{ab} _{cd}	Anaerobic Digestion ^{ab} _c	Co-Digestion ^{de}	Landfill ^{ad}	Dry Feed ^{bfg}	Wet Feed ^{bfg}	Unit
Emissions from Fuel Use	19	10	9	5.5	114	13	kg CO ₂ e / mt FW
Electricity Required	5	59	45	0	115	8	kWh / mt FW
Emissions from Electricity Use	4	45	34	0	87	6	kg CO ₂ e / mt FW

References: a Levis and Barlaz (2011), b Takata et al. (2012), c Takata et al. (2013), d Yoshida et al. (2012), e Edwards et al. (2017), f Kim and Kim (2010), g Ogino et al. (2007).

4.3.3.4 Impact Estimate of Food Waste Treatment Fugitive Emissions

LCA literature for all FW treatment options, except dry and wet animal feed production, consider fugitive emissions of CH₄ and N₂O when FW decomposes anaerobically.

All reviewed LCAs on composting consider some emissions of CH₄ and N₂O, and no biogenic CO₂ emissions. Across studies, assumptions about chemical composition of input FW, FW decomposition rate, and turning frequency affect the estimated magnitude of fugitive non-CO₂ GHG emissions. No adjustments are made to reported fugitive emissions from composting LCA literature and the optimization model input data uses the average across the studies (Table 4-6).

Table 4-6: Reported Values of Non-CO₂ Fugitive GHG Emissions Per Unit FW Treated for Composting Systems.

Reference	Levis and Barlaz (2011)	Takata et al. (2013)	Yoshida et al. (2012)	Takata et al. (2012)	Average
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GHG Emissions (kg CO ₂ e / mt FW)	83	18	109	18	57
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Most reviewed anaerobic digestion and anaerobic co-digestion LCAs estimate fugitive emissions as a leakage of CH₄ from the digester (Edwards et al., 2017; Levis & Barlaz, 2011; Yoshida et al., 2012). Two out of four LCA studies on anaerobic digestion assumed no leaks and excluded fugitive emissions entirely (Takata et al., 2013; Takata et al., 2012). As with composting, no adjustments are made to the reported fugitive emissions values for anaerobic digestion. The optimization model input data uses the average reported value across studies (Table 4-7 and

Table 4-8).

Table 4-7: Reported Values of Non-CO₂ Fugitive GHG Emissions Per Unit FW Treated for Anaerobic Digestion Systems.

Reference	Levis and Barlaz (2011)	Takata et al. (2012)	Takata et al. (2013)	Yoshida et al. (2012)	Average
GHG Emissions (kg CO _{2e} / mt FW)	21	0	0	74	24

Table 4-8: Reported Values of Non-CO₂ Fugitive GHG Emissions Per Unit FW Treated for Anaerobic Co-Digestion Systems.

Reference	Yoshida et al. (2012)	Edwards et al. (2017)	Edwards et al. (2017)	Average
GHG Emissions (kg CO ₂ e / mt FW)	50	4	6	20

Because Takata et al. (2012) and Takata et al. (2013) did not discuss leakage of CH₄, the value reported in Table 4-7 is zero CO₂e. Here, this is interpreted as assuming a perfect system with no leaks. The average of the four values for co-digestion includes the two estimates of zero CO₂e.

Landfills are a widely studied system in LCA literature, but studies on bioreactor landfills specifically are limited. To include fugitive emissions specific to a bioreactor landfill, the optimization model input data uses GHG emission data reported by the Columbia Sanitary Landfill to the EPA, expressed as an average emission in CO₂e per mt FW over the last five years of reported data (

Table 4-9).

The Columbia Sanitary Landfill is mandated to report GHG emissions to the EPA GHG Reporting Program. This program uses a first-order decay model to estimate landfill CH₄ generation using a site-specific decay rate and estimated fraction of degradable waste, adjusted for oxidation of CH₄ into CO₂ through soil cover and the CH₄ that is recovered by the landfill gas (LFG) collection system for combustion (Bronstein, Coburn, & Schmeltz, 2013). The landfill also reports emissions of CH₄, N₂O, and CO₂ resulting from the combustion of landfill gas ("Protection of the Environment, Subpart HH," 2021). These GHG flows are characterized using IPCC AR5 GWP₁₀₀ values (

Table 4-3) and summed as emissions of CO₂e for each year (

Table 4-9) (

Equation 1).

Equation 1: Fugitive Emissions from Bioreactor Landfill for One Mt FW for Year

$$Impact = \frac{(F_{CH_4} + C_{CH_4}) * GWP_{CH_4} + (C_{N_2O}) * GWP_{N_2O}}{FW} * 1,000 kg \frac{kg CO_2e}{mt CO_2e}$$

Where F_{CH_4} = annual fugitive emissions of CH₄ from landfill (mt)
 C_{CH_4} = annual CH₄ emissions due to LFG combustion (mt)
 C_{N_2O} = annual N₂O emissions due to LFG combustion (mt)
 GWP_{CH_4} = IPCC GWP₁₀₀ characterization for CH₄
 GWP_{N_2O} = IPCC GWP₁₀₀ characterization for N₂O
 FW = annual mass of FW (mt), from Equation 2

Equation 2: FW As A Fraction of Total MSW In Bioreactor Landfill for One Year

$$FW = \frac{MSW}{MSW_{OW} * \frac{MSW_{FW}}{MSW_{OW}}}$$

Where MSW = annual mass of mixed waste (mt)
 MSW_{OW} = organic waste fraction of MSW (% mass)
 MSW_{FW} = FW fraction of MSW (% mass)

Because landfill CH₄ is attributed to the organic fraction of waste, the emission allocated per unit mass mixed MSW is divided by the mass fraction of organic waste in the Columbia landfill's MSW, assumed to be the same for all years as it was in the 2016-2017 waste audit (Missouri Department of Natural Resources, 2018). Then this value is multiplied by the relative fraction of FW to organic waste to estimate a value of fugitive emissions for the FW fraction only (

Table 4-9) (Equation 2). The average fugitive emission for the bioreactor landfill across all five years of data is 334 kg CO_{2e} / mt FW (

Table 4-9).

Table 4-9: Reported Annual Emissions and Waste in Columbia Sanitary Landfill and This Study's Estimates for Landfill Fugitive GHG Emissions Per Unit FW.

	2014	2015	2016	2017	2018	Unit
Fugitive CH₄^{b,c,d,e,f}	1,894	1,887	1,792	1,533	1,232	mt
LFG Combustion: CH₄^{b,c,d,e,f}	0.61	0.50	0.49	0.61	0.61	mt
LFG Combustion: N₂O^{b,c,d,e,f}	0.12	0.10	0.10	0.12	0.12	mt
GWP₁₀₀ - CH₄^a	28					mt CO ₂ e/ mt CH ₄
GWP₁₀₀ - N₂O^a	265					mt CO ₂ e/ mt N ₂ O
Total GWP (mt CO₂e)	53,080	52,877	50,216	42,973	44,454	mt CO ₂ e
Total Waste Generation^{b,c,d,e,f}	150,340	159,823	158,764	193,063	205,486	mt
Organic Fraction of Mixed Waste^g	38.5					% mass
FW Fraction of Mixed Waste^g	17.8					% mass
Environmental Emission Per Unit (kg CO₂e / mt FW)	424	397	380	267	202	kg CO ₂ e / mt W

References: a Intergovernmental Panel on Climate Change (2014), Intergovernmental Panel on Climate Change (2014) Intergovernmental Panel on Climate Change (2014) Intergovernmental Panel on Climate Change (2014) Intergovernmental Panel on Climate Change (2014) b U.S. Environmental Protection Agency (2014), c U.S. Environmental Protection Agency (2015), d U.S. Environmental Protection Agency (2016a), e U.S. Environmental Protection Agency (2017b), f U.S. Environmental Protection Agency (2018), g Missouri Department of Natural Resources (2018).

Even though the annual mass of waste disposed in the landfill increased from 2014-2018, the annual fugitive CH₄ shows a decreasing trend (

Table 4-9). The Columbia Sanitary Landfill's reports show a decrease in both the annual modeled fugitive CH₄ and recovered CH₄ from year to year even though the total volume of landfill gas and mass of waste both increased (U.S. Environmental Protection Agency, 2014, 2015, 2016a, 2017b, 2018). According to the rules governing the calculations used in the GHG Reporting Program ("Protection of the Environment, Subpart HH," 2021), the fugitive CH₄ emissions are a function of the recovered CH₄ minus oxidized CH₄ and the efficiency of the gas collection system to collect and destroy recovered CH₄ during landfill operating hours. The recovered CH₄ is a function of the volume of total landfill gas and the average measured CH₄ concentration (Bronstein et al., 2013). The measured CH₄ concentration decreases each year from 53.8% in 2014 to 43.8% in 2018, while the CH₄ oxidation rate remains the same, total landfill gas volume increases, and net collection of CH₄ decreases across those years (U.S. Environmental Protection Agency, 2014, 2015, 2016a, 2017b, 2018). This may explain the decrease in net CH₄ emissions. This could be due to an increase in fractions of waste that do not release CH₄ as they decompose, i.e., a decrease in the organic fraction of waste.

4.3.3.5 Food Waste Treatment Electricity Offsets

Some of the considered FW treatment options are assumed to generate electricity from combusting CH₄ produced by decomposing FW: anaerobic digestion, anaerobic co-digestion, and landfilling with CH₄ capture. Though the anaerobic digester in Columbia uses collected CH₄ in a gas-fire boiler for building heat (section 3.2.3), the system in the model is assumed to produce electricity. This electricity can be used in the local electric grid, and therefore is assumed to offset electricity from the local grid. The study regions varied in LCA literature and estimates for GHG emissions from electricity use are based on a range of fuel mixes. This also affected estimates for electricity offsets. Therefore, adjustments are made to estimates to represent the fuel mix in Missouri. This ensures that the study maintains a consistent assumption for the background data integral to calculating electricity offsets. This process is identical to the process for adjusting the emissions for input electricity. Using estimates for output kWh produced by a FW treatment option per mt of FW treated, the estimate for electricity offset is recalculated using the emission factor from EPA's 2018 eGRID data for the SRMW subregion (U.S. Environmental Protection Agency,

2020d). The model input data uses an average estimate of offsets across all studies. The average electricity generated per mt FW treated by anaerobic digestion is 218 kWh, offsetting 166 kg CO_{2e} on average, and by anaerobic co-digestion is 126 kWh, offsetting 96 kg CO_{2e} on average (Table 4-10). Landfill electricity generation is addressed separately.

Table 4-10: Reported Values for Electricity Production by Anaerobic Digestion and Anaerobic Co-Digestion and This Study's Estimate for Offset GHG Emissions Per Unit FW.

Reference	Anaerobic Digestion				Anaerobic Co-Digestion		
	Levis and Barlaz (2011)	Takata et al. (2013)	Takata et al. (2012)	Yoshida et al. (2012)	Yoshida et al. (2012)	Edwards et al. (2017)	Edwards et al. (2017)
Generated Electricity (kWh per mt FW)	210	284	284	95	191	75	112
Avoided Emission (kg CO _{2e} / mt FW)	-159	-216	-216	-72	-145	-57	-85

For landfilling, the avoided GHG emissions from electricity generated by FW are calculated using Columbia's report of electricity collected at the bioreactor landfill from the last five years of available data (City of Columbia Power and Light, 2019). This accounts for electricity generation specific to Columbia's bioreactor landfill. To determine the electricity generated by every mt FW landfilled, annual kWh generated divided by total waste landfilled in a year using mass data from the GHG reporting program (U.S. Environmental Protection Agency, 2014, 2015, 2016a, 2017b, 2018), and allocated only to the organic waste fraction using composition data from the 2016-2017 waste audit (Missouri Department of Natural Resources, 2018). This value is then allocated to the fraction of FW relative to organic waste, assuming the organic fraction and FW fraction of MSW are similar across all years (Equation 3). The GHGs offset by electricity produced from landfill gas are calculated using the emission factor from EPA's 2018 eGRID data for the SRMW subregion (U.S. Environmental Protection Agency, 2020d). From 2014 to 2018, the landfill generated 91-146 kWh per mt FW landfilled (

Table 4-11). The model input parameter uses an average of 111 kWh per mt FW, which offsets 84.5 kg CO_{2e} per mt FW.

Equation 3: Annual Electricity Production at Landfill Allocated to FW Fraction.

$$kWh \text{ per } mt \text{ FW} = \frac{E}{FW}$$

Where E = annual electric production from landfill (mt)

FW = annual mass of FW (mt), from Equation 2

Table 4-11: Annual Electricity Generated by Columbia's Sanitary Landfill and This Study's Estimate for Offset GHG Emissions from Electricity Per Unit FW from 2014-2018.

Year	2014	2015	2016	2017	2018	unit
Annual Electricity Produced ^a	18,266,000	14,149,000	14,359,000	16,676,000	15,544,000	kWh
Annual Mixed Waste Generation ^{b,c,d,e,f}	150,340	159,823	158,764	193,063	205,486	mt
Organic Waste Fraction of Mixed Waste ^g	38.5					% weight
FW Fraction of Mixed Waste ^g	17.8					% weight
Electricity Produced Per Unit FW	146	106	109	104	91	kWh / mt FW
Emission Factor for EPA SRMW ^g	0.76					kg CO ₂ e / kWh
Avoided Emissions Per Unit FW	111	81	83	79	69	kg CO ₂ e / mt FW

References: a City of Columbia Power and Light (2019), b U.S. Environmental Protection Agency (2014), c U.S. Environmental Protection Agency (2015), d U.S. Environmental Protection Agency (2016a), e U.S. Environmental Protection Agency (2017b), f U.S. Environmental Protection Agency (2018), g U.S. Environmental Protection Agency (2020d).

4.3.3.6 Waste Treatment Fertilizer Offsets

All LCAs for FW treatment systems that produce a nutrient-rich soil amendment include an offset for avoiding synthetic fertilizer production (Edwards et al., 2017; Levis & Barlaz, 2011; Takata et al., 2013; Takata et al., 2012; Yoshida et al., 2012). All LCAs included in this study provided some estimate of emissions for avoided fertilizer production. Across these studies, assumptions for the quantities of nutrients in the soil amendment and the degree to which the nutrients can replace those in synthetic fertilizers differ based on assumptions about FW composition. Because of the complexity in the estimates and variation, the average of reported values are used in optimization model input data (

Table 4-12). Furthermore, Bernstad Saraiva Schott et al. (2016) found that including this emission was not decisive in overall rankings of different options in a FW treatment LCA.

Table 4-12: Reported Values for Per-Unit Avoided GHG Emissions Due to Nutrient Replacement of N and P by Soil Amendment Produced by FW Treatment Options.

System	Avoided Emissions for Fertilizer Displacement (kg CO _{2e} / mt FW)					
Reference	Levis and Barlaz (2011)	Takata et al. (2012)	Takata et al. (2013)	Yoshida et al. (2012)	Edwards et al. (2017)	Average
Composting	-17	-39	-40	-3		-25
Anaerobic Digestion	-17	-23		-4		-15
Anaerobic Co-Digestion				-9	-13	-11

Grey box at the intersection of the column (study) and row (treatment option) indicates that the particular study did not include that treatment option.

4.3.3.7 Carbon Storage

When LCAs studying waste management of organic material estimate GHG emissions from degradation, some authors also include an estimate of carbon remaining in organic material in landfills and in soil when soil amendments (compost, digestate) are applied. These are considered a sink of biogenic carbon (Barlaz, 1998; Christensen et al., 2009). The amount of carbon stored per unit FW is determined by the assumed level of carbon in the FW as well as other factors like moisture content and rate of degradation in the waste management process (Bernstad & la Cour Jansen, 2012; Edwards et al., 2017; Levis & Barlaz, 2011; Yoshida et al., 2012). Assumptions relating to carbon storage for the same type of treatment varied widely across studies. In composting systems, for example, Levis and Barlaz (2011) assumed that 10 kg of carbon per applied Mg of compost remained in the soil after 100 years and 170 kg carbon per applied Mg of compost formed as humus over 100 years, whereas Yoshida et al. (2012) assumed about 14% of input carbon, or 30 kg, in compost was stored in the soil in an inactive form with no assumption about time. Further, the GHG emissions avoided by the stored carbon varied across studies. Levis and Barlaz (2011) did not disclose assumptions regarding the magnitude of saved CO_{2e} for each unit of carbon stored, whereas for each kg of stored carbon (Yoshida et al., 2012) and Edwards et al. (2017) credited about 3.65 kg avoided CO₂. The studies also varied in their assumptions about the carbon content of the waste materials. Due to the variation and complexity in these estimates, reported values are used in the optimization model input data as-is (Table 4-13).

Table 4-13: Reported Values of Per-Unit Avoided GHG Emissions for Carbon Stored in The Ground When Soil Amendment Produced by FW Treatment Is Applied to Ground.

Reference	Carbon Storage Emissions (kg CO ₂ e / mt FW)			Average
	Levis and Barlaz (2011)	Yoshida et al. (2012)	Edwards et al. (2017)	
Composting	-219	-68		-143
Anaerobic Digestion	-219	-61		-140
Anaerobic Co-Digestion		-62	-34	-48
Landfill	-200	-52		-126

Grey box at the intersection of the column (study) and row (treatment option) indicates that the particular study did not include that treatment option.

4.3.3.8 Food Waste Treatment Animal Feed Offsets

All reviewed LCA studies on animal feed produced from FW provided an estimate for avoided emissions from conventional feed, which result from agricultural and manufacturing activities in its production (Kim & Kim, 2010). Studies used a consistent method to estimate this avoided emission as a product of the wet mass of the feed from FW and some value for the emissions required to produce a unit of conventional feed. By using the wet mass, this method disregards the function of feed as providing nutrition and attributes the offset to the bulk mass of feed, including water. This leads to overestimates of potential avoided emissions for wet animal feed produced from FW that contains more moisture and, consequently, underestimates the total GWP for these systems. For this reason, avoided emissions for animal feed production are recalculated to adjust for the moisture content of animal feed produced from FW (Equation 4). None of the reviewed studies consider moisture in their offset estimation.

Equation 4: Estimation for Dry Weight of Animal Feed Produced from FW.

$$DM = WM * (100\% - MC)$$

Where DM = dry mass of feed (kg)

WM = Wet mass of animal feed (kg)

MC = moisture content of wet feed (%)

Following an adjustment of the feed byproduct for moisture content to get a dry matter equivalent, the emission factor for conventional feed must also be adjusted for dry matter. Dourmad et al. (2014) estimates that each kg of conventional pig feed grown using conventional agriculture emits 0.552 kg CO₂e / kg wet feed. Sol, Castillejos, Lopez-Verge, Muns, and Gasa (2019) estimates that conventional pig feed contains 13% moisture. Adjusted for moisture, the emission factor is 0.634 kg CO₂e / kg dry feed. The moisture-adjusted estimates of avoided emissions used for optimization model input data are in Table 4-14. Avoided emissions for dry feed average -199 kg CO₂e / mt FW and those for wet feed average -110 kg CO₂e / mt FW.

Table 4-14: Characteristics of Animal Feed Product from FW from Literature and Per-Unit Estimates for Animal Feed Offsets Used in This Study.

	Dry Feed					Wet Feed			
Source	a	a	a	b	c	b	c	a	a
Feed from FW wet mass (kg / mt FW)	240	200	508	125	670	430	1,000	1,399	976
Feed from FW moisture content	9%	5%	9%	22%	10%	69%	88%	80%	84%
Feed from FW dry mass (kg / mt FW)	218	190	462	98	603	133	120	280	156
Avoided Emission Per Unit (kg CO ₂ e / mt FW)	-138	-121	-295	-62	-381	-84	-76	-177	-102

References: a Ogino et al. (2007), b Kim and Kim (2010), c Takata et al. (2012). For Ogino et al. (2007) wet mass estimate 1,399 kg / mt FW, water was added to process.

4.3.4 Waste Treatment Environmental Impacts by Life Cycle Stage

After adjustments are made to the GHG estimates for some life cycle stages, the emissions are presented as an average emission per mt FW processed through each life cycle stage for each treatment option (Table 4-15).

Table 4-15: Per-Unit GHG Emissions for Each Life Cycle Stage Expressed as An Average Across Studies for A Particular Treatment Option.

	Stage	Composting	Anaerobic Digestion	Co-Digestion	Landfill	Dry Feed	Wet Feed
Emissions (kg CO ₂ e / mt FW)	Fuel	19	10	9	4	114	13
	Electricity	4	45	34	0	87	6
	Fugitive	57	24	20	334	0	0
Offsets (kg CO ₂ e / mt FW)	Electricity	0	-166	-96	-85	0	0
	Fertilizer	-25	-15	-11	0	0	0
	Feed	0	0	0	0	-199	-110
	Carbon Storage	-143	-142	-53	-126	0	0

These data (Table 4-15) are used as input data for estimating the environmental performance of FW treatment options in the optimization model. See section 4.5 for more details.

4.3.5 Waste Collection and Transportation Emissions

The waste collection vehicle is assumed to be a heavy-duty vehicle that runs on compressed natural gas (CNG), as is the case for part of Columbia's fleet (City of Columbia, 2021f). According to an LCA on heavy-duty vehicle fuel usage, a heavy-duty vehicle using CNG releases 3.13 kg CO₂e for every km traveled, compared to 3.16 kg CO₂e / km for gasoline or 3.35 kg CO₂e / km for diesel based on measured consumption of each fuel in heavy-duty vehicles (Maimoun, Reinhart, Gammoh, & McCauley Bush, 2013). This estimate of per-km emissions is a weighted average of emissions due to fuel consumption while driving and idling across a single day's waste collection route in an urban environment. The estimate includes emissions from fuel production in addition to combustion. In the optimization model, the emissions are calculated per unit distance traveled by the truck. In this model it is assumed emissions do not change with the weight of the truck though this is often an important consideration in LCA.

4.3.6 Cost and Capacity Estimates

4.3.6.1 Transportation Cost and Capacity Estimates

The costs associated with operating waste collection vehicles per unit distance driven are outlined in Table 4-16. The American Transportation Research Institute estimates that operation costs, excluding driver wages and benefits, total \$0.581 / km (American Transportation Research Institute, 2018). The American Transportation Research Institute estimates that driver wages and benefits per km are \$0.453. The total truck operation cost per km is \$1.038.

Table 4-16: Costs To Operate Waste Collection Vehicles, In \$ / Km. Reference: American Transportation Research Institute (2018).

Item	Cost per km
Fuel	\$0.229
Lease and Purchase Payments	\$0.164
Repair and Maintenance	\$0.104
Insurance	\$0.047
Permits and Licenses	\$0.014
Tires	\$0.024
Wages	\$0.346
Benefits	\$0.107

Total	\$1.038
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According to BioCycle magazine, FW collection vehicles range in capacity from 3 cubic yards to 27 cubic yards (Goldstein, 2014). The midpoint of this range, 15 cubic yards, was chosen as the capacity for the waste collection vehicle in this model. According to the EPA's guide on waste volume-to-weight conversion for various waste materials, this is equivalent to about 10 mt of FW (U.S. Environmental Protection Agency, 2016b).

The model does not estimate any costs associated with launching a separated FW collection program and assumes it is possible to integrate a program into the existing household waste collection in Columbia, MO. Potential costs associated with a household FW collection program could include new waste collection vehicles, hiring and training employees, public outreach and education, permitting, storage, and equipment replacement (U.S. Environmental Protection Agency, 1997). New waste collection vehicles could cost anywhere from \$150,000-\$350,000 each depending on size and technical features, and Columbia budgeted \$300,000 for each CNG vehicle costs for FY 2013 (City of Columbia, 2012; Trucks and Parts, 2020). Furthermore, the model does not include estimates of potential revenues from municipal FW management like tipping fees and potential sale price for byproducts since cost structures can be complicated, may include subsidies (U.S. Environmental Protection Agency, 1997), or may be a function of the final system design costs (DSM Environmental Services Inc., 2017).

4.3.6.2 Food Waste Treatment Facility Cost and Capacity Estimates

The costs of FW treatment modeled in this study are fixed costs and operating costs (Table 4-17). All costs are from literature and case studies on the FW treatment methods of interest. Fixed costs are associated with establishing a FW treatment facility and include the cost of building, site work, equipment, engineering, and legal work. The fixed costs for all options are annualized using a 15-year lifetime according to Komilis and Ham (2004) and 7% discount rate, as recommended by the EPA (U.S. Environmental Protection Agency, 2017a). Annualized costs are divided by 52 to represent the costs for a week of collection. For each option, fixed cost was obtained for a facility of a given capacity (Table 4-17). Because of a lack of specific data on

processing FW into animal feed, fixed costs are assumed to be the same for dry and wet animal feed facilities.

Table 4-17: Weekly Capacity, Fixed Costs Amortized Weekly, And Per-Unit Operating Costs.

	Windrow Composting 1	Windrow Composting 2	Anaerobic Digestion	Anaerobic Co-Digestion	Bioreactor Landfill	Dry Animal Feed	Wet Animal Feed
Capacity (mt/week)	45	325	250	144	205	214	214
Fixed Cost (\$/week)	\$0	\$4,184	\$26,617	\$4,236	\$0	\$17,419	\$17,419
Operating Cost (\$/mt)	\$9.08	\$9.08	\$64.82	\$32.04	\$14.00	\$23.84	\$28.95
Reference	abc	bc	de	de	d	df	df

References: a Kreitner (2018); b van Haaren et al. (2010); c Komilis and Ham (2004); d Kim, Song, Song, Kim, and Hwang (2011); e Moriarty (2013); f DSM Environmental Services Inc. (2017).

Facilities already in operation – composting and landfilling – have an assumed fixed cost of \$0 because the facilities are already in place and require no additional capital financing (Table 4-17). This also allows the model to distinguish between costs of continuing to use existing facilities and the costs of opening new facilities for new treatment options or, in the case of composting, to expand beyond current capacity. Operating costs represent the cost of processing a unit of FW at a given facility. They include the cost of utilities, insurance, labor costs, depreciation, and maintenance. Sources arrive at a value per mass FW by summing all of these costs over some period of time and dividing by the mass of FW treated in that time.

4.4 Model Formulation

The model is a mixed integer linear programming (MILP) coded in the General Algebraic Modeling System (GAMS) environment solved by the CPLEX solver. Depending on the objective function used – to minimize cost or minimize environmental impacts – the solver determines a route to collect FW generated by all customers within the waste utility service area for one week and how to allocate the collected FW to existing and potential FW treatment facilities.

4.4.1 Sets

Symbol	Description
I	Set of treatment facilities $I = \{i_1, i_2, i_3, i_4, i_5, i_6, i_7\}$
J	Set of collection points $J = \{j_0, \dots, j_{109}\}$

4.4.2 Parameters

Symbol	Description	Unit
C_i	Capacity of treatment facility i	mt / week
O	Capacity of collection vehicle	mt
T	Transportation economic cost	\$/km
TE	Transportation environmental impact	kg CO ₂ e / km
TC_i	Cost of processing a unit of FW at facility i	\$/ mt
F_i	Fixed cost of opening facility i	\$/ week
D_{ij}	Distance from treatment facility i to collection point j	km
Dr_j	Distance within collection area represented by point j	km
Env_i	Environmental impact of treating unit of FW in treatment facility i	kg CO ₂ e / mt
Dis_{ji}	Distance from collection point j to treatment facility i	km
$Dist_{jj'}$	Distance from collection point j to collection point j'	km
Δ	Tolerance for overfilling truck capacity	-
A_j	FW generated at collection point j	mt / week

4.4.3 Decision Variables

Symbol	Description
$X_{jj'}$	$\begin{cases} 1 \text{ if vehicle visits collection point } j' \text{ immediately after } j \\ 0 \text{ otherwise} \end{cases}$
$XX_{jj'}$	$\begin{cases} 1 \text{ if vehicle visits treatment facility between point } j \text{ and } j' \\ 0 \text{ otherwise} \end{cases}$
$Y_{jj'}$	$\begin{cases} 1 \text{ if vehicle visits collection point } j' \text{ after point } j \text{ in a tour} \\ 0 \text{ otherwise} \end{cases}$
$R_{jj'}$	$\begin{cases} 1 \text{ if vehicle visits collection point } j' \text{ after point } j \text{ in a tour} \\ \text{and vehicle } l \text{ drops off waste at facility } i \text{ from point } j \\ 0 \text{ otherwise} \end{cases}$
Zji_{ji}	$\begin{cases} 1 \text{ if vehicle visits facility } i \text{ immediately after collection} \\ \text{point } j \\ 0 \text{ otherwise} \end{cases}$
Zij_{ij}	$\begin{cases} 1 \text{ if vehicle visits collection point } j \text{ immediately after} \\ \text{facility } i \\ 0 \text{ otherwise} \end{cases}$
W_i	$\begin{cases} 1 \text{ if facility } i \text{ is open} \\ 0 \text{ otherwise} \end{cases}$
B_i	Mass of FW treated in facility i
V_j	Load of vehicle after visiting collection point j
Vji_{ji}	Load of vehicle when visiting treatment facility i from collection point j
u_j	Ordered position of collection point j in a tour by vehicle
$Q_{jj'}$	Mass of FW transported to facility by vehicle between points j and j'
TR	Total trips made to treatment facilities by waste collection vehicle

4.4.4 Objective Functions

$$\text{Objective 1} = \sum_j \sum_{j'} T * ((Dist_{jj'} + Dr_{j'})X_{jj'} - Dist_{jj'} * XX_{jj'}) + \sum_j \sum_i T * Dis_{ji} * Zji_{ji} + \sum_i \sum_j T * D_{ij} * Zij_{ij} + \sum_i B_i * TC_i + \sum_i F_i * W_i$$

$$\text{Objective 2} = \sum_j \sum_{j'} TE * ((Dist_{jj'} + Dr_{j'})X_{jj'} - Dist_{jj'} * XX_{jj'}) + \sum_j \sum_i TE * Dis_{ji} * Zji_{ji} + \sum_i \sum_j TE * D_{ij} * Zij_{ij} + \sum_i B_i * Env_i$$

4.4.5 Description of Objective Functions

The first objective function minimizes the total economic cost in U.S. dollars of the solution as the sum of the transportation cost and treatment costs. The transportation costs are a product of the cost to operate the waste collection vehicle per km traveled (Table 4-16) and the total

distance traveled on the FW collection route determined by the solver. The total FW collection route consists of driving distance from centroid to centroid of collection point areas (section 4.3.2.2), the road length within the collection point areas (section 4.3.2.3), the driving distance from collection point to FW treatment facility, and driving distance from facility to collection point. The term $-Dist_{jj'} * XX_{jj'}$ ensures that the distance between two collection points is not counted if the FW collection vehicle visited a FW treatment facility in between those two points. The treatment costs are the sum of fixed and operation costs. Fixed costs are equal to the weekly fixed costs for the facility if it is part of the solution (Table 4-17). The operation costs (Table 4-17) are equal to the per-unit costs of processing FW through a given treatment facility multiplied by the amount of FW that the solver allocates to that treatment facility.

The second objective function minimizes the environmental impacts and is almost identical to the first. In this objective function, the transportation cost in economic dollars is replaced with the climate impacts for each km traveled by the waste collection vehicle (section 4.3.5). The operation costs have been replaced by the environmental parameter value, discussed in the solution approach (Table 4-18). There is no equivalent term for environmental impacts associated with the opening of a facility, consistent with guidance on environmental burdens for machinery and buildings (Clift et al., 2000).

4.4.6 Constraints

$$\sum_j X_{j,j} = 1 \quad \forall j \quad (1)$$

$$\sum_j X_{j,j'} = 1 \quad \forall j \quad (2)$$

$$u_j - u_{j'} + (|J| - 1) * X_{j,j'} + (|J| - 3) * X_{j',j} \leq (|J| - 2) \quad \begin{matrix} \forall j, j' \\ s.t. j \neq 0, j' \neq 0, j \neq j' \end{matrix} \quad (3)$$

$$X_{j,j'} = 0 \quad \begin{matrix} \forall j, j' \\ s.t. j = j' \end{matrix} \quad (4)$$

$$u_j \geq 1 \quad \begin{matrix} \forall j \\ s.t. j \neq 0 \end{matrix} \quad (5)$$

$$u_j \leq |J| - 1 \quad \begin{matrix} \forall j \\ s.t. j \neq 0 \end{matrix} \quad (6)$$

$$\begin{aligned}
u_j &= 0 & j = 0 \in j & (7) \\
\sum_i Zji_{ji} &\leq 1 & \forall j & (8) \\
\sum_i Zij_{ij} &\leq 1 & \forall j & (9) \\
Zji_{j_0i} &= 0 & \forall i, j = 0 \in j & (10) \\
Zij_{ij'} &\geq X_{jj'} + Zji_{ji} - 1 & \forall j, j', i & (11) \\
\sum_i Zji_{ji} &\geq u_j - (|J| - 2) & \forall j & (12) \\
XX_{jj'} &\leq \frac{1}{2}(X_{jj'} + Zji_{ji}) & \forall j, j' & (13) \\
XX_{jj'} &\geq X_{jj'} + Zji_{ji} - 1 & \forall j, j' & (14) \\
u_{j'} - u_j &\leq (|J| + 1) * Y_{jj'} & \begin{array}{l} \forall j, j' \\ s.t. i \neq j \end{array} & (15) \\
Y_{jj'} &= 1 - Y_{j'j} & \begin{array}{l} \forall j, j' \\ s.t. j \neq j' \end{array} & (16) \\
Y_{jj'} &= 0 & \forall j, j' s.t. j = j' & (17) \\
R_{j'j} &\leq Y_{j'j} & \forall j', j & (18) \\
R_{j'j} &\leq \sum_i Zji_{ji} & \forall j', j & (19) \\
R_{j'j} &\geq Y_{j'j} + \sum_i Zji_{ji} - 1 & \forall j', j & (20) \\
Q_{j'j} &\geq V_{j'} - (O + Delta) * (1 - R_{j'j}) & \forall j', j & (21) \\
Q_{j'j} &\leq V_{j'} + (O + Delta) * (1 - R_{j'j}) & \forall j', j & (22) \\
Q_{j'j} &\leq R_{j'j} * (O + Delta) & \forall j', j & (23) \\
V_j &= \sum_{j'} A_{j'} * Y_{j'j} + A_j - \sum_{j'} Q_{j'j} & \forall j & (24) \\
Vji_{ji} &\geq V_j - (1 - Zji_{ji}) * (O + Delta) & \forall j, i & (25) \\
Vji_{ji} &\leq V_j & \forall j, i & (26) \\
Vji_{ji} &\leq Zji_{ji} * (O + Delta) & \forall j, i & (27) \\
B_i &= \sum_j Vji_{ji} & \forall i & (28) \\
B_i &\leq C_i * W_i & \forall i & (29) \\
TR &= \sum_j \sum_i Zji_{ji} & & (30) \\
X_{jj'} &= 0 \text{ or } 1 & \forall j, j' & (37) \\
Y_{jj'} &= 0 \text{ or } 1 & \forall j, j' & (38) \\
R_{jj'} &= 0 \text{ or } 1 & \forall j, j' & (39)
\end{aligned}$$

$$\begin{aligned}
Zji_{ji} &= 0 \text{ or } 1 & \forall j, i & \quad (40) \\
Zij_{ij} &= 0 \text{ or } 1 & \forall j, i & \quad (41) \\
W_i &= 0 \text{ or } 1 & \forall i & \quad (42) \\
B_i &\geq 0 & \forall i & \quad (43) \\
V_j &\geq 0 & \forall j & \quad (44) \\
Vji_{ji} &\geq 0 & \forall j, i & \quad (45) \\
u_j &\geq 0, \text{ integer} & \forall j & \quad (46) \\
Q_{jj'} &\geq 0, \text{ integer} & \forall j, j' & \quad (47) \\
TR &\geq 0, \text{ integer} & & \quad (48)
\end{aligned}$$

4.4.7 Description of Constraints

The traveling salesman problem is solved by Constraints (1)-(7), where subtours are eliminated by Constraint (3). These constraints ensure the FW collection vehicle starts the collection route at the landfill location j_0 , visits each collection point j exactly once, and completes the route at the landfill.

Constraints (8)-(9) ensures at most one treatment facility i is visited immediately before and after a collection point j . An exception is made for the FW collection vehicle origin j_0 in Constraint (10), so that no treatment facilities i are unnecessarily visited before FW is collected.

Constraint (11) ensures that if the waste collection vehicle visits a facility i from collection point j , it exits facility i and goes to another collection point j' . After the last FW-generating point j has been visited, the FW collection vehicle must visit a collection facility before returning to the vehicle origin location j_0 . This is accomplished through Constraint (12).

It is necessary to keep track of the collection points j from which the FW collection vehicle visited a treatment facility i and proceeded to the next collection point j' , which is done in Constraints (13)-(14). This is used to calculate the route distance in the objective functions to make sure no cost or climate impact is applied to the distance between j and j' . Instead, the distance from point j to facility i , and the distance from facility i to point j' are counted in the objective functions.

Constraints (15)-(24) work together to determine the load V_j of the vehicle as it visits each collection point j and collects generated FW A_j in an ordered route. The order in which each collection point j is visited is defined in Constraints (15)-(17). Constraints (18)-(20) identify if each collection point j' is visited before another collection point j and if the FW collection vehicle visited a treatment facility i from collection point j' . The load of FW in the collection vehicle is defined in Constraints (21)-(23) for each collection point j' where that point j' is visited before another point j and a treatment facility is visited after point j' . This load must be less than the capacity within a defined tolerance value of 5% of the full truck capacity. Constraint (24) defines the FW collection vehicle load at each collection point j equal to the sum of all FW collected at points j' visited before j , minus the sum of all FW delivered to treatment facilities prior to visiting j . Constraints (25)-(27) build further on the rules for collection vehicle load. When Zji_{ji} is equal to one, these constraints force the deposited amount Vji_{ji} to be equal to the vehicle load V_j and also within the capacity of the FW collection vehicle within the tolerance; whereas when Zji_{ji} is equal to zero, the deposited amount Vji_{ji} is set equal to zero.

To determine B_i , the amount of FW treated at a treatment facility i , the FW deposited by the collection vehicle Vji_{ji} from every point j to facility i is summed in Constraint (28). B_i is restricted by Constraint (29) to be less than the capacity of FW treatment facility i and the facility i must be open.

The number of total trips from all collection points j to all treatment facilities i is determined by Constraint (30) to understand how many routes are required for the FW collection vehicle to collect and deliver all FW generated in the model.

Lastly, constraints (37)-(42) define the binary variables and (43)-(48) define the non-negative variables. The non-negative variable constraints guarantee that only positive flows of FW are considered in the solution in order to eliminate infeasibilities.

The traveling salesman problem captured in constraints (1)-(7) and the capacity constraint in (28) are typical for waste management system models. This model is unique in tracking the collection points from which a truck takes FW to a treatment facility. Most reviewed MSW

management models allocate an entire waste stream from a collection node to treatment node, estimating transportation emissions associated with distance.

4.5 Solution Approach

A large, complex optimization model may not reach a solution in a reasonable amount of time. For this reason, a two-step procedure was used to increase the likelihood of a solution. In the first step, the model is solved for a given objective and only a select set of constraints: (1), (2), (3). This essentially solves only the traveling salesman problem and uses the solution as a starting point for the second step in the model. In the second step, the full model is solved for a given objective and those results are used for solution analysis.

Performance is measured by GHG emissions and economic costs. Total emissions are the sum of treatment emissions and transportation emissions. Total costs are the sum of fixed treatment costs, variable treatment costs, and transportation costs. In this study, better environmental performance is interpreted as more negative CO₂e emissions due to activities that offset GHG emitting activities. In FW treatment, this includes such examples as using FW byproducts to generate electricity that would otherwise be generated by burning fossil fuels or as a replacement for animal feed otherwise produced from virgin materials.

When minimizing GHG emissions, the optimization model does not have any constraints that require a minimum level of capacity utilization before opening a facility. Therefore, large fixed costs are incurred even when only a small amount of FW is processed at a facility. The model may send small amounts of FW to a facility that may have higher treatment emissions as a tradeoff to minimize transportation emissions. When minimizing costs, fixed costs are part of the objective function that the model minimizes in determining which facility to open. In this study's analysis of solutions for minimizing GHG emissions, fixed costs are calculated manually for each solution and added in the total cost calculation only when the amount of FW sent to a facility is equal to at least a full truckload, or 10 mt. Because the two composting options are located in the same place and have the same environmental parameter value in all scenarios, the model is equally likely to send FW to either of them in the case that composting is the option that minimizes the objective function. Only one option, however, incurs a fixed cost if chosen. To

calculate cost, if the aggregated amount of FW treated at both facilities is less than the capacity of the existing composting option, then the incurred cost will be \$0. Otherwise, the incurred cost of the larger facility will be added to the total costs of the solution.

The model is solved for the average case and the robust case, described in the following sections.

4.5.1 Average Case

The average case model is solved using GAMS/CPLEX software using the midpoint values for the environmental parameter (Table 4-18). The model was solved once to minimize emissions and once to minimize costs. The model is run with a limit of twelve hours or terminates earlier if the model reaches a solution within ten percent of the optimal solution identified by the model.

Table 4-18: Input Data for Optimization Model Environmental Parameter.

	Environmental Parameter (kg CO ₂ e / mt FW)					
Level	Composting	Anaerobic Digestion	Co-Digestion	Landfill	Dry Feed	Wet Feed
Best Case (-)	-88	-247	-100	126	1	-91
Average Case	-4	-87	-17	269	101	-36
Worst Case (+)	80	84	63	334	201	19

4.5.2 Robust Case

The RO model is solved to minimize emissions for scenarios that represent different combinations of the treatment facilities at their best or worst environmental parameter value (Table 4-18). There are seven treatment facilities in the model, but two of these represent the same technology (composting) at different capacities but with identical environmental parameter in every scenario. Therefore, six unique environmental parameters exist at their high and low levels for a total of sixty-four combinations or scenarios. The sixty-four scenarios are each solved once for the objective minimize impact for a total of sixty-four solutions. These solutions provide insights for the conditions under which certain options perform better than others and the degree to which different options perform both environmentally and economically.

In the RO model, a loop statement is used in GAMS to automate the process of running sixty-four separate models. In each loop, the environmental parameters for all six treatment

options are updated to represent each of the sixty-four combinations of best- and worst-case values. The loop also creates variables that store the model output for analysis.

4.5.3 Additional Runs

After the initial RO results are generated, additional model runs are conducted to investigate interesting cases and uncover more specific insights. Procedures and any modifications to the model parameters for additional runs are described and the results are presented in section 5.3.

5. Results

5.1 Average Case Results

In the minimum cost solution, 44 mt of FW is allocated to the composting facility each week, while the remaining 160 mt is allocated to the landfill. For the minimum environmental impact solution, all 204 mt FW is allocated to the anaerobic digester each week (Figure 5-1).

Figure 5-1: Weekly Allocation of FW In Average Case Solutions for Both Objectives.

As expected, the minimum cost solution costs less than the minimum impact scenario (Figure 5-2). The minimum cost solution uses existing facilities and is assumed to not incur any fixed costs; the sum of the variable and transportation costs total \$4,400 /week. The minimum impact scenario uses a facility that does not yet exist in Columbia, incurring high fixed costs that contribute to a total of \$38,300 /week. This is nearly nine times as costly than the minimum cost solution.

The annualized cost of anaerobic digestion using a seven percent discount rate and fifteen-year lifetime is \$1,124,105. If anaerobic digestion treats the 10,608 mt FW produced every year,

the operation costs are \$687,611. Annual revenue from electricity would be \$223,854 based on the average kWh per mt (Table 4-10) and the average charge for electricity in Missouri at 9.68 cents per kWh (U.S. Energy Information Administration, 2020a). It is assumed the digestate generates no revenues. This yields a profit of -\$1,587,861. Typically, tipping fees are set to recover these costs (Moriarty, 2013), which would need to be about \$150 per mt. To incentivize waste generators to use landfilling alternatives like anaerobic digestion, the tipping fee should be less than that of the landfill (Moriarty, 2013). Currently, the tipping fee at the Columbia Sanitary Landfill is \$50 per mt (City of Columbia, 2021g).

Figure 5-2: Weekly Total Costs in Average Case Solutions for Both Objectives.

The transportation costs of the two scenarios are about the same (Figure 5-2). The minimum cost solution incurs \$1,725 in transportation costs per week and the minimum impact solution incurs \$1,718. This indicates that transportation in this model does not have a large influence on the facilities selected for waste treatment, nor is it the major influence for the total environmental impact or total cost of a solution. The minimum cost scenario relied on existing facilities no fixed costs due to use of existing facilities, while the minimum impact scenario incurs high fixed costs. Anaerobic digestion has both high fixed costs and high variable costs, contributing 56% and 40% to total costs, respectively, in the minimum impact solution (Table 4-17).

Figure 5-3: Weekly Environmental Impact in Average Case Solutions for Both Objectives.

The minimum cost solution results in a net positive environmental impact of 51,000 kg CO₂e / week while the minimum impact scenario results in a net negative impact of -7,800 kg CO₂e / week, a difference of 58,800 kg CO₂e / week to treat only residential FW (Figure 5-3). Both solutions result in slightly less than 10,000 kg CO₂e / week for collecting FW. Weekly treatment impacts in the minimum cost scenario (41,000 kg CO₂e) are significantly less than if all FW had been landfilled (52,900 kg CO₂e).

This efficient frontier (Figure 5-4) is developed by solving the model for a given objective while the other objective is modeled as a constraint. The constraint levels for the minimize cost efficient frontier are defined as the quartile values between the impact value for the minimum impact solution (-7,802 kg CO₂e / week) and the impact value for the minimum cost solution (51,048 kg CO₂e / week). The constraint levels for the minimize impact efficient frontier are defined as the quartile values between the cost for the minimum for the minimum cost solution (\$4,362 / week) and the cost for the minimum impact solution (\$32,285). Figure 5-4: Efficient Frontier for Average Case Solutions for Both Model Objectives.

Figure 5-5: Efficient Frontier for Average Case Solutions for Both Model Objectives.

Ideal performance is low emissions and low cost, on the bottom left of the frontier. The general trend here is that greater cost efficiency comes worse environmental efficiency. For example, anaerobic digestion and co-digestion + wet feed are environmentally efficient but not cost-efficient. Landfilling + composting is cost-efficient but not environmentally. There are two solutions in the graphs for both objective functions that could be considered a compromise between cost and environmental efficiency: composting and co-digestion + composting. Though composting and co-digestion + composting solutions do not achieve net negative environmental impacts, they perform much better on the environmental objective while only yielding a slight increase in weekly costs.

5.2 Robust Results

5.2.1 General Picture of Impacts

Over all sixty-four solutions, the transportation impact is always positive and relatively constant, ranging from 8,667 kg CO₂e / week to 10,578 kg CO₂e / week (Figure 5-6). The impact due to treatment of Columbia's residential and commercial FW has a wider range that spans positive and negative values, from -50,433 kg CO₂e / week to 4,018 kg CO₂e / week. There does not appear to be a strong relationship between treatment emissions and transportation emissions for a given solution.

Figure 5-6: Weekly Environmental Impacts Across All Robust Model Solutions.

Even though the transportation impacts remain positive across all solutions, the results suggest that it is possible to select FW treatment scenarios that result in net negative impacts (Figure 5-3). This means, for the proposed model, it is possible for the benefits of the FW treatment options to outweigh the impacts from transportation. This is dependent on how FW

treatment system byproducts are used, which is explored with regards to composting in section 5.3.4. Specific transportation impacts are discussed in section 5.2.3.3.

5.2.2 Solutions Categorized by Treatment Option

Figure 5-7 shows the sum of solutions in which each treatment technology is included out of the sixty-four total solutions, on its own or in a combination.

Figure 5-7: Number of Solutions in Which Each Treatment Option Is Selected to Treat FW In A Solution.

Anaerobic digestion is the most frequently occurring treatment option, included in thirty-two solutions. Wet feed ranks second, included in twenty solutions. Co-digestion is included in sixteen solutions. Compost is included in eight solutions. Dry feed is included in four solutions. Landfill is included in zero. The ranking of frequency follows the order of increasing average environmental parameter (Table 4-18).

Figure 5-8: Number of Occurrences in A Solution for Each Treatment Option at Its Best- Or Worst-Case Environmental Parameter.

To understand the context and conditions in which certain options are chosen, the frequency of selection is examined for when an option is selected when its environmental parameter is best, at the low end of its range of emissions, and when its environmental parameter is worst, at the high end of its range. Each option is included in a solution whenever its environmental parameter

is at its lowest value, with the exception of wet feed that is chosen at both its lowest and highest value (Figure 5-8).

5.2.3 Solutions Categorized by Treatment Option Combination

To simplify comparisons, the sixty-four solutions are categorized into seven different solution types. Solution types are characterized by the single treatment option or combination of treatment options that received a significant amount of waste: anaerobic digestion, combination of co-digestion + wet animal feed, combination of co-digestion + compost, combination of co-digestion + dry animal feed, wet animal feed, compost only, dry animal feed only.

Figure 5-9: Frequency of Each Solution Type in Sixty-Four Solutions.

Anaerobic digestion is the most frequently occurring solution type, followed by combinations using co-digestion and another option, then wet feed only, compost only and lastly dry feed. Landfilling is not included in any solutions. Four of the solution types use only one option on its own. Three solution types use a combination of options, which always includes co-digestion. The assumed co-digestion facility in the model has a capacity of 144 mt FW per week, which falls short of the 204 mt FW generated by residents. Thus it could only be chosen in combinations under the constraint that all FW is treated. The effects of increasing the capacity for the modeled co-digestion facility are explored in section 5.3.2.

In 50% of the sixty-four solutions, anaerobic digestion treats FW, regardless of the level of the other options (

Table 5-1). When anaerobic digestion is part of a solution, its environmental parameter is at its low level. The environmental parameters for all other options are at their high level (+) or low level (-). This means that anaerobic digestion is chosen at its low level, no matter the level of the other environmental parameters.

Table 5-1: Solution Type, Frequency of Solution Type, And Level of Environmental Parameter for All Treatment Options When Solution Type Occurs.

Solution Type	Frequency	Level of Environmental Parameter					
		Compost	Anaerobic Digestion	Co-Digestion	Landfill	Dry Feed	Wet Feed
Anaerobic Digestion	50%	+/-	-	+/-	+/-	+/-	+/-
Co-Digestion + Wet Feed	12.5%	+/-	+	-	+/-	+/-	-
	3.1%	+	+	-	+/-	+	+
Co-Digestion + Compost	6.3%	-	+	-	+/-	+/-	+
Co-Digestion + Dry Feed	3.1%	+	+	-	+/-	-	+
Wet Feed Only	12.5%	+/-	+	+	+/-	+/-	-
	3.1%	+	+	+	+/-	+	+
Compost Only	6.3%	-	+	+	+/-	+/-	+
Dry Feed Only	3.1%	+	+	+	+/-	-	+

Row entry is FW treatment method used in solution type. Minus symbol (-) indicates the environmental parameter for the option in the column header is at its lowest, or best-case, value in the solution type. Plus symbol (+) indicates the environmental parameter for the option in the column header is at its highest, or worst-case, value in the solution type. Shaded boxes indicate level for the environmental parameter of the options that treat FW in the solution type.

Landfilling is not part of any solutions at its high or low level of environmental impact parameter, indicating it has the worst environmental performance of all included options.

Anaerobic digestion at its low level is always part of the solution and has better environmental performance than any other option at their high or low environmental impact parameter.

Wet feed at its low level performs better than dry feed and composting regardless, but only outperforms anaerobic digestion or co-digestion at their high level. Co-digestion at its low level treats waste in combination with wet feed at both its high and low level. These results suggest that co-digestion performs better than wet feed if given sufficient capacity, which is explored in section 5.3.2.

When co-digestion and composting are both at their low level, they treat food waste as a combination regardless of dry feed's level and while anaerobic digestion and wet feed are at their high level. Composting is the sole choice in the solution under the same conditions, but when co-digestion is at its high level. This indicates that co-digestion is better than composting. This is further supported by the relative waste allocation in the co-digestion + composting scenarios, which allocated more waste to co-digestion than composting every time.

When co-digestion and dry feed are both at their low level, they treat food waste in combination while all other options are at their high level. Dry feed treats waste alone when all other options, including co-digestion, are at their high level. This indicates that co-digestion is better than dry feed.

Wet feed is the only option chosen at its highest environmental parameter, but only when the environmental parameter of all other options are at their worst. This is due to the relatively low maximum for the environmental parameter of wet feed systems (Table 4-18). Compared to other options, wet feed has the lowest energy inputs that contribute relatively few climate impacts (Table 4-5). Compared to dry feed, wet feed has lower energy inputs because the product is heated to kill pathogens and not to remove moisture; however, the high moisture content of wet feed (>20%) may make it an undesirable option if the feed is not used before it expires or if it must be transported a long distance (Westendorf & Myer, 2004). Additional scenarios are explored in section 05.3 to find a threshold distance when it is not longer environmentally preferable to transport FW to a feed facility.

5.2.3.1 Impacts by Solution Type

Table 5-2 presents the range of climate impacts for each solution type. The ranges are relatively narrow and do not overlap.

Table 5-2: Range of Weekly Environmental Impacts for Each Solution Type.

Solution Type	Rank	Total Weekly Impacts (kg CO ₂ e)	
		min	max
AD ONLY	1	-40,700	-40,050
CO-D AND WET FEED (-)	2	-11,110	-10,860
CO-D AND COMPOST	3	-10,790	-10,546
WET FEED (-)	4	-9,906	-9,718
COMPOST	5	-8,056	-7,332
CO-D AND DRY FEED	6	-5,505	-5,260
CO-D AND WET FEED (+)	7	-4,118	-4,102
DRY FEED	8	8,920	8,928
WET FEED (+)	9	12,869	13,269

The environmental impacts range from -40,700 to 13,269 kg CO₂e per week. The solution types are ranked by average impact from 1 to 9 (Table 5-2). Anaerobic digestion is better than the next best solution by about 29,000 kg CO₂e per week. A combination of co-digestion + wet feed at its low environmental impact parameter ranks second, closely followed by a combination of co-digestion + compost and then wet feed at its low environmental impact parameter. Composting, a combination of co-digestion + dry feed, and a combination of co-digestion + wet feed at its high environmental parameter ranks lower but still achieve net negative impact. Dry feed ranks 8 and wet feed at its high environmental impact parameter rank 9, both with positive environmental impact.

These rankings support the conclusions drawn from

Table 5-1 that anaerobic digestion has the best environmental performance, followed by co-digestion, wet feed, composting, then dry feed.

5.2.3.2 Costs by Solution Type

The range of costs for each solution type are in Table 5-3. These are relatively narrow and do not overlap, so further discussion will compare costs of solution types using the average cost for each solution type. Solutions including compost had the lowest costs and ranks best for economic performance, whereas solutions including a feed facility rank in the middle, and anaerobic digestion ranks low.

Table 5-3: Range of Weekly Costs for Each Solution Type.

Rank	Facility	Total Weekly Costs	
		Minimum	Maximum
9	AD ONLY	\$ 38,247	\$ 38,358
7	CO-D + WET FEED	\$ 30,190	\$ 30,433
2	CO-D + COMPOST	\$ 15,725	\$ 15,770
4	WET FEED ONLY	\$ 27,781	\$ 27,910
1	COMPOST ONLY	\$ 8,378	\$ 8,502
3	CO-D + DRY FEED	\$ 1,521	\$ 30,825
8	CO-D + WET FEED	\$ 30,474	\$ 30,474
6	DRY FEED ONLY	\$ 29,109	\$ 29,111
5	WET FEED ONLY	\$ 27,932	\$ 27,939

Though anaerobic digestion has the best environmental performance over all solutions, it is also the most expensive treatment option on average in the model (Table 5-3). On average, its costs are about five times as expensive as the cheapest option (composting) and about 26% more than the next most expensive option. Anaerobic digestion has both the greatest fixed costs per week and greatest variable costs per ton of mt FW. Anaerobic digestion incurs high capital costs for equipment like reactors and biogas treatment and processing systems. The capital cost used in this model may be an overestimate for a dry anaerobic digester since the estimate is based on a large wet type digester, which tend to be more expensive because of longer processing times (Moriarty, 2013).

Figure 5-10: Average Weekly Total Cost of Each Solution Type.

The total costs for the solutions using wet feed only, a combination of co-digestion + wet feed, a combination of co-digestion + dry feed, and dry feed only are similar (Figure 5-11, Table 5-3). The solutions that use a combination of co-digestion and a feed facility have higher fixed costs than using a feed facility alone, but the lower variable costs for processing FW through co-digestion compared to animal feed result in about the same total costs. This particular co-digestion facility does not have a prohibitive fixed cost like the standalone anaerobic digestion facility; its fixed cost is based on the cost for an add-on to an existing wastewater treatment plant make it much cheaper than anaerobic digestion or even a new composting facility (Table 4-17).

Solutions of wet feed and dry feed are nearly equal in cost due to assumed equal fixed costs (Table 4-17). The variable costs for wet feed are slightly less because the process requires less input energy, resulting in wet feed appearing preferable over dry feed for cost by about \$1,200 per week. Some farms use their own anaerobic digesters for digesting food waste with manure to make electricity or as a renewable source of natural gas (U.S. Environmental Protection Agency, 2020c). A feed facility may be a cheaper option for a farmer to handle large amounts of FW or a feasible option for farmers that do not raise livestock to produce manure.

In this model, there were two composting options. One represents the existing composting facility in Columbia and incurs no fixed costs in the model. The larger composting facility represents an expansion on the facility. Both have identical variable costs and environmental parameter. In all solutions in which composting is included, the total FW treated by composting exceeded the capacity of the smaller existing compost option.

5.2.3.3 Transportation Impacts by Solution Type

The impacts of transportation are calculated as the average transportation emissions across all solutions of the same type divided by the total amount of FW treated in a week (Table 5-4).

The relative burden for each treatment option is calculated as the average transportation emissions described previously as a percentage of the sum of transportation emissions and the maximum environmental impact parameter for each treatment option (Table 4-18).

Table 5-4: Average Per-Unit Transportation Emissions by Solution Type

	ANAEROBIC DIGESTION	CO-DIGESTION + WET FEED	CO-DIGESTION + COMPOST	WET FEED	COMPOST	CO-DIGESTION + DRY FEED	DRY FEED
AVERAGE TRANSPORTATION EMISSIONS (KG CO₂E / MT FW)	49	44	44	44	50	44	43
RELATIVE BURDEN	37%	41%, 70%	41%, 36%	70%	38%	41%, 18%	18%

When compared to other studies, the contributions to overall climate impacts from transportation in these results are relatively high. In their studies of animal feed, Ogino et al. (2007) found transportation to the feed facility contributed 4-8% to impacts of dry feed and 45-53% to those of wet feed. Kim and Kim (2010) found that transportation impacts contributed 6% to dry feed impacts, 27% to wet feed impacts, and 14% to composting impacts. This study's impacts may be high due to the method used in estimating the distance traveled within a collection point area and over-estimating the length of roads where FW is collected (section 4.3.2.3).

The average distance for each full transportation route including collection points and a trip to a facility ranges from 107-125 km for all solution types. The average trip distance is calculated as the total distance traveled by the truck in the solution type to collect and treat all waste divided by the number of trips made to treatment facilities in a solution. Landfilling does not have a value as it was not included in any solutions.

Table 5-5: Average Distance for Each Full Route in Each Solution Type.

	ANAEROBIC DIGESTION	CO- DIGESTION + WET FEED	CO- DIGESTION + COMPOST	WET FEED	COMPOST	CO- DIGESTION + DRY FEED	DRY FEED

AVERAGE TRIP DISTANCE (KM)	125	107	113	113	121	106	119
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The route distance is anywhere from eight to thirteen times greater than the average distance from a collection point to any waste treatment facility (

Table 4-2). This implies the climate impacts of the full route including driving for both collection and transportation to the treatment facility is eight to thirteen times greater than if only the distance from collection point to treatment facility was used to estimate transportation impacts.

5.2.4 Efficient Frontier

This efficient frontier (Figure 5-11) shows the minimum level of impact at levels of investment across all sixty-four solutions. Ideal performance is low emissions and low cost, on the bottom left of the frontier. Worse performance is high emissions and high cost, on the top right of the frontier. For example, at about \$38,000 / week, in which all the waste is treated at an anaerobic digestion facility, the minimum impact is about -40,000 kg CO₂e / week. You cannot achieve lower emissions without increased costs.

The general trend of the model optimization results shows that increased investment yields better environmental performance (Figure 5-11). Similarly, better economic performance generally results in poorer environmental performance. For set of sixty-four solutions, sixty achieved net negative emissions. All solutions have net positive costs as revenues were not included in the modeled costs.

Figure 5-11: Efficient Frontier for Robust Optimization Model When Environmental Impact Is Minimized.

At the lower-cost portion of the frontier (\$8,300 / week), the results show that net negative emissions are possible (-8,000 kg CO₂e / week) (Figure 5-11). In this solution, composting stood alone as the best options (Figure 4). At the higher-cost portion of the frontier (\$40,000 / week),

anaerobic digestion is selected with -40,500 kg CO₂e / week. This is about five times the magnitude of the environmental performance of the lowest-cost solution with about four and a half times the cost.

The efficient frontier (Figure 5-11) excludes some solutions. These are considered dominated solutions where there is at least one solution that performs better for the objective function at a lower cost. In the range of \$28,000-\$31,000 / week, four dominated solutions have a net positive environmental impact. In these scenarios, the environmental parameter of the best option is positive. Two of the four solutions used wet feed at its worst-case value resulting in about \$28,000 / week and 13,000 kg CO₂e / week. These are dominated by the solutions using composting and those using a combination of co-digestion + composting. The remaining two solutions used dry feed at its best-case value, resulting in about \$29,000 / week and 9,000 kg CO₂e / week. These are dominated by the solutions using a combination of co-digestion + wet feed. The solutions co-digestion + wet feed and co-digestion + dry feed have a net negative environmental impact but are still dominated by other solutions.

If anaerobic digestion is removed from the efficient frontier, then the difference between the best and the next best solution is not as large (Figure 5-11). The solution with minimum impact of -11,100 kg CO₂e / week uses a combination of co-digestion + wet feed and costs \$30,000. In that solution, most waste is treated by co-digestion and if given sufficient capacity it would be the sole treatment method for the minimum impact solution (see section 5.3.2).

Figure 5-12: Efficient Frontier for Optimization Model When Environmental Impact Is Minimized and Anaerobic Digestion Is Excluded.

The next best solution with impacts around -10,700 kg CO₂e / week uses a combination of co-digestion + composting and costs around \$15,700 / week (Figure 5-12). The small difference in weekly impact between these two solutions costs about 45% less. Another group of four solutions close in impact around -8,000 kg CO₂e / week use composting only and cost around \$6,500 / week. For a difference in 1,800 kg CO₂e / week, the composting costs 47% less than the next best solution of co-digestion + wet feed.

5.3 Additional Runs

In this section, interesting cases and questions with regards to each treatment option are explored further.

5.3.1 Anaerobic Digestion: When Does it Exit the Solution?

Anaerobic digestion's environmental performance is attributed to a portfolio of benefits, but there is some uncertainty regarding the end use of digestate. Digestate used as a soil amendment may not actually replace fertilizer due to constraints like plant nutrient needs or method of application. FW from homes is variable in composition and may not consistently have enough nutrients to replace conventional fertilizer and may require conversion by soil microbes to a plant-available form (Baldwin, 2006). Further, the estimate for soil carbon storage is based on a period of 100 years (Levis & Barlaz, 2011) or literature does not discuss any assumptions about time (Edwards et al., 2017; Yoshida et al., 2012).

Thus, it is imperative to explore when anaerobic digestion's best-case value exits the solution and what level of offsets are needed for anaerobic digestion to remain the best option. A scenario is selected in which all treatment options have their best-case environmental parameter value (Table 4-18). The anaerobic digestion value is modified in each alternative scenario (Table 5-6) and the model is solved for the objective minimize impact. Anaerobic digestion exits the solution when a significant amount of food waste is no longer allocated to it.

Table 5-6: Environmental Parameter for Alternative Scenarios for Anaerobic Digestion While All Other Treatment Options Assume Their Best-Case Environmental Parameter Value

Scenario	Environmental Parameter (kg CO ₂ e / mt FW)
Original	-247

Alternative 1	-87
Alternative 2	-100
Alternative 3	-119

No FW is allocated to anaerobic digestion in Alternative 1 when its environmental parameter is -87 kg CO₂e / mt FW. Instead, co-digestion receives a majority of the food waste up to its capacity while the remainder is sent to composting. In Alternative 2, the environmental parameter for anaerobic digestion is further reduced to -100 kg CO₂e / mt FW and most FW (139 mt) is treated at the co-digestion facility while the rest is treated at anaerobic digestion (62 mt). An insignificant mass of FW (3 mt) is treated by composting. Because most FW is allocated to co-digestion, this facility is favored over anaerobic digestion and would likely treat all the waste given sufficient capacity. In that scenario, anaerobic digestion and composting have the same environmental parameter so the transportation emissions may have favored co-digestion's geography in Columbia. In these particular solutions, the more FW that is allocated to the anaerobic digestion facility, the greater the impacts due to transportation.

Figure 5-13: Effect of Changing Environmental Parameter of Anaerobic Digestion on Weekly Waste Allocation. A1 Corresponds to Alternative 1 From Table 5-6 And So On.

In Alternative 3, the environmental parameter is reduced even further to -119 kg CO₂e / mt FW, resulting in most food waste allocated to anaerobic co-digestion. 15 mt is still treated by co-digestion. These results suggest that anaerobic digestion exits the solution when its environmental parameter is somewhere between -87 and -100 kg CO₂e. The difference between the environmental parameter for anaerobic digestion at its worst-case value (Table 4-18) and the presumed exit point of -100 kg CO₂e / mt FW is 173 kg. To achieve an offset of this magnitude

with electricity generation alone, it would require 228 kWh produced for every mt FW anaerobically digested.

Some studies suggest that this is possible in practice with existing anaerobic digestion systems. Takata et al. (2013)'s LCA uses data from a digester in Japan using a dry thermophilic system that can produce 413 kWh for every mt of FW treated. A study of the East Bay Municipal Utility District anaerobic co-digester suggests this is also possible for a wet co-digestion system. Under certain operating parameters, like longer retention times in the digester, their co-digester can achieve about 254 kWh per mt (Moriarty, 2013). This may, however, require more input electricity to operate or larger fixed costs to handle longer processing times.

There are other benefits to anaerobic digestion beyond climate and environmental impacts. As a renewable source of fuel – at least compared to fossil fuels – biogas produced from FW does not have the same health impacts when combusted, does not risk the same environmental damages as oil pipeline spills, and could reduce dependence on foreign energy sources (Moriarty, 2013).

If anaerobic digestion treated all the municipal FW generated in Columbia in a year (section 3.1), it could provide power for up to 210 homes. This estimate uses the average electricity generation per mt FW for anaerobic digestion from Table 4-10 and yearly electricity requirements for the average home according to the U.S. Energy Information Administration (2019). For the same amount of FW, anaerobic co-digestion could provide power to 121 homes (Table 4-10) and landfilling, 107 homes (

Table 4-11). For reference, the city used about 1,250,000 MWh in 2019, 16% of which came from renewable sources in the city and purchased from outside the city (City of Columbia Power and Light, 2019). Using anaerobic digestion for municipal FW has the potential to increase the total renewable portfolio to around 17%.

5.3.2 Co-Digestion: Expand Capacity

Three of the seven solution types use a combination of options, which always includes co-digestion. To test if co-digestion would be selected alone if given sufficient capacity, some scenarios were modified to expand the co-digestion capacity to 205 mt and new solutions generated. The fixed costs are assumed to scale with capacity and are adjusted from \$4,223 to \$6,012 / week. In each of the modified scenarios, the capacity for all other treatment options remains unchanged. Three scenarios are tested. Each scenario's original solution uses one of the three types of treatment combinations: co-digestion + composting, co-digestion + dry feed, co-digestion + wet feed.

In the original solutions that use co-digestion in combinations, wet feed is part of the solution while its environmental parameter is at its best-case value and anaerobic digestion at its worst-case value. Compost enters the solution when anaerobic digestion and wet feed are both at their worst-case environmental parameter value. Dry feed entered the solution when the environmental parameter for wet feed and compost were at their worst (Table 5-7).

Table 5-7: Environmental Parameter for Scenarios That Resulted in A Combination Co-Digestion and Another Option.

Original Solution Description	Environmental Parameter (kg CO ₂ e / mt FW)					
	Compost	AD	Co-D	Landfill	Dry Feed	Wet Feed
Co-D + Wet Feed	-88 (-)	73 (+)	-100 (-)	126 (-)	1 (-)	-91 (-)
Co-D + Compost	-88 (-)	73 (+)	-100 (-)	126 (-)	1 (-)	19 (+)
Co-D + Dry Feed	80 (+)	73 (+)	-100 (-)	126 (-)	1 (-)	19 (+)

In all sixteen original solutions that include co-digestion and one other option, the co-digestion facility treats waste up to its capacity while the other option in the solution receives the difference between the total waste and the co-digestion capacity, about 60 mt. For the three new solutions, the co-digestion option saw an increase in the waste it treated (Figure 5-14).

Figure 5-14: Effect of Increasing Co-Digestion Capacity on FW Allocation.

With increased capacity, the co-digestion option treats virtually 100% of the FW in all of these solutions. Insignificant amounts of waste are treated at other facilities in the cases of co-digestion + compost and of co-digestion + wet feed. This may be explained by tradeoffs between impacts of treatment and transportation when the model is minimizing environmental impacts. For example, the decision to treat a small amount of FW at a treatment facility with a higher environmental parameter may minimize emissions if the waste collection vehicle drives a shorter distance there as opposed to a treatment facility with a lower environmental parameter.

In the new solutions total costs are decreased compared to the original ones, mainly due to decreased fixed costs associated with only using one facility (Figure 5-15). Overall weekly costs decreased by about 53% when co-digestion is chosen alone instead of in combination with a feed facility. In these cases, eliminating the high fixed costs of feed facilities (Table 4-17), the fixed costs decrease by 72%. Variable costs only decreased by about 10% in both cases. Transportation costs increased by less than 5% in each case.

Figure 5-15: Effect of Increasing Co-Digestion Capacity on Total Costs.

When co-digestion is chosen alone instead of in combination with composting, the reduction in total cost is less than in the cases with feed facilities (Figure 5-15). Overall costs decreased by 11%, due to a 33% decrease in fixed costs but a 24% increase in variable costs.

Increasing the capacity for co-digestion also decreases overall climate impacts in these scenarios (Figure 5-16). When comparing co-digestion treating FW alone to solutions using it in combination with wet feed or composting, the difference is small at less than 1,000 kg CO₂e / week. A more dramatic decrease of 6,100 kg CO₂e / week emerges by using co-digestion alone rather than in combination with dry feed.

Figure 5-16: Effect of Increasing Co-Digestion Capacity on Environmental Impacts.

Expanding the capacity of co-digestion in the model reduced costs and impacts compared to a combination of facilities. By using co-digestion alone rather than in combination with wet feed, costs were reduced dramatically but impact remained relatively unchanged. In the case of composting, costs and impact were only reduced slightly. In the case of dry feed, the cost and impacts were reduced dramatically. This is true if co-digestion is at its best-case environmental parameter value, but may increase overall emissions at its worst-case value. These results suggest the scenarios in which co-digestion is in combination with other options may actually be masking instances where co-digestion is favored and should treat all waste at its best case environmental performance given sufficient capacity.

5.3.3 Landfill: When Does it Enter the Solution?

Landfilling is not a part of any of the sixty-four solutions when optimizing for environmental performance due to its positive environmental impact even in the best case (Table 4-18). This best-case value is only smaller than the worst-case value for dry feed. Alternative scenarios are tested with decreasing values for the landfill environmental parameter to understand when landfilling becomes a part of the solution. By using the worst-case values for all other options, an upper bound on the best-case value for landfill to be part of the solution is estimated.

Table 5-8: Environmental Parameter for Alternative Scenarios for Landfilling.

Scenario	Compost	AD	Co-D	Landfill	Dry Feed	Wet Feed
Original	80 (+)	73 (+)	63 (+)	125 (-)	201 (+)	19 (+)
Alternative 1	80 (+)	73 (+)	63 (+)	94 (-)	201 (+)	19 (+)
Alternative 2	80 (+)	73 (+)	63 (+)	31 (-)	201 (+)	19 (+)
Alternative 3	80 (+)	73 (+)	63 (+)	13 (-)	201 (+)	19 (+)
Alternative 4	80 (+)	73 (+)	63 (+)	6 (-)	201 (+)	19 (+)
Alternative 5	80 (+)	73 (+)	63 (+)	3 (-)	201 (+)	19 (+)

The solutions to the alternative scenarios suggest that landfilling enters the solution once its environmental parameter value is somewhere between 31 and 13kg CO₂e / mt FW (Figure 5-17). This is similar to the worst-case value for wet feed. The worst-case environmental impact parameter for wet feed ranks best out of the worst-case values for all model treatment options.

Figure 5-17: Effects of Decreasing Landfilling Environmental Parameter on Weekly Waste Allocation. A1 Corresponds to Alternative 1 From Table 5-8 And So On.

LCAs of bioreactor landfills have varying results for GWP, some supporting the conclusion that bioreactor landfills can achieve this level of environmental impact and some that do not. For example, Broun and Sattler (2016) estimates bioreactor landfills with energy recovery to emit 803 kg CO₂e / mt waste treated while Levis and Barlaz (2011) estimates it to be -10 kg CO₂e / mt

organic waste. Landfill emissions are primarily made of CH₄, and these two studies model CH₄ emissions using a first-order decay model with different assumptions. Broun and Sattler (2016) assumed the waste is composed of generic mixed MSW with a generic bioreactor decay constant ($k = 0.12$), while Levis and Barlaz (2011) assumed a separate decay constant for food waste ($k = 0.432$) and branches ($k = 0.045$), which are considered part of the functional unit while landfilling is compared with other FW disposal options like composting. Further, Broun gives the bioreactor landfill model no credit for carbon storage while Levis gives carbon storage about -200 kg CO_{2e} per mt FW landfilled. These studies also differ for other assumptions that impact their final results, like landfill lifetime, CH₄ emissions over landfill lifetime, and CH₄ collection efficiency over landfill lifetime, all which affect the magnitude of the electricity offsets as well.

Levis and Barlaz (2011) developed a unit process model for landfill life cycle emissions that is used in S-WOLF. It would be interesting to work with Columbia's landfill managers to explore the necessary operating parameters for the landfill needed to achieve something in the range of 13-31 kg CO_{2e} / mt FW. When compared with current operating parameters, the landfill managers may be able to assess the feasibility of achieving that state.

In this model, landfilling sees benefits in the form of carbon storage and electricity generation. Without these benefits, the landfill environmental parameter is 334 kg CO_{2e} / mt FW. For landfilling to be part of the solution, benefits would need to offset 334 kg CO_{2e} / mt FW. If landfill-generated electricity is used to achieve these offsets alone, it would require 439 kWh for every mt of FW treated. This may not be currently feasible or at least requires significant changes when compared to current electricity generation figures at the landfill. Over 2014-2018, the Columbia landfill produced an average of 76-121 kWh / mt waste (City of Columbia Power and Light, 2019).

5.3.4 Composting: Which Offsets are Most Important?

Composting is touted as a simple solution for reducing the climate impacts of FW. Project Drawdown, an interdisciplinary approach to modeling the potential global GHG reduction of various solutions across many sectors, describes compost as flexible and scalable (Project Drawdown, 2021a). Project Drawdown estimates that increased adoption of composting can

reduce CH₄ production from organic waste by 50% compared to landfills and open dumps before any credit is given to carbon storage and to avoided use of synthetic fertilizers. This is based on a growth from 13% of organic waste composted increasing to 38% in low- and middle-income countries and 57% in high-income countries (Project Drawdown, 2021a). In this model, composting without any fertilizer or carbon storage benefits emits 80 kg CO_{2e} / mt FW treated, which is 68% lower than landfilling with credit electricity offsets but no carbon storage benefits at 253 kg CO_{2e} / mt FW (Table 4-15). This supports Drawdown's conclusion that composting is better than landfilling even without credits from its use on soil. How does the inclusion of credits affect its ranking over other options?

There are four solutions from the original sixty-four in which compost is selected on its own to treat FW while receiving offsets for fertilizer displacement and carbon storage. In these scenarios, compost is at its best-case environmental parameter value while anaerobic digestion, co-digestion, and wet feed were at their worst-case environmental parameter value (

Table 5-9). Landfill and dry feed were at either their best- or worst-case environmental parameter value.

Table 5-9: Environmental Parameters for Solutions in Which Composting Is the Only Treatment Option.

Scenario	Compost	AD	Co-D	Landfill	Dry Feed	Wet Feed
Original 1	-88 (-)	73 (+)	63 (+)	126 (-)	201 (+)	19 (+)
Original 2	-88 (-)	73 (+)	63 (+)	126 (-)	1 (-)	19 (+)
Original 3	-88 (-)	73 (+)	63 (+)	334 (+)	1 (-)	19 (+)
Original 4	-88 (-)	73 (+)	63 (+)	334 (+)	201 (+)	19 (+)

When compost is used, it may not completely displace fertilizer or may simply be used in addition to fertilizer to enhance soil organic matter. If the environmental parameter for composting does not include the credit for displacing fertilizer production, soil carbon storage would be the sole offset. The estimate for the environmental parameter with only carbon storage as an offset is -63 kg (Table 4-15). When replacing the environmental parameter in the original solutions from above where composting is selected as the only treatment option, compost is still the only treatment option included in the solutions (Figure 5-18).

Figure 5-18: FW Allocation in Solutions When Composting Environmental Parameter Does Not Receive Credit for Fertilizer Displacement.

If the credit for carbon storage is not included, the environmental parameter with only the credit from fertilizer is 55 kg CO₂e / mt FW. In these solutions, composting does not treat any of the waste; instead, it is treated by dry feed and wet feed (Figure 5-19).

Figure 5-19: FW Allocation in Solutions When Composting Environmental Parameter Does Not Receive Credit for Carbon Storage.

These results suggest that in order to perform better than dry feed at its best value and wet feed at its worst, composting needs credit for carbon storage. In other words, compost must be applied as a soil amendment and form soil carbon. Otherwise, it only outperforms landfilling. It is expected that this would be true with and without the fertilizer credit, because the worst-case value of composting is significantly better than the best-case value of landfilling (Table 4-18).

In the solutions without a fertilizer credit, the total environmental impacts increase, but are still negative and thus environmentally beneficial (Figure 5-20). From the original solutions that average -7,797 kg CO₂e, the total impacts increase across the new solutions by an average of 62% to -2,935 when the fertilizer credit is not included. Costs were not significantly impacted.

Figure 5-20: Average Total Environmental Impacts for Solutions when Composting Environmental Parameter Is at Its Best Compared to Alternative Solutions with Credits for Fertilizer and Carbon Storage Removed.

In the solutions without a carbon storage credit, the total environmental impacts increase significantly because composting is no longer the preferred option and the next best options have environmental parameters that are positive (

Table 5-9). These results emphasize the importance of carbon storage as a credit to composting for net negative GHG emissions. This is consistent with a study on organic waste management in Columbia by a consulting company in 2019 (Weis, Martin, Mitchell, & Craggs, 2019). Using the EPA Warm model and collection vehicle fuel consumption data from the city, they found that impacts from transportation outweighed the benefits of composting if carbon storage benefits are not fully realized (i.e., not all compost used as soil amendment).

5.3.5 Wet Feed: Transportation Thresholds

A concern with wet feed processing is transporting the high-moisture feed byproduct to an end-use facility (Westendorf & Myer, 2004). To avoid this, a wet feed facility can be located at a site where it is used, like a swine farm (Kim & Kim, 2010; Westendorf & Myer, 2004). But how far can a FW be transported before it is no longer beneficial? In one model scenario, the distance to the wet feed facility is increased by 40 km, 80 km, and 160 km outside of Columbia to determine a threshold distance for transporting FW to make wet feed no longer yields net negative environmental impact. In this scenario, the environmental parameter for wet feed is at its best while the remaining facilities are at their worst (Table 5-10).

Table 5-10: Environmental Parameter Values for Solution in Which Wet feed Is the Only Treatment Option for Use in Alternative Scenarios for Estimating a Maximum Distance for a Feed Facility.

Scenario	Compost	AD	Co-D	Landfill	Dry Feed	Wet Feed
Original	80 (+)	73 (+)	63 (+)	334 (+)	201 (+)	-91(-)

When the FW is transported 40 km to the wet feed facility, the solution has negative climate impacts, meaning the benefits of offsetting feed production outweigh impacts of transportation (Figure 5-21). When the FW is transported 80 km or more to a feed facility, however, the solution has net positive environmental impacts (3,390 kg CO₂e / week). This indicates that the wet feed facility no longer has an environmental benefit when FW is transported somewhere between 40 and 80 km to the facility.

Figure 5-21: Effects of Increased Distance to Wet Feed Facility on Weekly Treatment and Transportation Impacts.

When the distance is increased to the wet feed facility, the average route distance determined by the model increases by just under two times the distance added compared to the original model (Table 5-11). The average route distance is defined as the total distance traveled by the truck in the solution across all trips divided by the number of trips. For example, when the wet feed facility is located 40 km farther, the average trip distance increases by 73 km.

Table 5-11: Number of Trips and Distance for the Collection Route in the Original Scenario and the Alternative Scenarios in which Distance to the Wet Feed Facility is Increased.

Scenario	Trips to Facility	Average Route Distance (km)	Change from Original
Original	24	116	-
+40 km	26	189	+73
+80 km	26	264	+148
+160 km	30	315	+199

Transporting FW farther costs significantly more. Compared to the original scenario, increasing the distance by 40 km increases the transportation costs by 76%, increasing by 80 km increases transportation costs by 146%, and increasing by 160 km increases costs by 246% (Table 5-12).

Table 5-12: Change in Transportation Costs After Increasing Distance to Wet Feed Facility.

Scenario	Transportation Costs	Change from Original
Original	\$ 1,505	-
+40 km	\$ 2,649	76%
+80km	\$ 3,710	146%
+160 km	\$ 5,111	240%

Are there farms located this close to Columbia? Missouri as a state ranks sixth in pork production in the U.S. (Missouri Department of Agriculture, 2021), and hog farmers in Columbia's

home county of Boone County produced more than 88,000 pigs in 2017 (U.S. Department of Agriculture, 2017). Most of these appear to be located outside of Mid-Missouri, as there are only five swine farms within 40 km of the assumed location of the feed facility in the model, and three additional farms if that radius is expanded to 80 km (National Swine Registry, 2018). Therefore, there exist potential farms to where Columbia's FW could be transported for feed processing and yield a net environmental benefit.

In another set of alternative scenarios, the distance to transport FW from a collection point is increased to determine when the wet feed facility no longer ranks better than composting. In this scenario, AD and co-digestion must be at their worst-case environmental impact parameter; if these facilities are at their low end, wet feed would never be part of the solution (Table 5-13).

Table 5-13: Environmental Parameter Values for Solution in Which Wet Feed Is the Only Treatment Option for Use in Alternative Scenarios for Determining When Wet Feed Exits Solution.

Scenario	Compost	AD	Co-D	Landfill	Dry Feed	Wet Feed
Original	-88 (-)	73 (+)	63 (+)	126(-)	1 (-)	-91(-)

In the alternative scenarios, the distance to the wet feed facility is increased by 8, 16, and 40 km and the model is solved to minimize impact. The wet feed facility no longer receives any waste at +40 km (Figure 5-22). In the +16 km scenario, however, the wet feed facility receives only about 20% of the waste while composting receives the majority. This indicates that wet feed is no longer a favorable option somewhere between +8 and +16 km, given that compost is at its best environmental performance.

Figure 5-22: Effects of Increased Distance to Wet Feed Facility on Waste Allocation

According to the National Swine Registry Breeder Directory, there are no hog farms within 16 km of Columbia (National Swine Registry, 2018). Therefore, if composting is at its lowest environmental parameter (i.e., compost is used and displaces fertilizer and carbon is stored), it would be the preferable option to wet feed.

The optimization model does not model the transportation of a finished byproduct to an end-user; however, assuming that FW contains ~70% moisture (Bisinella et al., 2017) and that wet feed contains about 70-88% moisture (Kim & Kim, 2010; Ogino et al., 2007; Takata et al., 2012), it is assumed the transportation impacts above for moving FW to a feed facility would be similar to transporting feed the same distance. Since the low environmental impact estimate for dry feed is positive (Table 4-18), there is no threshold at which transporting dry feed would yield a net negative environmental impact.

6. Conclusion and Future Work

6.1 Conclusions

In this study, an optimization model using life cycle estimates for environmental impacts is developed to determine the optimal FW treatment solutions in Columbia, MO, for minimum costs and minimum environmental impacts. This model captures collection, transportation, and treatment activities for existing and potential FW treatment options. As demonstrated in a literature review, there is considerable variability in life cycle estimates for FW treatment options rooted in both technological features and modeling decisions. Therefore, a robust optimization model is developed to understand the impacts of the variability on whether some FW treatment solutions rank better than others.

Results of average case and robust case results both show that landfilling is the most cost-effective FW treatment solution and that the best option for reducing environmental impacts of FW management is anaerobic digestion, by a large margin. They also both show that composting and co-digestion + composting are solutions that are much more environmentally efficient than landfilling without increasing FW management costs to the same degree as some FW treatment options that could reduce GHG emissions to a much greater degree. While the efficient frontiers for both cases show some similarities, the average case results suggest that anaerobic digestion is the only treatment method capable of yielding net negative GHG emissions.

Robust optimization results show potential for negative greenhouse gas emissions for each FW treatment option except for landfilling. The results and additional model runs give more insight into what affects the environmental performance ranking of certain FW treatment options over others under variable conditions. Importantly, this work adds to the field more discussion on optimization of environmental impacts. It also highlights key issues with respect to animal feed from FW when compared to other options.

While anaerobic digestion is still considered the best option, its ranking depends more on the electricity generation from CH₄ than from use as a soil amendment. This is also presumed to be true for co-digestion. Co-digestion at the wastewater treatment plant was a more cost-effective

method than anaerobic digestion alone but did have the same level of GHG reduction due to its reduced electricity generation capacity. For composting, the benefits of carbon storage are key for its dominance over wet feed and dry feed while the inclusion of fertilizer displacement impacts are less consequential. This means that using compost on soils is critical for its environmental benefits. While both wet and dry feed are favorable options given their displacement of conventional animal feed, dry feed requires high energy inputs for dehydration that maximize transportation efficiency, pig uptake, and shelf stability. Wet feed is the only treatment option that is part of a solution at its highest environmental impact, making it a potentially viable option given transportation of FW to a facility or feed to an end-user is minimal. These conclusions are consistent with conclusions from literature on LCAs of FW management while synthesizing results further to address particular uncertainties in the final rankings.

Results also highlight the importance of assumptions regarding energy and offsets in the modeling of FW treatment options. Again, this is consistent with problems highlighted in literature. Offsetting electricity production affects rankings of options significantly in regions like Missouri with highly fossilized energy sources. This work shows that if offsets are not able to be realized due to some unexpected disturbance, decision makers should consider options with lower energy inputs and no fugitive emissions, like wet animal feed production. The study demonstrates that the role of transportation is important for some options (e.g., wet feed), but follows the LCA convention that collection activities will likely yield the same impacts for any waste treatment options.

This work also highlights specific ways in which using alternatives to landfilling align with the Columbia Climate Action and Adaptation Plan. First, any landfilling alternatives would be considered waste diversion that would prevent fugitive CH₄ emissions to the atmosphere. Second, FW treatment options that generate electricity can support the goal to increase the use of renewable energy in the city's energy portfolio. Lastly, all of these alternatives have the potential to reduce the portion of the city's GHG emissions that come from solid waste. More work needs to be done to harmonize the methods between the city's inventory and methods used in this study, but reductions in any of these solutions could be seen as a small dent in the city's total

GHG emissions or great progress in the municipal emissions. However, it should be noted that this study focuses on the FW fraction of MSW, which only constitutes about 1/3 of the total landfilled waste at Columbia's sanitary landfill.

6.2 Future Work

Because environmental impacts are not only limited to GHG emissions, work in the waste management optimization space should expand to other environmental impacts. Though the issue of climate change is of great importance, life cycle practitioners should use optimization methods to explore the significance of environmental tradeoffs in their studies. It is critical to understand how mobilizing massive resources and efforts to solve one environmental problem – climate change – can impact other climate problems such as eutrophication or air acidification. Furthermore, robust optimization work with specific LCA models should consider variability in individual parameters rather than the full range of environmental impacts found in literature. This could capture the effects of changing key parameters alone and in combination.

This work also has a considerably narrow focus when it comes to the full MSW management system. There still remains 80% of the waste fractions in Columbia's MSW, a category of waste that is only one third of the total landfilled waste in Columbia. This work also does not consider the changes in the wider waste management system. Important issues could include how adding extra transportation routes would affect the total waste system's environmental impacts or quality of service. Studies could also investigate how landfilling costs would be reduced when FW is diverted, potentially extending the lifetime of the landfill. Furthermore, full cost accounting could consider revenues. Revenues from waste management, such as use of tipping fees or selling electricity generated from waste, are an important component of balancing waste management costs and determining which methods are feasible. The implementation of carbon markets could significantly impact costs and the feasibility of waste management options.

Finally, this work highlights how making animal feed from FW is an attractive option for reducing GHG emissions in the face of uncertainty. This idea, however, is still underexplored, especially in the context of the United States. Transportation of FW or wet feed still remains an important discussion, but work could be done in specific process design to determine an optimal

moisture content for animal feed from FW to balance the GHG emitted from energy inputs and GHGs occurring when transported in a specified geographic context.

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Appendix A: GAMS Code for Average Case Model

Sets

I set of treatment facility /i1*i7/

*i1 is compost, i2 is anaerobic digestion, i3 is landfilling, i4 is dry animal feed, i5 is wet animal feed

*J0 is the location of depot

J Set of collection points /j0*j109/

Alias (J,JJ);

Alias (I,II);

Parameters

C(I) Capacity of treatment facility i (mt per week) /i1 45, i2 325, i3 250, i4 144, i5 205, i6 214, i7 214/

O Capacity of vehicle (mt) /10/

Delta tolerance for over- or under-shooting truck capacity - equal to 5 percent of truck capacity (mt) /0.5/

T Transportation economic unit cost for collection vehicle (\$ per km) /0.54/

TE Transportation environmental unit cost for collection vehicle (kg co2e per km) /3.13/

TC(i) Cost of processing a unit of food waste at facility i (\$ per mt) /i1 9.08, i2 9.08, i3 73.22, i4 32.04, i5 14.00, i6 49.89, i7 43.89/

F(i) Fixed cost of operating facility i (\$ per week)/i1 0, i2 5993, i3 26908, i4 5256, i5 0, i6 21683, i7 21683/

Env(i) Environmental cost of treating one unit of food waste in treatment facility i (kg co2e per mt) /i1 -4, i2 -4, i3 -87, i4 -17, i5 269, i6 101, i7 -36/

*These are midpoint values for average case

\$include inputdata.txt;

Binary Variables

X(J,JJ) 1 if vehicle moves directly from collection point j to jj otherwise 0

Y(J,JJ) 1 if vehicle visits collection point j visited anytime in a tour before jj 0 otherwise

W(I) 1 if facility i is open otherwise 0

Zij(J,I) 1 if vehicle visit facility i immediately after collection point j otherwise 0

Zij(I,J) 1 if vehicle visit collection point j immediately after facility i otherwise 0

R(J,JJ) 1 if vehicle visits j before jj AND vehicle drops off waste at some facility i from point j 0 otherwise

XX(J,JJ) equals one if J immediately before JJ and J immediately before treatment facility stop;

Positive Variables

B(I) Amount of food waste treated in facility i

V(J) Load of vehicle after visiting collection point j

Vji(J,I) Load of vehicle when visiting treatment facility i from collection point j

u(J) ordered position of collection point in a tour by vehicle position number does not reset for multiple tours in a collection period

Q(J,JJ) amount of waste dropped off by vehicle from jj when j visited before jj and when vehicle visits facility i due to vehicle reaching capacity

TR number of trips made to treatment facilities;

Free variable

obj1 Objective function variable for total cost

obj2 Objective function variable for total environmental impact

TRANSCOST variable for transportation cost

TRANSIMP variable for transportation impact

TREATCOST variable for treatment cost
TREATIMP variable for treatment impact;

Equations

Objec1 Total cost in \$

Objec2 Total environmental impact

Constraint1(J) ensures that each collection point j is only visited once by any vehicle except for depot

Constraint2(J) If a vehicle arrives at a collection point it leaves that point

Constraint3(J, JJ) Subtour elimination constraint for each vehicle

*Constraint4 If vehicle arrives at a customer location it leaves that location

*Constraint5 order of points j not j0 in tour must be greater than 1

*Constraint6 order of all points j not j0 in tour must be less than the number of points in the set

*Constraint7 order of point j0 must be 0

Constraint8(J) ensures that each trip by vehicle from a cp j to facility i by vehicle occurs only once

Constraint9(j) ensures that there is a single trip if any made from treatment facility i to collection point j

*Constraint10 vehicle cannot visit a treatment facility i immediately after depot j0

Constraint11(j, jj, i) ensures that Zij is 1 at the collection point jj immediately following the collection point j where waste was transported to a facility i

Constraint12(j) must visit treatment facility immediately after last collection point visited prior to returning to depot at end of days route

Constraint13(j, jj) identify if a treatment facility is visited between J and JJ

Constraint14(j, jj) identify if a treatment facility is visited between J and JJ

Constraint15(J, JJ) defines that Y is 1 if vehicle visits cp jj after j 0 otherwise

Constraint16(J, JJ) ensures that Y cannot be 1 for vehicle visiting jj to j AND j to jj - symmetry constraint

*Constraint17 point j cannot be before point j

Constraint18(JJ, J) says that R is less than Y if visit jj before j

Constraint19(JJ, J) says that R is less than Z if waste was dropped off at a facility from that point jj

Constraint20(JJ, J) says that R is 1 if jj comes before j AND waste dropped off at facility from that point jj

Constraint21(JJ, J) says that at points where R is 1 Q is greater than the vehicle load minus capacity plus tolerance

Constraint22(JJ, J) says that at points where R is 1 Q is less than the vehicle load plus capacity plus tolerance

Constraint23(JJ, J) says that at points where R is 1 Q is less than capacity plus tolerance

Constraint24(JJ) Load of collection vehicle as it visits waste collection points

Constraint25(J, I) waste taken by vehicle from cp to treatment facility is truck load and some tolerance when zji is 1

Constraint26(j, i) determine amount deposited at treatment facility immediately after J

Constraint27(j, i) determine amount deposited at treatment facility immediately after J

Constraint28(I) Food waste treated at a facility as a function of the truck load and trips from j to i

Constraint29(I) Treatment facility capacity constraint

Constraint30 total number of trips equal to sum over all trips from collection point to treatment facility

calc1 calculate cost of transportation

calc2 calculate cost of treatment

calc3 calculate impact of transportation

calc4 calculate impact of treatment;

*objective functions

objec1.. sum((J, JJ), T*((Dist(J, JJ)+Dr(JJ))*X(J, JJ)-

dist(j, jj)*xx(j, jj))+sum((J, I), T*Dis(J, I)*Zji(J, I))+sum((I, J), T*D(I, J)*Zij(I, J))+sum(I, B(I)*TC(I))+sum(I, F(I)*W(I)) =e= obj1;

objec2.. sum((J,JJ),TE*((Dist(J,JJ)+Dr(JJ))*X(J,JJ)-
dist(j,jj)*xx(j,jj)))+sum((J,I),TE*Dis(J,I)*Zji(J,I))+sum((I,J),TE*D(I,J)*Zij(I,J))+sum(I,B(I)*Env(I)) =e=
obj2;

*calculating individually the costs and impacts we wish to analyze

calc1.. TRASCOST =e= sum((J,JJ),T*((Dist(J,JJ)+Dr(JJ))*X(J,JJ)-
dist(j,jj)*xx(j,jj)))+sum((J,I),T*Dis(J,I)*Zji(J,I))+sum((I,J),T*D(I,J)*Zij(I,J));
calc2.. TREATCOST =e= sum(I,B(I)*TC(I))+sum(I,F(I)*W(I));
calc3.. TRANSIMP =e= sum((J,JJ),TE*((Dist(J,JJ)+Dr(JJ))*X(J,JJ)-
dist(j,jj)*xx(j,jj)))+sum((J,I),TE*Dis(J,I)*Zji(J,I))+sum((I,J),TE*D(I,J)*Zij(I,J));
calc4.. TREATIMP =e= sum(I,B(I)*Env(I));

*Traveling Salesman Problem

Constraint1 (J).. sum(JJ,X(jj,j))=e=1;
Constraint2(J).. sum(JJ,X(J,JJ))=e=1;
Constraint3(J,JJ)\$((ORD(J)<>1)AND(ORD(JJ)<>1)AND(ORD(J)<>ORD(JJ))).. u(J)-
u(JJ)+(card(J)-1)*X(J,JJ)+(card(J)-3)*X(JJ,J) =l= (card(J)-2);
*Constraint4
X.FX(j,jj)\$ (ORD(j)=ORD(jj))=0;
*Constraint5
U.LO(J)\$ (ORD(J)<>1)=1;
*Constraint6
U.UP(J)\$ (ORD(J)<>1)=CARD(J)-1;
*Constraint7
U.FX(J)\$ (ORD(J)=1)=0;

*visit at most one treatment facility immediately before and immediately after J

Constraint8(J).. sum(I,Zji(J,I))=l=1;
Constraint9(j).. sum(i,Zij(i,j))=l=1;
*Constraint10
Zji.fx('j0',I)=0;

*link visit into treatment facility I with visit exiting from treatment facility I

Constraint11(j,jj,i).. Zij(i,jj) =G= X(j,jj)+Zji(j,i)-1;

*must visit treatment facility immediately after last collection point visited prior to returning to depot at end of route

Constraint12(j).. SUM(I,Zji(J,I)) =G= U(J)-(CARD(J)-2);

*identify if a treatment facility is visited between J and JJ

Constraint13(j,jj).. xx(j,jj) =L= 0.5*(X(J,JJ)+SUM(I,Zji(J,I)));
Constraint14(j,jj).. xx(j,jj) =G= X(J,JJ)+SUM(I,Zji(J,I))-1;

*determine if visited J before JJ

Constraint15(J,JJ)\$ (ord(J)<>ord(JJ)).. u(JJ)-u(J) =l= (card(J)+1)*Y(J,JJ);
Constraint16(J,JJ)\$ (ord(J)<>ord(JJ)).. Y(J,JJ) =e= 1-Y(JJ,J);
*Constraint17
Y.fx(j,jj)\$ (ord(j)=ord(jj))=0;

*determine if visited J before JJ and also visit treatment facility immediately after J

Constraint18(JJ,J).. R(JJ,J) =L= Y(JJ,J);
Constraint19(JJ,J).. R(JJ,J) =L= sum(I,Zji(JJ,I));
Constraint20(JJ,J).. R(JJ,J) =G= Y(JJ,J) + SUM(I,Zji(JJ,I))-1;

*determine load of vehicle if J visited before JJ and also visit treatment facility immediately after J

Constraint21(JJ,J).. Q(JJ,J) =G= V(JJ)-(O+DELTA)*(1-R(JJ,J));

```

Constraint22(JJ,J).. Q(JJ,J) =L= V(JJ);
Constraint23(JJ,J).. Q(JJ,J) =L= R(JJ,J)*(O+DELTA);

*determine load of vehicle immediately after visiting J
Constraint24(J).. V(J) =e= sum(JJ,A(JJ)*Y(JJ,J))+A(J)-sum(JJ,Q(JJ,J));

*determine amount deposited at treatment facility immediately after J
Constraint25(J,I).. Vji(J,I) =G= V(J)-(1-Zji(J,I))*(O+DELTA);
Constraint26(J,I).. Vji(J,I) =L= V(J);
Constraint27(J,I).. Vji(J,I) =L= Zji(J,I)*(O+DELTA);

*determine total amount treated at facility I
Constraint28(I).. B(I) =e= sum((J),Vji(J,I));
Constraint29(I).. B(I) =l= C(i)*W(i);

*sum of visits to treatment facilities is total trips
Constraint30.. TR =E=sum((j,i),zji(j,i));

free variable obj3 this;
equation objec3 that;
objec3.. obj3=E=sum(i,c(i));

model model_step1 /objec1,constraint1,constraint2,constraint3/;
model model_step2 /all/;
option mip=cplex;
OPTION OPTCR=0.01;
option reslim = 43200;

model_step1.optfile=1;
model_step2.optfile=1;
$Onecho > cplex.opt
mipemphasis=3
MIPstart=2
$Offecho

model_step1.prioropt = 1;
model_step2.prioropt = 1;
W.prior(I) = 1;
X.prior(J,JJ) = 2;
Zji.prior(J,I) = 3;
Zij.prior(I,J) = 3;

Solve model_step1 using mip minimizing obj1;

parameter X_STEP1(J,JJ) temp values;
X_STEP1(J,JJ)=X.L(J,JJ);
X.FX(J,JJ)=X_STEP1(J,JJ);

*creating the efficient frontier; value is median impact between min impact and min cost baseline
models
Solve model_step2 using mip minimizing obj3;
Solve model_step2 using mip minimizing obj1;
EXECUTE_UNLOAD 'foodwaste_output.gdx';

```

Appendix B: GAMS Code for Robust Model

Sets

I set of treatment facility /i1*i7/

*i1 is compost, i2 is anaerobic digestion, i3 is landfilling, i4 is dry animal feed, i5 is wet animal feed

*J0 is the location of depot

J Set of collection points /j0*j109/

Alias (J,JJ);

Alias (I,II);

Parameters

C(I) Capacity of treatment facility i (mt per week) /i1 45, i2 325, i3 250, i4 144, i5 200, i6 214, i7 214/

O Capacity of vehicle (mt) /10/

Delta tolerance for over- or under-shooting truck capacity - equal to 5 percent of truck capacity (mt) /0.5/

T Transportation economic unit cost for collection vehicle (\$ per km) /0.54/

TE Transportation environmental unit cost for collection vehicle (kg co2e per km) /3.13/

TC(i) Cost of processing a unit of food waste at facility i (\$ per mt) /i1 9.08, i2 9.08, i3 73.22, i4 32.04, i5 14.00, i6 49.89, i7 43.89/

F(i) Fixed cost of operating facility i (\$ per week)/i1 0, i2 5993, i3 26908, i4 5256, i5 0, i6 21683, i7 21683/

Env(i) Environmental cost of treating one unit of food waste in treatment facility i (kg co2e per mt) /i1 -4, i2 -4, i3 -87, i4 -17, i5 269, i6 101, i7 -36/

*These are midpoint values for average case

\$include inputdata.txt;

Binary Variables

X(J,JJ) 1 if vehicle moves directly from collection point j to jj otherwise 0

Y(J,JJ) 1 if vehicle visits collection point j visited anytime in a tour before jj 0 otherwise

W(I) 1 if facility i is open otherwise 0

Zji(J,I) 1 if vehicle visit facility i immediately after collection point j otherwise 0

Zij(I,J) 1 if vehicle visit collection point j immediately after facility i otherwise 0

R(J,JJ) 1 if vehicle visits j before jj AND vehicle drops off waste at some facility i from point j 0 otherwise

XX(J,JJ) equals one if J immediately before JJ and J immediately before treatment facility stop;

Positive Variables

B(I) Amount of food waste treated in facility i

V(J) Load of vehicle after visiting collection point j

Vji(J,I) Load of vehicle when visiting treatment facility i from collection point j

u(J) ordered position of collection point in a tour by vehicle position number does not reset for multiple tours in a collection period

Q(J,JJ) amount of waste dropped off by vehicle from jj when j visited before jj and when vehicle visits facility i due to vehicle reaching capacity

TR number of trips made to treatment facilities;

Free variable

obj1 Objective function variable for total cost

obj2 Objective function variable for total environmental impact

TRANSCOST variable for transportation cost

TRANSIMP variable for transportation impact

TREATCOST variable for treatment cost

TREATIMP variable for treatment impact;

Equations

Objec1 Total cost in \$

Objec2 Total environmental impact

Constraint1(J) ensures that each collection point j is only visited once by any vehicle except for depot

Constraint2(J) If a vehicle arrives at a collection point it leaves that point

Constraint3(J, JJ) Subtour elimination constraint for each vehicle

*Constraint4 If vehicle arrives at a customer location it leaves that location

*Constraint5 order of points j not j0 in tour must be greater than 1

*Constraint6 order of all points j not j0 in tour must be less than the number of points in the set

*Constraint7 order of point j0 must be 0

Constraint8(J) ensures that each trip by vehicle from a cp j to facility i by vehicle occurs only once

Constraint9(j) ensures that there is a single trip if any made from treatment facility i to collection point j

*Constraint10 vehicle cannot visit a treatment facility i immediately after depot j0

Constraint11(j, jj, i) ensures that Zij is 1 at the collection point jj immediately following the collection point j where waste was transported to a facility i

Constraint12(j) must visit treatment facility immediately after last collection point visited prior to returning to depot at end of days route

Constraint13(j, jj) identify if a treatment facility is visited between J and JJ

Constraint14(j, jj) identify if a treatment facility is visited between J and JJ

Constraint15(J, JJ) defines that Y is 1 if vehicle visits cp jj after j 0 otherwise

Constraint16(J, JJ) ensures that Y cannot be 1 for vehicle visiting jj to j AND j to jj - symmetry constraint

*Constraint17 point j cannot be before point j

Constraint18(JJ, J) says that R is less than Y if visit jj before j

Constraint19(JJ, J) says that R is less than Z if waste was dropped off at a facility from that point jj

Constraint20(JJ, J) says that R is 1 if jj comes before j AND waste dropped off at facility from that point jj

Constraint21(JJ, J) says that at points where R is 1 Q is greater than the vehicle load minus capacity plus tolerance

Constraint22(JJ, J) says that at points where R is 1 Q is less than the vehicle load plus capacity plus tolerance

Constraint23(JJ, J) says that at points where R is 1 Q is less than capacity plus tolerance

Constraint24(JJ) Load of collection vehicle as it visits waste collection points

Constraint25(J, I) waste taken by vehicle from cp to treatment facility is truck load and some tolerance when zji is 1

Constraint26(j, i) determine amount deposited at treatment facility immediately after J

Constraint27(j, i) determine amount deposited at treatment facility immediately after J

Constraint28(I) Food waste treated at a facility as a function of the truck load and trips from j to i

Constraint29(I) Treatment facility capacity constraint

Constraint30 total number of trips equal to sum over all trips from collection point to treatment facility

calc1 calculate cost of transportation

calc2 calculate cost of treatment

calc3 calculate impact of transportation

calc4 calculate impact of treatment;

*objective functions

objec1.. sum((J, JJ), T*((Dist(J, JJ)+Dr(JJ))*X(J, JJ)-

dist(j, jj)*xx(j, jj))+sum((J, I), T*Dis(J, I)*Zji(J, I))+sum((I, J), T*D(I, J)*Zij(I, J))+sum(I, B(I)*TC(I))+sum(I, F(I)*W(I)) =e= obj1;

objec2.. sum((J, JJ), TE*((Dist(J, JJ)+Dr(JJ))*X(J, JJ)-
dist(j, jj)*xx(j, jj))+sum((J, I), TE*Dis(J, I)*Zji(J, I))+sum((I, J), TE*D(I, J)*Zij(I, J))+sum(I, B(I)*Env(I)) =e=
obj2;

*calculating individually the costs and impacts we wish to analyze

calc1.. TRANCOST =e= sum((J, JJ), T*((Dist(J, JJ)+Dr(JJ))*X(J, JJ)-
dist(j, jj)*xx(j, jj))+sum((J, I), T*Dis(J, I)*Zji(J, I))+sum((I, J), T*D(I, J)*Zij(I, J));
calc2.. TREATCOST =e= sum(I, B(I)*TC(I))+sum(I, F(I)*W(I));
calc3.. TRANSIMP =e= sum((J, JJ), TE*((Dist(J, JJ)+Dr(JJ))*X(J, JJ)-
dist(j, jj)*xx(j, jj))+sum((J, I), TE*Dis(J, I)*Zji(J, I))+sum((I, J), TE*D(I, J)*Zij(I, J));
calc4.. TREATIMP =e= sum(I, B(I)*Env(I));

*Traveling Salesman Problem

Constraint1 (J).. sum(JJ, X(jj, j))=e=1;
Constraint2(J).. sum(JJ, X(J, JJ))=e=1;
Constraint3(J, JJ)\$((ORD(J)<>1)AND(ORD(JJ)<>1)AND(ORD(J)<>ORD(JJ))).. u(J)-
u(JJ)+(card(J)-1)*X(J, JJ)+(card(J)-3)*X(JJ, J) =l= (card(J)-2);
*Constraint4
X.FX(j, jj)\$ (ORD(j)=ORD(jj))=0;
*Constraint5
U.LO(J)\$ (ORD(J)<>1)=1;
*Constraint6
U.UP(J)\$ (ORD(J)<>1)=CARD(J)-1;
*Constraint7
U.FX(J)\$ (ORD(J)=1)=0;

*visit at most one treatment facility immediately before and immediately after J

Constraint8(J).. sum(I, Zji(J, I))=l=1;
Constraint9(j).. sum(i, Zij(i, j))=l=1;
*Constraint10
Zji.fx('j0', I)=0;

*link visit into treatment facility I with visit exiting from treatment facility I

Constraint11(j, jj, i).. Zij(i, jj) =G= X(j, jj)+Zji(j, i)-1;

*must visit treatment facility immediately after last collection point visited prior to returning to depot at end of route

Constraint12(j).. SUM(I, Zji(J, I)) =G= U(J)-(CARD(J)-2);

*identify if a treatment facility is visited between J and JJ

Constraint13(j, jj).. xx(j, jj) =L= 0.5*(X(J, JJ)+SUM(I, Zji(J, I)));
Constraint14(j, jj).. xx(j, jj) =G= X(J, JJ)+SUM(I, Zji(J, I))-1;

*determine if visited J before JJ

Constraint15(J, JJ)\$ (ord(J)<>ord(JJ)).. u(JJ)-u(J) =l= (card(J)+1)*Y(J, JJ);
Constraint16(J, JJ)\$ (ord(J)<>ord(JJ)).. Y(J, JJ) =e= 1-Y(JJ, J);
*Constraint17
Y.fx(j, jj)\$ (ord(j)=ord(jj))=0;

*determine if visited J before JJ and also visit treatment facility immediately after J

Constraint18(JJ, J).. R(JJ, J) =L= Y(JJ, J);
Constraint19(JJ, J).. R(JJ, J) =L= sum(I, Zji(JJ, I));
Constraint20(JJ, J).. R(JJ, J) =G= Y(JJ, J) + SUM(I, Zji(JJ, I))-1;

*determine load of vehicle if J visited before JJ and also visit treatment facility immediately after J

Constraint21(JJ, J).. Q(JJ, J) =G= V(JJ)-(O+DELTA)*(1-R(JJ, J));

```

Constraint22(JJ,J).. Q(JJ,J) =L= V(JJ);
Constraint23(JJ,J).. Q(JJ,J) =L= R(JJ,J)*(O+DELTA);

*determine load of vehicle immediately after visiting J
Constraint24(J).. V(J) =e= sum(JJ,A(JJ)*Y(JJ,J))+A(J)-sum(JJ,Q(JJ,J));

*determine amount deposited at treatment facility immediately after J
Constraint25(J,I).. Vji(J,I) =G= V(J)-(1-Zji(J,I))*(O+DELTA);
Constraint26(J,I).. Vji(J,I) =L= V(J);
Constraint27(J,I).. Vji(J,I) =L= Zji(J,I)*(O+DELTA);

*determine total amount treated at facility I
Constraint28(I).. B(I) =e= sum((J),Vji(J,I));
Constraint29(I).. B(I) =l= C(i)*W(i);

*sum of visits to treatment facilities is total trips
Constraint30.. TR =E=sum((j,i),zji(j,i));

free variable obj3 this;
equation objec3 that;
objec3.. obj3=E=sum(i,c(i));

model model_step1 /objec2,constraint1,constraint2,constraint3/;
model model_step2 /all/;
option mip=cplex;
OPTION OPTCR=0.01;
option reslim = 43200;

model_step1.optfile=1;
model_step2.optfile=1;
$Onecho > cplex.opt
mipemphasis=3
MIPstart=2
$Offecho

model_step1.prioropt = 1;
model_step2.prioropt = 1;
W.prior(I) = 1;
X.prior(J,JJ) = 2;
Zji.prior(J,I) = 3;
Zij.prior(I,J) = 3;

parameter X_STEP1(J,JJ) temp values;
SET g /g1/;
*set for environmental parameter values for each of the 64 scenarios
table newval(g,i)
    i1 i2 i3 i4 i5 i6 i7
g1 -88 -88 -247 -100 181 1 -91
g2 80 80 -247 -100 181 1 -91
g3 -88 -88 73 -100 181 1 -91
g4 80 80 73 -100 181 1 -91
g5 -88 -88 -247 63 181 1 -91
g6 80 80 -247 63 181 1 -91
g7 -88 -88 73 63 181 1 -91
g8 80 80 73 63 181 1 -91
g9 -88 -88 -247 -100 338 1 -91

```


g10 80 80 -247 -100 338 1 -91
 g11 -88 -88 73 -100 338 1 -91
 g12 80 80 73 -100 338 1 -91
 g13 -88 -88 -247 63 338 1 -91
 g14 80 80 -247 63 338 1 -91
 g15 -88 -88 73 63 338 1 -91
 g16 80 80 73 63 338 1 -91
 g17 -88 -88 -247 -100 181 201 -91
 g18 80 80 -247 -100 181 201 -91
 g19 -88 -88 73 -100 181 201 -91
 g20 80 80 73 -100 181 201 -91
 g21 -88 -88 -247 63 181 201 -91
 g22 80 80 -247 63 181 201 -91
 g23 -88 -88 73 63 181 201 -91
 g24 80 80 73 63 181 201 -91
 g25 -88 -88 -247 -100 338 201 -91
 g26 80 80 -247 -100 338 201 -91
 g27 -88 -88 73 -100 338 201 -91
 g28 80 80 73 -100 338 201 -91
 g29 -88 -88 -247 63 338 201 -91
 g30 80 80 -247 63 338 201 -91
 g31 -88 -88 73 63 338 201 -91
 g32 80 80 73 63 338 201 -91
 g33 -88 -88 -247 -100 181 1 19
 g34 80 80 -247 -100 181 1 19
 g35 -88 -88 73 -100 181 1 19
 g36 80 80 73 -100 181 1 19
 g37 -88 -88 -247 63 181 1 19
 g38 80 80 -247 63 181 1 19
 g39 -88 -88 73 63 181 1 19
 g40 80 80 73 63 181 1 19
 g41 -88 -88 -247 -100 338 1 19
 g42 80 80 -247 -100 338 1 19
 g43 -88 -88 73 -100 338 1 19
 g44 80 80 73 -100 338 1 19
 g45 -88 -88 -247 63 338 1 19
 g46 80 80 -247 63 338 1 19
 g47 -88 -88 73 63 338 1 19
 g48 80 80 73 63 338 1 19
 g49 -88 -88 -247 -100 181 201 19
 g50 80 80 -247 -100 181 201 19
 g51 -88 -88 73 -100 181 201 19
 g52 80 80 73 -100 181 201 19
 g53 -88 -88 -247 63 181 201 19
 g54 80 80 -247 63 181 201 19
 g55 -88 -88 73 63 181 201 19
 g56 80 80 73 63 181 201 19
 g57 -88 -88 -247 -100 338 201 19
 g58 80 80 -247 -100 338 201 19
 g59 -88 -88 73 -100 338 201 19
 g60 80 80 73 -100 338 201 19
 g61 -88 -88 -247 63 338 201 19
 g62 80 80 -247 63 338 201 19
 g63 -88 -88 73 63 338 201 19
 g64 80 80 73 63 338 201 19;

PARAMETER

*parameters for storing the values generated in the optimization runs within each loop g
obj1_g(g) total cost for run g
obj2_g(g) total environmental impact for run g
B_g(g,i) waste treated at each facility i for run g
TRANSCOST_G(g) cost of transportation for run g
TREATCOST_G(g) cost of treatment for run g
TRANSIMP_G(g) environmental impact of transportation for run g
TREATIMP_G(g) environmental impact of treatment for run g
TR_G(g) total number of visits by truck to facility for run g
OUTPUTMODSTATUS(g) records modelstat
OUTPUTSOLVERSTATUS(g) records solver stat
SOLVETIME(g) records solver time
OUTPUTPB(G) output primal bound of run g
OUTPUTDB(G) output dual bound of run g
PATH(G,J) path taken by the truck in
W_G(g,i) facilities open in run g where 1 is open and 0 is closed but free facilities probably automatically 1;

```
LOOP(G,  
  LOOP(I,  
    env(i)=newval(g,i)  
  );  
  B.UP(I)=0;  
  Solve model_step1 using mip minimizing obj2;  
  B.UP(I)=SUM(J,A(J));  
  X_STEP1(J,JJ)=X.L(J,JJ);  
  X.FX(J,JJ)=X_STEP1(J,JJ);  
  Solve model_step2 using mip minimizing obj3;  
  Solve model_step2 using mip minimizing obj2;  
  obj1_g(g) = obj1.L;  
  obj2_g(g) = obj2.L;  
  W_G(g,i) = w.L(i);  
  B_g(g,i) = B.L(i);  
  TRANSCOST_G(g) = TRANSCOST.L;  
  TREATCOST_G(g) = TREATCOST.L;  
  TRANSIMP_G(g) = TRANSIMP.L;  
  TREATIMP_G(g) = TREATIMP.L;  
  TR_G(g) = TR.L;  
  OUTPUTSOLVERSTATUS(g) = model_step2.solvestat;  
  OUTPUTMODSTATUS(g) = model_step2.modelstat;  
  SOLVETIME(g) = model_step2.RESUSD;  
  OUTPUTPB(G)=model_step2.objVal;  
  OUTPUTDB(G)=model_step2.objEst;  
  PATH(G,J) = U.L(j);  
);
```

DISPLAY

```
obj1_g,obj2_g,B_g,PATH,TRANSCOST_G,TREATCOST_G,TRANSIMP_G,TREATIMP_G,TR_G  
,OUTPUTSOLVERSTATUS,OUTPUTMODSTATUS,SOLVETIME,OUTPUTPB,OUTPUTDB;  
execute_unload 'filename',  
obj1_g,obj2_g,B_g,PATH,TRANSCOST_G,TREATCOST_G,TRANSIMP_G,TREATIMP_G,TR_G  
,OUTPUTSOLVERSTATUS,OUTPUTMODSTATUS,SOLVETIME,OUTPUTPB,OUTPUTDB;
```

Appendix C: Model Input Data

table D(i,j) distance from treatment facilities back to j0 (km)

	J0	J1	J2	J3	J4	J5	J6	J7	J8	J9
J10	J11	J12	J13	J14	J15	J16	J17	J18	J19	
J20	J21	J22	J23	J24	J25	J26	J27	J28	J29	
J30	J31	J32	J33	J34	J35	J36	J37	J38	J39	
J40	J41	J42	J43	J44	J45	J46	J47	J48	J49	
J50	J51	J52	J53	J54	J55	J56	J57	J58	J60	
J61	J62	J63	J64	J65	J66	J67	J68	J69	J71	
J72	J73	J74	J75	J76	J77	J78	J79	J80	J82	
J83	J84	J85	J86	J87	J88	J89	J90	J91	J93	
J94	J95	J96	J97	J98	J99	J100	J101	J102	J104	
J105	J106	J107	J108	J109						
I1	0	6.817	4.53	4.126	7.775	7.813	7.852	10.838	11.174	
10.323	6.588	7.778	9.12	10.632	10.192	8.288	10.536	11.643		
13.838	14.81	18.777	12.648	11.553	11.277	8.731	9.873			
18.236	12.147	11.124	9.832	12.022	10.929	11.789	12.795			
15.579	16.137	15.884	16.8	18.175	19.433	21.083	15.414			
14.046	12.606	10.138	10.285	10.936	12.202	11.727	12.749			
13.528	14.262	13.703	11.904	12.325	13.426	13.681	14.631	19.288	17.66	
19.803	21.272	22.683	21.742	23.031	22.322	16.772	12.32	14.235	15.536	
12.245	15.841	16.705	13.373	16.709	17.5	19.444	22.557	21.447	23.906	
14.904	13.791	15.469	20.729	23.947	24.827	15.946	16.417	19.669	20.604	
21.203	22.232	24.094	16.44	17.662	19.601	21.126	24.362	24.223	17.273	
20.592	22.862	27.235	19.34	20.413	22.072	23.498	25.794	25.799	26.598	
I2	0	6.817	4.53	4.126	7.775	7.813	7.852	10.838	11.174	
10.323	6.588	7.778	9.12	10.632	10.192	8.288	10.536	11.643		
13.838	14.81	18.777	12.648	11.553	11.277	8.731	9.873			
18.236	12.147	11.124	9.832	12.022	10.929	11.789	12.795			
15.579	16.137	15.884	16.8	18.175	19.433	21.083	15.414			
14.046	12.606	10.138	10.285	10.936	12.202	11.727	12.749			
13.528	14.262	13.703	11.904	12.325	13.426	13.681	14.631	19.288	17.66	
19.803	21.272	22.683	21.742	23.031	22.322	16.772	12.32	14.235	15.536	
12.245	15.841	16.705	13.373	16.709	17.5	19.444	22.557	21.447	23.906	
14.904	13.791	15.469	20.729	23.947	24.827	15.946	16.417	19.669	20.604	
21.203	22.232	24.094	16.44	17.662	19.601	21.126	24.362	24.223	17.273	
20.592	22.862	27.235	19.34	20.413	22.072	23.498	25.794	25.799	26.598	
I3	0	6.817	4.53	4.126	7.775	7.813	7.852	10.838	11.174	
10.323	6.588	7.778	9.12	10.632	10.192	8.288	10.536	11.643		
13.838	14.81	18.777	12.648	11.553	11.277	8.731	9.873			
18.236	12.147	11.124	9.832	12.022	10.929	11.789	12.795			
15.579	16.137	15.884	16.8	18.175	19.433	21.083	15.414			
14.046	12.606	10.138	10.285	10.936	12.202	11.727	12.749			
13.528	14.262	13.703	11.904	12.325	13.426	13.681	14.631	19.288	17.66	
19.803	21.272	22.683	21.742	23.031	22.322	16.772	12.32	14.235	15.536	
12.245	15.841	16.705	13.373	16.709	17.5	19.444	22.557	21.447	23.906	
14.904	13.791	15.469	20.729	23.947	24.827	15.946	16.417	19.669	20.604	
21.203	22.232	24.094	16.44	17.662	19.601	21.126	24.362	24.223	17.273	
20.592	22.862	27.235	19.34	20.413	22.072	23.498	25.794	25.799	26.598	
I4	23.003	17.916	19.179	20.435	17.315	17.115	16.56	15.312		
23.271	20.181	16.98	15.901	14.83	13.689	20.85	15.998	14.874		
12.921	10.76	10.073	9.419	21.402	18.948	18.479	16.923			
13.141	9.658	18.494	17.472	16.433	14.128	13.458	11.694			
11.067	9.673	8.6	9.79	7.825	6.358	5.614	4.823	20.161		

20.296	17.087	14.723	12.42	12.215	10.601	10.644	9.867	
9.102	11.866	11.588	11.38	10.159	9.618	9.032	8.082	7.265
5.617	6.198	4.598	4.88	3.611	3.599	19.754	14.876	11.883
11.184	9.862	9.275	9.415	9.279	9.363	5.414	3.278	3.574
17.46	12.336	11.665	5.233	2.077	1.322	13.225	12.045	11.562
8.554	7.807	2.892	12.737	11.355	9.383	8.252	4.182	6.545
8.803	8.128	6.402	15.217	10.232	9.243	10.283	7.77	10.812
I5	0	6.817	4.53	4.126	7.775	7.813	7.852	10.838
10.323	6.588	7.778	9.12	10.632	10.192	8.288	10.536	11.643
13.838	14.81	18.777	12.648	11.553	11.277	8.731	9.873	
18.236	12.147	11.124	9.832	12.022	10.929	11.789	12.795	
15.579	16.137	15.884	16.8	18.175	19.433	21.083	15.414	
14.046	12.606	10.138	10.285	10.936	12.202	11.727	12.749	
13.528	14.262	13.703	11.904	12.325	13.426	13.681	14.631	19.288
19.803	21.272	22.683	21.742	23.031	22.322	16.772	12.32	14.235
12.245	15.841	16.705	13.373	16.709	17.5	19.444	22.557	21.447
14.904	13.791	15.469	20.729	23.947	24.827	15.946	16.417	19.669
21.203	22.232	24.094	16.44	17.662	19.601	21.126	24.362	24.223
20.592	22.862	27.235	19.34	20.413	22.072	23.498	25.794	25.799
I6	14.34	9.253	12.564	12.537	11.611	11.649	11.688	12.178
11.221	10.369	10.382	11.948	13.106	10.555	10.239	10.304	8.409
9.787	11.120	13.832	13.929	12.694	8.362	7.894	6.337	8.578
13.388	7.909	6.886	5.848	6.283	7.387	8.509	10.752	
10.732	9.199	11.036	11.952	11.198	12.499	12.531	7.299	
5.930	4.490	6.260	6.904	5.827	7.212	7.097	7.874	7.844
2.538	5.730	5.634	5.917	6.031	6.286	7.779	7.564	8.398
9.548	10.959	10.017	11.307	13.770	8.200	4.204	4.038	3.811
4.116	4.981	5.211	4.985	5.776	7.720	10.833	9.722	12.181
2.067	3.744	9.004	12.223	13.103	2.745	3.216	7.945	7.403
10.507	12.370	3.239	4.461	6.399	7.925	11.161	11.022	4.071
9.661	14.034	7.643	7.212	8.871	10.297	12.593	12.598	13.397
I7	14.397	9.310	12.621	12.593	11.668	11.706	11.745	12.235
11.278	10.426	10.439	12.005	13.163	10.612	10.296	10.361	8.466
9.844	11.177	13.889	13.986	12.751	8.419	7.951	6.394	8.635
13.445	7.966	6.943	5.905	6.340	7.444	8.566	10.809	
10.789	9.256	11.093	12.009	11.255	12.556	12.588	9.465	
5.987	4.547	6.317	6.961	5.884	7.269	7.154	7.931	7.901
2.595	5.787	5.691	5.974	6.088	6.343	7.836	7.621	8.455
9.605	11.016	10.074	11.364	13.827	8.170	4.261	4.095	3.868
4.173	5.038	5.268	5.042	5.833	7.777	10.889	9.779	12.238
2.124	3.801	9.061	12.280	13.160	2.715	3.186	8.002	7.373
10.564	12.427	3.209	4.431	6.369	7.895	11.131	10.992	4.041
9.631	14.004	6.122	7.182	8.841	10.267	12.563	12.568	13.367;

Table Dis(j,i) Distance from collection point j to facility i (km)

	I1	I2	I3	I4	I5	I6	I7	
J0	0.00	0.00	0.00	23.00	0.00	14.34	14.40	
J1	6.82	6.82	6.82	17.92	6.82	9.25	9.31	
J2	4.53	4.53	4.53	19.18	4.53	12.56	12.62	
J3	4.13	4.13	4.13	20.44	4.13	12.54	12.59	
J4	7.78	7.78	7.78	17.32	7.78	11.61	11.67	
J5	7.81	7.81	7.81	17.12	7.81	11.65	11.71	
J6	7.85	7.85	7.85	16.56	7.85	11.69	11.75	
J7	10.84	10.84	10.84	15.31	10.84	12.18	12.24	
J8	11.17	11.17	11.17	23.27	11.17	11.22	11.28	
J9	10.32	10.32	10.32	20.18	10.32	10.37	10.43	

J10	6.59	6.59	6.59	16.98	6.59	10.38	10.44
J11	7.78	7.78	7.78	15.90	7.78	11.95	12.01
J12	9.12	9.12	9.12	14.83	9.12	13.11	13.16
J13	10.63	10.63	10.63	13.69	10.63	10.56	10.61
J14	10.19	10.19	10.19	20.85	10.19	10.24	10.30
J15	8.29	8.29	8.29	16.00	8.29	10.30	10.36
J16	10.54	10.54	10.54	14.87	10.54	8.41	8.47
J17	11.64	11.64	11.64	12.92	11.64	9.79	9.84
J18	13.84	13.84	13.84	10.76	13.84	11.12	11.18
J19	14.81	14.81	14.81	10.07	14.81	13.83	13.89
J20	18.78	18.78	18.78	9.42	18.78	13.93	13.99
J21	12.65	12.65	12.65	21.40	12.65	12.69	12.75
J22	11.55	11.55	11.55	18.95	11.55	8.36	8.42
J23	11.28	11.28	11.28	18.48	11.28	7.89	7.95
J24	8.73	8.73	8.73	16.92	8.73	6.34	6.39
J25	9.87	9.87	9.87	13.14	9.87	8.58	8.64
J26	18.24	18.24	18.24	9.66	18.24	13.39	13.45
J27	12.15	12.15	12.15	18.49	12.15	7.91	7.97
J28	11.12	11.12	11.12	17.47	11.12	6.89	6.94
J29	9.83	9.83	9.83	16.43	9.83	5.85	5.91
J30	12.02	12.02	12.02	14.13	12.02	6.28	6.34
J31	10.93	10.93	10.93	13.46	10.93	7.39	7.44
J32	11.79	11.79	11.79	11.69	11.79	8.51	8.57
J33	12.80	12.80	12.80	11.07	12.80	10.75	10.81
J34	15.58	15.58	15.58	9.67	15.58	10.73	10.79
J35	16.14	16.14	16.14	8.60	16.14	9.20	9.26
J36	15.88	15.88	15.88	9.79	15.88	11.04	11.09
J37	16.80	16.80	16.80	7.83	16.80	11.95	12.01
J38	18.18	18.18	18.18	6.36	18.18	11.20	11.26
J39	19.43	19.43	19.43	5.61	19.43	12.50	12.56
J40	21.08	21.08	21.08	4.82	21.08	12.53	12.59
J41	15.41	15.41	15.41	20.16	15.41	7.30	9.47
J42	14.05	14.05	14.05	20.30	14.05	5.93	5.99
J43	12.61	12.61	12.61	17.09	12.61	4.49	4.55
J44	10.14	10.14	10.14	14.72	10.14	6.26	6.32
J45	10.29	10.29	10.29	12.42	10.29	6.90	6.96
J46	10.94	10.94	10.94	12.22	10.94	5.83	5.88
J47	12.20	12.20	12.20	10.60	12.20	7.21	7.27
J48	11.73	11.73	11.73	10.64	11.73	7.10	7.15
J49	12.75	12.75	12.75	9.87	12.75	7.87	7.93
J50	13.53	13.53	13.53	9.10	13.53	7.84	7.90
J51	14.26	14.26	14.26	11.87	14.26	2.54	2.60
J52	13.70	13.70	13.70	11.59	13.70	5.73	5.79
J53	11.90	11.90	11.90	11.38	11.90	5.63	5.69
J54	12.33	12.33	12.33	10.16	12.33	5.92	5.97
J55	13.43	13.43	13.43	9.62	13.43	6.03	6.09
J56	13.68	13.68	13.68	9.03	13.68	6.29	6.34
J57	14.63	14.63	14.63	8.08	14.63	7.78	7.84
J58	19.29	19.29	19.29	7.27	19.29	7.56	7.62
J59	17.66	17.66	17.66	7.87	17.66	8.40	8.46
J60	19.80	19.80	19.80	5.62	19.80	9.63	9.69
J61	21.27	21.27	21.27	6.20	21.27	9.55	9.61
J62	22.68	22.68	22.68	4.60	22.68	10.96	11.02
J63	21.74	21.74	21.74	4.88	21.74	10.02	10.07
J64	23.03	23.03	23.03	3.61	23.03	11.31	11.36
J65	22.32	22.32	22.32	3.60	22.32	13.77	13.83

J66	16.77	16.77	16.77	19.75	16.77	8.20	8.17
J67	12.32	12.32	12.32	14.88	12.32	4.20	4.26
J68	14.24	14.24	14.24	11.88	14.24	4.04	4.10
J69	15.54	15.54	15.54	10.93	15.54	3.81	3.87
J70	12.25	12.25	12.25	11.18	12.25	5.44	5.50
J71	15.84	15.84	15.84	9.86	15.84	4.12	4.17
J72	16.71	16.71	16.71	9.28	16.71	4.98	5.04
J73	13.37	13.37	13.37	9.42	13.37	5.21	5.27
J74	16.71	16.71	16.71	9.28	16.71	4.99	5.04
J75	17.50	17.50	17.50	9.36	17.50	5.78	5.83
J76	19.44	19.44	19.44	5.41	19.44	7.72	7.78
J77	22.56	22.56	22.56	3.28	22.56	10.83	10.89
J78	21.45	21.45	21.45	3.57	21.45	9.72	9.78
J79	23.91	23.91	23.91	1.90	23.91	12.18	12.24
J80	14.90	14.90	14.90	17.46	14.90	7.75	7.72
J81	13.79	13.79	13.79	12.34	13.79	2.07	2.12
J82	15.47	15.47	15.47	11.67	15.47	3.74	3.80
J83	20.73	20.73	20.73	5.23	20.73	9.00	9.06
J84	23.95	23.95	23.95	2.08	23.95	12.22	12.28
J85	24.83	24.83	24.83	1.32	24.83	13.10	13.16
J86	15.95	15.95	15.95	13.23	15.95	2.75	2.72
J87	16.42	16.42	16.42	12.05	16.42	3.22	3.19
J88	19.67	19.67	19.67	11.56	19.67	7.95	8.00
J89	20.60	20.60	20.60	9.99	20.60	7.40	7.37
J90	21.20	21.20	21.20	8.55	21.20	8.00	7.97
J91	22.23	22.23	22.23	7.81	22.23	10.51	10.56
J92	24.09	24.09	24.09	2.89	24.09	12.37	12.43
J93	16.44	16.44	16.44	12.74	16.44	3.24	3.21
J94	17.66	17.66	17.66	11.36	17.66	4.46	4.43
J95	19.60	19.60	19.60	9.38	19.60	6.40	6.37
J96	21.13	21.13	21.13	8.25	21.13	7.93	7.90
J97	24.36	24.36	24.36	4.18	24.36	11.16	11.13
J98	24.22	24.22	24.22	6.55	24.22	11.02	10.99
J99	17.27	17.27	17.27	13.02	17.27	4.07	4.04
J100	20.59	20.59	20.59	8.80	20.59	7.39	7.36
J101	22.86	22.86	22.86	8.13	22.86	9.66	9.63
J102	27.24	27.24	27.24	6.40	27.24	14.03	14.00
J103	19.34	19.34	19.34	15.22	19.34	7.64	6.12
J104	20.41	20.41	20.41	10.23	20.41	7.21	7.18
J105	22.07	22.07	22.07	9.24	22.07	8.87	8.84
J106	23.50	23.50	23.50	10.28	23.50	10.30	10.27
J107	25.79	25.79	25.79	7.77	25.79	12.59	12.56
J108	25.80	25.80	25.80	10.81	25.80	12.60	12.57
J109	26.60	26.60	26.60	9.50	26.60	13.40	13.37;

Table Dist(j,jj) Distance between one collection point j to another (km)

J0	J1	J2	J3	J4	J5	J6	J7	J8	J9	J10
J11	J12	J13	J14	J15	J16	J17	J18	J19	J20	
J21	J22	J23	J24	J25	J26	J27	J28	J29	J30	
J31	J32	J33	J34	J35	J36	J37	J38	J39	J40	
J41	J42	J43	J44	J45	J46	J47	J48	J49	J50	J51
J52	J53	J54	J55	J56	J57	J58	J59	J60	J61	J62
J63	J64	J65	J66	J67	J68	J69	J70	J71	J72	
J73	J74	J75	J76	J77	J78	J79	J80	J81	J82	
J83	J84	J85	J86	J87	J88	J89	J90	J91	J92	

J93	J94	J95	J96	J97	J98	J99	J100	J101	J102	
J103	J104	J105	J106	J107	J108	J109				
J0	0.00	0.00	4.53	4.13	7.75	7.81	7.89	10.84	11.25	10.33
6.59	7.77	9.11	10.62	10.27	8.28	10.52	11.66	14.20	14.81	
16.78	12.72	11.35	11.28	8.76	9.86	16.24	12.91	11.32	10.28	
12.02	10.32	11.18	12.18	13.79	14.35	13.84	15.01	16.44		
17.82	19.30	15.69	14.32	12.88	10.14	10.29	10.94	12.07	11.73	
12.75	13.53	14.16	12.26	11.66	12.51	12.97	13.68	19.39	19.18	
15.87	18.08	18.00	18.52	18.47	19.76	20.53	17.05	12.60		
15.65	15.44	12.24	15.75	16.61	17.12	16.62	17.40	19.38	22.50	
19.57	21.84	15.17	13.74	15.44	20.67	26.10	22.68	15.89		
16.61	20.10	20.01	20.61	22.29	22.87	16.15	18.31	19.54		
20.53	24.31	24.17	17.24	20.54	22.58	27.23	19.28	20.51		
22.05	23.61	25.74	25.93	26.73						
J1	0.00	0.00	0.00	0.00	4.39	4.46	4.53	7.48	6.16	0.00
0.00	4.76	4.95	6.46	5.18	0.00	5.44	7.02	9.11	11.46	
11.70	7.64	6.26	6.19	0.00	0.00	11.16	7.82	6.23	0.00	
0.00	0.00	6.09	7.09	8.71	9.26	8.75	9.93	11.35	12.74	
14.21	10.60	9.23	7.79	5.05	5.20	5.85	6.99	6.64	7.66	
8.44	9.07	7.17	6.58	7.42	7.88	8.59	14.31	14.09	10.79	
12.99	12.91	13.43	13.39	14.68	15.44	11.96	7.51	10.56		
10.36	7.16	10.66	11.53	12.04	11.53	12.31	14.30	17.41	14.48	
16.75	10.09	8.65	10.35	15.58	21.01	17.59	10.80	11.52		
15.02	14.92	15.52	17.20	17.78	11.07	13.23	14.46	15.44		
19.22	19.08	12.16	15.45	17.50	22.14	14.19	15.42	16.96		
18.53	20.65	20.85	21.64							
J2	4.53	0.00	0.00	0.00	3.86	3.92	4.00	6.95	7.46	6.53
0.00	3.88	5.22	6.73	6.47	4.39	6.17	7.77	10.37	10.92	
12.96	8.93	7.55	7.49	4.94	6.04	12.42	9.12	9.25	7.72	
8.20	6.49	7.35	8.80	9.97	10.53	10.01	11.19	12.62	14.00	
15.47	11.34	12.55	11.11	6.31	6.46	7.11	8.25	7.90	8.93	
9.70	12.39	8.43	7.84	8.68	9.14	9.86	10.66	17.40	12.05	
14.25	14.17	14.70	14.65	15.94	16.70	15.27	10.82	9.16		
13.67	8.42	9.16	9.97	9.54	9.75	10.56	17.61	16.64	15.74	
18.01	13.40	11.96	13.66	18.89	19.43	18.85	14.11	14.83		
18.33	18.23	18.83	20.51	19.05	14.38	16.54	17.77	18.75		
22.53	22.39	15.47	18.76	20.81	22.40	17.50	18.73	20.27		
21.84	23.96	24.16	24.95							
J3	4.13	6.74	0.00	0.00	5.11	5.18	5.25	8.20	8.71	7.79
0.00	5.14	6.48	7.99	7.73	5.65	7.42	9.02	11.63	12.18	
14.22	10.19	8.81	8.74	6.20	7.29	13.68	10.37	9.52	8.48	
9.46	7.75	8.61	10.06	11.23	11.78	11.27	12.45	13.87	15.26	
16.73	13.89	12.52	11.08	7.57	7.72	8.37	9.51	9.16	10.18	
10.96	12.36	9.69	9.10	9.94	10.40	11.11	11.92	17.38	13.31	
15.51	15.43	15.95	15.91	17.20	17.96	15.24	10.79	10.42		
13.64	9.68	13.94	14.81	10.80	14.81	15.60	17.58	17.90	17.00	
19.27	13.37	11.94	13.64	18.86	24.30	20.11	14.09	14.81		
18.30	18.21	18.80	20.49	20.30	14.35	16.51	17.74	18.73		
22.50	22.36	15.44	18.73	20.78	25.43	17.48	18.70	20.24		
21.81	23.93	24.13	24.92							
J4	7.78	6.07	3.89	5.14	0.00	0.00	0.00	4.01	9.08	8.15
3.10	2.99	2.24	4.17	8.09	3.79	4.53	5.57	8.31	7.80	
9.95	10.55	9.17	9.11	4.78	5.32	9.18	9.63	8.59	7.55	
8.02	5.98	5.95	6.61	8.11	8.66	8.15	9.33	10.75	12.14	
13.61	12.96	11.59	10.15	6.13	6.28	6.93	6.82	6.73	7.80	
8.48	11.43	10.90	7.74	8.44	8.38	8.63	9.72	10.92	10.19	

12.39	12.31	12.83	12.79	14.08	14.84	14.32	9.87	12.92	
12.71	8.24	13.02	13.88	8.96	13.89	9.34	13.99	14.78	13.88
16.15	12.45	11.01	12.71	15.27	17.57	16.99	13.16	13.88	
17.38	17.28	17.88	19.56	17.18	13.42	15.58	16.81	17.80	
21.58	21.44	14.52	17.81	19.85	20.53	16.55	17.78	19.32	
20.88	23.01	23.20	24.00						
J5	7.81	6.11	3.92	5.18	0.00	0.00	0.00	3.83	7.74
0.00	0.00	0.00	3.99	6.76	3.09	4.87	5.37	8.31	8.23
10.90	9.21	7.84	7.77	4.09	5.02	10.36	9.67	8.63	7.59
7.32	5.61	5.75	6.41	7.91	8.46	7.95	9.13	10.55	11.94
13.41	13.00	11.63	10.19	5.44	5.58	6.24	6.62	7.03	7.60
8.28	11.47	7.55	6.96	7.80	8.18	8.43	9.52	10.72	9.99
12.19	12.11	12.63	12.59	13.88	14.64	14.36	9.90	8.28	12.75
7.54	13.06	13.92	8.66	13.93	9.14	13.79	14.58	13.68	15.95
12.48	11.05	12.75	15.07	17.37	16.79	13.20	13.92	17.41	
17.32	17.92	19.60	16.98	13.46	15.62	16.85	17.84	21.61	
21.48	14.55	17.84	19.89	20.33	16.59	17.82	19.36	20.92	
23.05	23.24	24.04							
J6	7.85	6.15	3.96	5.22	0.00	0.00	0.00	3.27	9.15
3.18	3.07	0.00	3.43	8.17	3.87	3.99	4.82	8.46	7.95
10.11	10.63	9.25	9.18	4.86	4.56	9.80	9.71	8.67	7.63
8.09	5.22	5.19	5.86	7.35	7.91	7.40	8.57	10.00	11.38
12.86	13.04	11.67	10.23	6.21	6.36	7.01	6.07	5.98	7.05
7.73	11.51	10.97	6.99	7.68	7.62	7.88	8.97	10.16	9.43
11.63	11.56	12.08	12.03	13.32	14.08	14.40	9.94	13.00	
12.79	8.31	13.10	13.96	8.21	8.35	8.58	13.23	14.02	13.12
15.39	12.52	11.09	12.79	14.52	16.81	16.23	13.24	13.96	
17.45	17.36	17.96	16.00	16.43	13.50	15.66	16.89	17.88	
17.62	21.51	14.59	17.88	19.93	19.78	16.63	17.86	19.39	
20.96	23.09	23.28	24.08						
J7	10.84	9.13	6.95	8.20	4.03	3.83	3.20	0.00	10.00
4.67	4.56	0.00	0.00	9.02	5.36	4.73	3.67	5.00	6.01
9.09	13.60	10.10	10.75	6.35	4.66	8.55	12.05	9.74	8.70
8.43	5.43	4.63	4.71	6.10	6.66	6.15	7.32	8.75	10.13
11.61	12.13	12.27	9.12	6.91	7.17	6.86	4.92	5.82	5.80
6.58	9.87	7.99	7.20	6.54	6.48	6.74	7.72	8.92	8.18
10.39	10.31	10.83	10.78	12.07	12.83	15.84	10.43	9.39	8.78
8.14	8.27	7.52	7.06	7.20	7.44	11.99	12.78	11.87	14.14
13.01	11.58	11.11	13.27	15.57	14.99	13.73	14.45	10.31	
10.96	11.56	14.75	15.18	13.99	11.65	11.31	11.49	16.37	
15.93	15.08	12.30	14.35	18.53	17.12	12.29	13.81	15.40	
19.99	17.72	18.51							
J8	11.17	4.42	7.41	8.67	8.81	7.70	8.96	9.97	0.00
5.59	5.90	7.24	8.75	0.00	6.41	7.72	9.30	14.46	16.96
17.05	2.79	3.51	3.45	5.82	7.06	16.51	5.08	5.21	5.95
9.22	7.51	8.37	9.38	14.06	14.62	14.11	15.28	16.71	18.09
19.57	5.84	5.98	8.89	7.34	7.48	8.13	9.27	8.92	9.95
10.73	11.04	10.51	8.86	9.70	10.16	10.88	15.68	16.06	16.14
18.34	18.27	18.79	18.74	20.03	20.79	9.56	9.48	12.53	12.32
9.44	12.63	13.49	14.00	13.50	14.28	16.26	19.38	19.83	22.10
9.37	10.62	12.32	17.55	22.98	22.94	12.77	13.49	16.99	
16.89	17.49	19.17	23.14	13.03	15.19	16.42	17.41	21.19	
21.05	14.13	17.42	19.46	24.11	16.16	17.39	18.93	20.49	
22.62	22.81	23.61							
J9	10.32	0.00	6.56	7.82	7.96	6.85	8.11	9.12	0.00
4.74	5.05	6.39	7.90	0.00	5.56	6.87	8.45	11.38	13.87

13.96	3.91	0.00	0.00	4.96	6.21	13.42	3.43	3.56	4.30
8.37	6.66	7.52	9.78	10.97	11.53	11.02	12.19	13.62	15.00
16.48	5.65	5.79	6.53	6.48	6.63	7.28	8.42	8.07	9.09
9.87	10.19	9.65	8.01	8.85	9.31	10.03	12.59	15.21	13.05
15.25	15.18	15.70	15.65	16.94	17.70	9.36	8.62	11.68	11.47
8.59	11.78	12.64	13.15	12.65	13.43	15.41	17.65	16.74	19.01
9.18	9.77	11.47	16.70	20.44	19.86	11.92	12.64	16.13	
16.04	16.64	18.32	20.05	12.18	14.34	15.57	16.56	20.34	
20.20	13.27	16.56	18.61	23.26	15.31	16.54	18.08	19.64	
21.77	21.96	22.76							
J10	6.59	0.00	0.00	0.00	3.10	0.00	3.24	4.70	5.62
0.00	0.00	2.71	4.22	4.64	0.00	3.65	5.25	8.17	9.42
10.76	7.10	5.72	5.66	3.11	3.81	10.22	7.28	7.42	5.89
6.37	4.66	5.52	6.29	7.77	8.33	7.82	8.99	10.42	11.80
13.28	9.51	10.36	8.92	4.48	4.63	5.28	6.50	6.07	7.48
8.16	7.81	6.60	6.01	6.85	8.06	8.31	9.39	10.58	9.85
12.05	11.98	12.50	12.45	13.74	14.50	13.09	8.64	7.33	11.49
6.59	7.33	8.14	7.71	7.92	9.02	11.55	14.44	13.54	15.81
11.22	9.78	11.48	12.84	17.23	16.65	11.93	12.65	11.78	
16.05	16.65	14.32	16.85	12.20	14.35	15.59	16.57	18.04	
20.21	13.29	16.58	18.62	20.20	15.32	16.55	18.09	19.65	
21.78	21.97	22.77							
J11	7.78	3.96	3.89	5.14	2.96	0.00	3.10	4.56	5.93
0.00	0.00	0.00	3.14	4.95	0.00	0.00	4.17	7.09	8.34
9.68	7.41	6.03	5.97	2.28	3.21	9.14	7.59	6.07	5.03
5.51	3.81	4.66	5.21	6.69	7.25	6.74	7.91	9.34	10.72
12.20	8.97	11.93	5.96	3.63	3.77	4.43	5.42	5.22	6.40
7.08	6.96	5.75	5.15	5.99	6.98	7.23	8.31	9.50	8.77
10.97	10.90	11.42	11.37	12.66	13.42	14.66	10.20	6.47	6.98
5.73	6.47	7.28	6.85	7.70	7.94	12.57	13.37	12.46	14.73
12.78	11.35	8.20	13.86	16.15	15.57	13.50	14.22	10.80	
11.46	12.06	15.34	15.77	13.76	15.92	17.15	11.98	16.96	
21.77	14.85	18.14	20.19	19.12	16.89	18.11	19.65	21.22	
20.57	23.54	24.33							
J12	9.12	5.30	5.23	6.49	2.24	0.00	0.00	0.00	7.28
2.71	0.00	0.00	0.00	6.29	2.63	0.00	0.00	6.02	7.27
8.61	8.75	7.37	7.31	3.63	0.00	8.07	8.94	7.41	6.38
6.86	3.49	3.46	4.14	5.62	6.18	5.67	6.84	8.27	9.65
11.13	10.22	10.36	7.21	4.97	5.12	5.77	4.35	4.25	5.33
6.01	8.30	7.09	5.26	5.97	5.91	6.16	7.24	8.43	7.70
9.90	9.83	10.35	10.30	11.59	12.35	13.93	11.36	7.82	6.84
6.20	6.33	6.95	6.49	6.63	6.87	11.50	12.29	11.39	13.66
13.94	12.51	9.54	12.79	15.08	14.50	14.66	15.38	9.73	
10.39	10.99	14.27	14.70	14.92	11.08	10.74	10.91	15.89	
18.25	16.01	11.73	13.78	18.05	18.04	11.72	13.24	14.83	
19.50	17.15	17.94							
J13	10.63	6.81	6.74	8.00	4.20	3.99	3.36	0.00	8.79
4.22	3.14	0.00	0.00	7.81	4.14	3.11	0.00	0.00	0.00
7.47	11.98	9.67	9.12	5.00	0.00	6.93	10.42	8.12	7.08
6.80	3.81	3.01	2.72	4.12	5.04	4.52	5.70	7.13	8.51
9.98	10.51	10.64	7.49	5.28	5.54	5.23	3.30	4.20	3.91
4.51	8.25	6.37	5.57	4.92	4.86	4.56	6.10	7.29	6.56
8.76	8.68	9.21	9.16	10.45	11.21	14.22	8.81	7.77	7.16
6.52	6.65	5.90	5.44	5.58	5.82	10.36	11.15	10.25	12.52
11.39	9.96	9.49	11.65	13.94	13.36	12.10	12.82	8.68	
9.34	9.94	13.13	13.56	12.37	10.03	9.69	9.86	14.75	

14.31	13.46	10.68	12.73	16.91	15.49	10.67	12.19	13.78	
18.36	16.09	16.89							
J14	10.19	3.44	6.43	7.69	7.83	6.72	7.97	8.99	0.00
4.61	4.92	6.26	7.77	0.00	5.43	6.74	8.32	12.04	14.54
14.63	3.08	2.53	2.46	4.83	6.07	14.09	4.09	4.23	4.97
8.24	6.53	7.39	8.40	11.64	12.20	11.68	12.86	14.29	15.67
17.14	6.32	6.45	8.78	6.35	6.50	7.15	8.29	7.94	8.96
9.74	10.06	9.52	7.88	8.72	9.18	9.90	15.29	15.08	13.72
15.92	15.84	16.37	16.32	17.61	18.37	10.03	8.49	11.55	
11.34	8.46	11.65	12.51	13.02	12.52	13.30	15.28	18.39	17.41
19.68	11.07	9.64	11.34	16.57	22.00	20.52	11.79	12.51	
16.00	15.91	16.51	18.19	20.72	12.05	14.21	15.44	16.43	
20.20	20.06	13.14	16.43	18.48	23.13	15.18	16.41	17.95	
19.51	21.64	21.83	22.63						
J15	8.29	0.00	4.40	5.65	3.76	3.09	3.90	5.36	6.44
0.00	0.00	2.63	4.14	5.46	0.00	0.00	5.17	7.19	9.68
9.78	7.92	6.54	6.47	0.00	2.85	9.24	6.75	5.71	4.67
5.15	3.45	4.31	5.49	6.79	7.35	6.83	8.01	9.44	10.82
12.29	8.62	8.75	5.60	3.27	3.42	4.07	5.20	4.86	5.88
6.66	6.60	5.39	4.79	5.64	6.10	6.81	8.41	9.60	8.87
11.07	10.99	11.52	11.47	12.76	13.52	13.01	8.56	6.12	6.62
5.37	6.11	6.93	6.50	6.70	7.52	10.34	13.46	12.56	14.83
11.14	9.71	7.84	11.62	16.25	15.67	11.85	12.57	10.56	
11.22	11.82	13.10	15.87	12.12	14.28	11.57	11.74	17.05	
16.19	13.21	12.56	14.61	19.22	15.24	12.55	14.07	15.66	
20.67	17.98	18.77							
J16	10.54	5.06	6.18	7.43	5.38	4.87	3.91	4.73	7.77
3.65	0.00	0.00	3.11	6.79	0.00	0.00	4.14	6.07	8.56
8.66	9.24	7.02	6.47	0.00	0.00	8.12	6.50	5.46	4.42
4.90	3.20	3.51	4.36	5.67	6.22	5.71	6.89	8.31	9.69
11.17	10.26	10.40	5.35	3.02	3.17	3.82	4.52	4.61	5.40
6.17	6.35	5.14	4.54	5.39	6.07	6.33	7.28	8.48	7.75
9.95	9.87	10.39	10.35	11.64	12.40	11.12	6.66	5.86	6.37
5.12	5.86	6.68	6.25	6.80	7.03	11.55	12.34	11.44	13.71
9.24	7.81	7.59	12.83	15.13	14.55	9.96	9.56	9.90	10.56
11.16	14.31	14.74	9.38	11.26	10.90	11.08	15.93	18.29	
10.21	11.89	13.94	18.09	13.35	11.88	13.41	14.99	19.55	
17.31	18.10								
J17	11.64	7.82	7.75	9.01	5.58	5.35	4.73	3.65	9.35
5.23	4.15	0.00	0.00	8.37	5.15	4.12	0.00	0.00	5.32
5.42	11.21	8.91	8.36	4.20	0.00	4.88	9.66	7.35	6.31
6.04	0.00	0.00	0.00	2.93	3.76	2.63	4.38	6.36	7.74
9.22	9.74	9.88	6.73	4.52	4.10	4.47	2.53	3.43	2.73
3.33	7.48	5.60	4.81	4.15	4.09	3.38	4.31	6.02	5.35
7.99	7.92	8.44	8.39	9.68	10.44	13.45	8.04	7.00	6.39
5.75	5.88	5.13	4.67	4.81	5.05	6.82	10.39	9.48	11.75
10.62	9.19	8.72	8.11	13.18	12.60	11.34	12.06	7.91	
8.57	9.17	9.59	12.79	11.60	9.26	8.92	9.10	13.98	13.54
12.69	9.91	11.96	16.14	14.73	9.90	11.42	13.01	17.59	15.33
16.12									
J18	13.84	9.15	10.31	11.57	8.35	7.93	8.44	6.13	11.07
7.79	6.71	5.64	0.00	10.09	6.83	5.70	0.00	0.00	0.00
4.19	12.54	10.24	9.69	5.92	3.96	0.00	10.99	8.68	7.64
7.37	4.38	0.00	0.00	0.00	0.00	0.00	0.00	4.20	5.58
8.19	11.07	11.21	8.06	5.85	5.43	5.80	3.87	4.76	3.25
3.40	8.82	6.93	6.14	5.48	5.42	4.72	3.98	5.17	4.44

5.83	5.75	6.28	6.23	7.52	8.28	14.79	9.38	8.33	7.73
7.09	7.22	6.47	6.01	6.14	6.38	5.97	8.22	7.32	9.59
11.96	10.52	10.06	7.26	11.01	10.43	12.67	13.39	9.25	
9.91	9.56	8.74	10.63	12.93	10.59	10.25	9.26	11.82	
14.18	14.02	11.24	11.34	13.98	16.06	11.23	10.80	12.77	
15.43	16.66	17.11							
J19	14.81	11.86	10.92	12.18	7.84	8.21	7.93	6.01	17.12
9.47	8.39	7.32	0.00	14.80	9.39	8.36	6.43	0.00	0.00
2.48	15.25	12.95	12.40	9.07	7.12	1.71	13.70	11.39	10.35
10.08	7.09	7.06	4.75	4.63	3.96	2.94	3.19	3.51	4.89
7.49	13.79	13.92	10.77	8.56	8.14	8.51	6.57	7.84	5.51
5.25	11.53	9.65	8.85	8.19	8.13	6.92	5.83	5.92	4.83
5.15	5.07	5.59	5.54	6.83	7.59	17.50	12.09	11.04	10.78
9.80	9.93	9.05	8.93	8.73	9.21	6.75	7.54	6.64	8.90
14.67	13.23	11.47	8.03	10.33	9.75	15.38	12.46	11.39	
11.02	10.33	9.51	9.94	15.65	12.73	10.98	10.03	11.13	
13.49	16.74	11.13	12.11	13.29	18.77	13.38	11.57	13.54	
14.75	17.74	16.42							
J20	18.78	11.96	13.56	14.82	9.99	10.37	10.08	9.29	17.22
11.04	9.96	8.89	7.67	14.90	10.08	8.95	6.06	4.21	2.48
0.00	15.35	13.05	12.50	9.17	7.21	0.00	13.80	11.49	10.45
10.18	7.18	7.15	4.84	4.72	4.06	3.04	3.29	0.00	0.00
5.64	13.88	14.02	10.87	8.66	8.24	8.61	6.67	7.94	5.61
5.34	11.62	9.74	8.95	8.28	8.22	7.01	5.93	6.02	4.92
5.24	5.16	5.98	5.64	6.93	6.94	17.60	12.18	11.14	10.88
9.89	10.03	9.14	9.03	8.82	9.31	6.84	8.96	6.73	8.25
14.76	13.33	11.57	8.13	9.67	9.09	15.48	12.55	11.48	
11.11	10.43	9.61	9.29	15.74	12.83	11.08	10.13	10.48	
12.84	16.83	11.23	12.21	12.64	18.87	13.47	11.67	13.64	
14.09	17.08	15.77							
J21	12.65	5.90	8.88	10.14	10.29	9.18	10.43	13.42	2.79
7.06	7.37	8.71	11.79	2.85	7.88	9.19	11.02	12.60	15.09
15.18	0.00	0.00	1.75	7.29	9.75	14.64	2.91	3.52	4.25
9.82	8.47	9.33	11.00	12.19	12.75	12.24	13.41	14.84	16.22
17.70	3.97	4.11	7.02	8.30	8.48	9.19	11.01	10.33	11.88
13.24	11.27	10.05	10.33	11.11	12.56	12.82	13.81	15.00	14.27
16.47	16.40	16.92	16.87	18.16	18.92	7.69	7.68	10.78	13.80
10.70	11.58	12.40	11.97	13.28	13.52	18.08	18.87	17.96	20.23
7.50	12.10	13.79	19.36	21.66	21.08	14.24	14.96	18.46	
18.36	18.96	20.84	21.27	14.51	16.67	17.90	18.89	22.46	
22.52	15.60	18.89	20.94	24.62	17.63	18.86	20.40	21.97	
24.09	24.29	25.08							
J22	11.55	4.80	7.79	9.05	9.19	8.08	9.34	10.35	3.67
5.97	6.28	7.62	9.34	2.69	6.79	6.93	8.57	10.14	12.63
12.73	0.00	0.00	0.00	4.86	7.44	12.19	0.00	0.00	3.06
10.26	6.34	7.60	8.55	9.74	10.30	9.78	10.96	12.39	13.77
15.24	4.42	4.55	5.30	6.16	6.31	6.96	8.55	7.75	9.43
10.78	8.18	10.50	10.78	8.53	10.11	10.36	11.36	12.55	11.82
14.02	13.94	14.47	14.42	15.71	16.47	8.13	6.62	9.67	9.47
8.27	9.77	10.64	11.15	10.64	11.42	15.62	16.41	15.51	17.78
7.94	7.76	9.46	16.91	19.20	18.62	9.91	10.63	14.13	
14.03	14.63	18.39	18.82	10.18	12.33	13.57	14.55	20.00	
18.19	11.27	14.56	16.61	22.17	13.30	14.53	16.07	17.64	
19.76	19.96	20.75							
J23	11.28	4.53	7.51	8.77	8.92	7.81	9.06	10.49	3.39
5.69	6.00	7.34	8.87	2.41	6.51	6.47	8.10	9.67	12.17

12.26	1.75	0.00	0.00	4.39	5.80	11.72	0.00	0.00	0.00
7.58	5.87	7.13	8.08	9.27	9.83	9.31	10.49	11.92	13.30
14.77	4.33	4.46	4.83	5.69	5.84	6.49	8.08	7.28	8.96
10.31	7.72	7.81	7.22	8.06	9.64	9.89	10.89	12.08	11.35
13.55	13.47	14.00	13.95	15.24	16.00	8.04	6.15	9.20	9.00
7.80	9.30	10.17	10.68	10.17	10.96	15.15	15.94	15.04	17.31
7.85	7.30	8.99	16.44	18.73	18.15	9.44	10.16	13.66	
13.56	14.16	17.92	18.35	9.71	11.87	13.10	14.09	19.54	
17.72	10.80	14.09	16.14	21.70	12.83	14.06	15.60	17.17	
19.29	19.49	20.28							
J24	8.73	0.00	4.94	6.19	4.74	4.07	4.88	6.34	6.06
2.86	2.26	3.61	4.99	5.08	0.00	0.00	0.00	4.20	8.12
10.70	7.53	4.94	4.39	0.00	0.00	10.16	4.43	3.39	0.00
0.00	0.00	2.92	3.92	7.71	5.74	7.76	8.93	10.36	11.74
13.22	6.29	6.43	3.28	1.88	2.03	2.68	3.82	3.47	4.49
5.27	5.21	4.00	3.40	4.25	4.71	5.42	6.22	8.74	7.26
12.00	11.92	12.44	12.39	13.68	14.44	9.05	4.59	4.73	5.23
3.98	4.72	5.54	5.11	5.31	6.13	8.95	14.39	13.49	15.75
7.17	5.74	6.45	10.23	17.18	16.60	7.89	8.61	9.17	9.83
10.43	11.71	16.79	8.15	10.31	11.54	10.35	17.98	16.16	
9.24	12.53	14.58	20.14	11.28	12.50	14.04	15.61	17.73	17.93
18.72									
J25	9.87	0.00	6.08	7.33	5.31	5.09	4.46	4.86	7.10
3.82	3.22	0.00	0.00	6.12	2.87	0.00	0.00	4.33	6.83
6.92	8.58	7.20	5.80	0.00	0.00	6.38	5.84	4.80	3.76
0.00	0.00	0.00	2.63	3.93	4.49	3.98	5.15	6.58	7.96
9.44	8.53	8.67	5.52	2.35	2.50	3.15	2.78	2.56	3.66
4.44	5.69	4.47	3.57	4.40	4.34	4.59	5.55	6.74	6.01
8.21	8.14	8.66	8.61	9.90	10.66	12.24	6.83	5.20	5.16
4.46	4.65	5.38	4.92	5.06	5.30	9.82	10.61	9.70	11.97
9.41	7.98	6.93	11.10	13.40	12.82	10.13	8.03	8.16	8.82
9.42	12.58	13.01	8.71	9.51	9.17	9.35	14.20	16.56	9.55
10.16	12.21	16.36	13.52	10.15	11.67	13.26	17.81	15.58	
16.37									
J26	18.24	11.42	13.02	14.28	9.22	10.64	9.31	8.75	16.68
10.50	9.42	8.35	7.13	14.36	9.54	8.41	5.52	0.00	1.71
0.00	14.81	12.51	11.96	8.63	6.67	0.00	13.26	10.95	9.91
9.64	6.64	6.61	4.30	4.18	3.52	0.00	0.00	0.00	0.00
5.88	13.34	13.48	10.33	8.12	7.70	8.07	6.13	7.40	5.07
4.80	11.08	9.20	8.41	7.74	7.68	6.47	5.39	5.48	4.38
4.70	4.62	6.22	5.10	6.39	7.18	17.05	11.64	10.60	10.34
9.35	9.48	8.60	8.49	8.28	8.77	6.30	7.09	6.19	8.49
14.22	12.79	11.03	7.59	9.91	9.33	14.94	12.01	10.94	
10.57	9.89	9.07	9.53	15.20	12.29	10.54	9.59	10.72	
13.08	16.29	10.69	11.66	12.88	18.33	12.93	11.13	13.10	
14.33	17.32	16.01							
J27	12.15	5.33	9.08	10.33	9.72	9.79	9.86	10.51	4.96
7.25	7.56	8.52	8.88	3.98	6.74	6.48	8.12	9.69	12.18
12.28	3.32	0.00	0.00	4.41	5.82	11.74	0.00	0.00	2.61
9.81	5.89	7.14	8.09	9.29	9.84	9.33	10.51	11.93	13.31
14.79	3.96	0.00	0.00	5.71	5.86	6.51	8.10	7.30	8.98
10.33	7.73	10.04	10.32	8.08	9.65	9.91	10.90	12.10	11.37
13.57	13.49	14.01	13.97	15.26	16.02	7.68	6.16	9.22	9.01
7.81	9.32	10.18	10.69	10.19	10.97	15.17	15.96	15.06	17.33
7.49	7.31	9.01	16.45	18.75	18.17	9.46	10.18	13.67	
13.58	14.18	17.93	18.36	9.72	11.88	13.11	14.10	19.55	

17.73	10.81	14.10	16.15	21.71	12.85	14.08	15.62	17.18	
19.31	19.50	20.30							
J28	11.12	4.31	9.28	9.32	8.70	8.77	8.84	9.49	5.24
7.54	6.08	7.50	7.86	4.26	5.72	5.46	7.09	8.67	11.16
11.25	3.60	0.00	0.00	3.39	4.80	10.71	0.00	0.00	0.00
6.57	4.86	6.12	7.07	8.26	8.82	8.31	9.48	10.91	12.29
13.77	4.12	0.00	0.00	4.69	4.83	5.48	7.08	6.27	7.95
9.31	6.71	6.80	6.21	7.05	8.63	8.89	9.88	11.07	10.34
12.54	12.47	12.99	12.94	14.23	14.99	7.83	5.14	8.20	7.99
6.79	8.29	9.16	9.67	9.16	9.95	14.15	14.94	14.03	16.30
7.65	6.29	7.99	15.43	17.73	17.15	8.44	9.16	12.65	12.56
13.15	16.91	17.34	8.70	10.86	12.09	13.08	18.53	16.71	
9.79	13.08	15.13	20.69	11.82	13.05	14.59	16.16	18.28	18.48
19.27									
J29	9.83	0.00	7.98	8.03	7.41	7.47	7.55	8.45	5.98
6.31	5.04	6.46	6.82	5.00	4.68	4.42	6.06	7.63	10.12
10.22	4.34	3.14	0.00	0.00	3.76	9.67	2.63	0.00	0.00
0.00	3.83	5.08	6.03	7.22	7.78	7.27	8.44	9.87	11.25
12.73	4.86	4.99	0.00	3.65	3.79	4.45	6.04	5.24	6.92
8.27	5.67	5.77	5.17	6.01	7.59	7.85	8.84	10.04	9.30
11.51	11.43	11.95	11.91	13.19	13.96	8.57	4.10	7.16	6.95
5.75	7.25	8.12	8.63	8.12	8.91	13.11	13.90	13.00	15.27
6.68	5.25	6.95	14.39	16.69	16.11	7.40	8.12	11.61	11.52
12.12	15.87	16.30	7.66	9.82	11.05	12.04	17.49	15.67	
8.75	12.04	14.09	19.65	10.79	12.01	13.55	15.12	17.25	17.44
18.23									
J30	12.02	0.00	8.23	9.48	8.00	7.33	8.14	8.54	9.25
6.12	5.52	6.48	6.72	8.27	5.16	4.90	5.93	7.66	10.15
10.25	10.73	7.91	7.36	0.00	0.00	9.71	7.39	6.35	0.00
0.00	0.00	3.87	4.87	4.98	5.32	7.30	6.10	9.90	11.29
9.50	7.12	5.76	0.00	0.00	0.00	0.00	3.40	3.05	4.08
4.19	0.00	2.11	2.39	3.22	3.80	4.31	5.24	8.29	6.27
10.44	10.30	11.70	10.79	12.08	10.73	8.48	0.00	2.84	4.56
2.76	3.87	4.69	4.26	5.73	6.52	8.50	11.61	10.49	12.96
6.61	5.24	4.57	9.78	13.51	13.88	6.46	6.54	8.72	9.38
9.98	11.26	13.18	6.36	8.24	9.47	9.90	14.23	14.09	7.19
10.46	12.51	17.16	10.73	10.44	11.97	13.54	15.67	15.86	
16.66									
J31	10.93	0.00	7.14	8.39	5.98	5.76	5.13	5.53	8.16
5.02	4.54	3.47	3.71	7.18	4.07	3.52	0.00	4.65	7.14
7.24	9.95	6.81	6.26	0.00	0.00	6.70	6.30	5.26	4.22
0.00	0.00	0.00	2.09	4.25	4.34	4.29	5.47	6.90	8.28
9.75	8.48	8.62	5.47	0.00	0.00	2.35	2.18	2.08	3.10
3.84	4.43	3.22	2.25	2.85	3.32	3.99	4.80	7.35	5.83
8.53	8.45	8.98	8.93	10.22	10.98	9.59	5.13	3.95	3.84
3.20	3.33	4.14	3.71	3.92	4.70	7.56	10.92	10.02	12.29
7.71	6.34	5.67	8.84	13.71	13.13	7.56	6.72	7.78	8.44
9.04	10.32	13.32	7.46	7.86	8.79	8.96	14.51	13.41	8.29
9.78	11.82	16.68	11.84	9.77	11.29	12.87	14.98	15.19	15.99
J32	11.79	6.54	7.99	9.25	5.96	5.74	5.11	4.62	9.02
5.60	4.52	3.45	2.99	8.04	4.64	3.51	0.00	0.00	6.28
6.38	9.93	7.63	7.08	3.53	0.00	5.84	8.38	6.07	5.03
3.84	0.00	0.00	0.00	2.53	3.23	2.87	4.01	6.03	7.42
7.99	8.46	8.60	5.45	2.32	0.00	2.21	0.00	1.18	1.99
2.77	5.29	3.41	2.61	2.73	2.66	2.92	3.72	5.33	4.76
6.72	6.63	7.17	7.12	8.41	9.22	12.18	5.99	4.81	4.20

3.56	3.69	3.71	3.25	3.39	3.62	6.26	9.11	8.21	10.53
8.57	7.20	6.53	7.55	11.95	11.37	8.42	7.08	6.49	7.15
7.75	9.03	11.56	8.32	7.83	7.49	7.67	12.26	12.12	9.15
8.49	10.53	14.91	13.45	8.48	10.00	11.58	13.69	13.90	14.70
J33	12.80	8.78	8.80	10.06	6.63	6.40	5.78	4.70	14.04
									11.10
6.28	5.20	4.13	2.71	11.72	5.49	4.35	0.00	0.00	4.54
4.64	12.17	9.87	9.32	4.54	2.62	4.10	10.62	8.31	7.27
4.85	2.09	0.00	0.00	0.00	0.00	0.00	2.86	4.13	5.89
7.36	10.71	10.84	7.69	3.33	2.91	3.28	0.00	0.00	1.04
2.19	6.30	4.41	3.62	2.95	2.88	2.24	3.25	4.45	3.72
5.77	5.69	6.21	6.17	7.45	8.59	14.42	9.01	5.81	5.21
4.57	4.70	3.93	3.47	3.61	3.84	5.25	8.16	7.26	9.90
11.59	10.15	7.54	6.54	11.32	10.74	12.30	7.78	6.71	
7.37	7.97	8.02	10.93	12.57	8.05	7.71	7.89	12.12	12.34
13.66	8.71	10.75	14.29	15.69	8.70	10.22	11.80	15.74	14.12
14.92									
J34	15.58	8.76	10.36	11.62	8.20	7.98	7.36	6.09	14.02
									11.08
7.84	6.76	5.69	4.47	11.70	6.88	5.75	2.85	0.00	4.33
4.43	12.15	9.85	9.30	5.97	4.02	3.89	10.60	8.29	7.25
6.98	3.99	2.52	0.00	0.00	0.00	0.00	1.82	3.07	4.32
5.97	10.68	10.82	7.67	5.46	3.59	3.56	1.60	2.49	0.00
0.00	8.43	4.63	3.84	3.21	3.15	3.06	2.11	3.31	2.73
4.70	4.61	5.15	5.10	6.39	7.20	14.40	8.99	7.94	7.01
4.79	5.99	4.20	3.73	3.87	4.11	4.11	7.22	6.19	8.50
11.57	10.13	7.70	5.39	9.93	9.35	12.28	8.68	7.62	8.28
7.69	6.87	9.54	12.55	8.96	8.62	7.39	10.73	11.05	10.32
8.49	9.47	12.89	15.67	9.60	8.93	10.90	12.63	15.03	15.82
J35	16.14	9.32	10.92	12.18	8.76	8.54	7.91	6.65	14.58
									11.64
8.40	7.32	6.25	5.03	12.26	7.44	6.31	3.40	0.00	3.92
4.02	12.71	10.41	9.86	5.74	4.57	3.48	11.16	8.85	7.81
5.32	4.54	3.22	0.00	0.00	0.00	0.00	0.00	2.02	3.27
4.89	11.24	11.38	8.23	4.22	3.96	3.90	2.12	2.83	1.67
0.00	7.71	4.98	4.18	3.55	3.47	2.82	0.00	2.47	0.00
3.63	3.55	4.07	4.03	5.32	6.12	14.96	9.54	6.17	6.78
5.13	5.75	4.54	4.08	4.22	4.45	3.87	6.02	5.12	7.43
12.12	8.15	7.47	5.16	8.85	8.27	9.36	8.45	7.38	8.04
7.46	6.64	8.47	9.25	8.73	8.39	7.16	9.66	12.02	10.09
8.26	9.24	11.82	16.23	9.37	8.70	10.67	13.27	14.80	15.59
J36	15.88	9.07	10.67	11.92	8.51	8.29	7.66	6.40	14.33
									11.39
8.15	7.07	6.00	4.77	12.00	7.19	6.05	3.25	0.00	3.12
3.22	12.46	10.15	9.60	6.28	4.32	0.00	10.91	8.60	7.56
7.29	4.29	2.91	0.00	0.00	0.00	0.00	0.00	0.00	4.61
7.22	10.99	11.12	7.97	5.76	5.35	5.72	2.84	3.74	2.66
2.82	8.73	6.85	6.06	4.46	4.40	4.34	3.39	4.59	3.85
4.86	4.78	5.31	5.26	6.55	7.31	14.70	9.29	8.25	7.64
7.00	7.13	5.44	4.98	5.12	5.36	6.46	7.25	6.35	8.62
11.87	10.44	8.98	7.75	10.04	9.46	12.59	13.31	8.90	
9.56	10.05	9.23	9.66	12.85	10.24	9.90	9.75	10.85	13.21
13.94	10.85	11.83	13.01	15.97	10.89	11.29	13.26	14.46	
16.31	16.14								
J37	16.80	9.98	11.58	12.84	9.43	9.20	8.58	7.31	15.24
									12.30
9.06	7.98	6.91	5.69	12.92	8.10	6.97	4.07	0.00	3.15
3.25	13.37	11.07	10.52	7.19	5.24	0.00	11.82	9.51	8.47
8.20	5.21	3.83	2.81	1.82	0.00	0.00	0.00	0.00	2.50
4.12	11.91	12.04	8.89	5.00	4.73	4.67	2.89	3.61	2.44
2.07	8.49	5.75	4.95	4.33	4.24	3.60	2.65	2.77	0.00

0.00	2.78	3.30	3.25	4.54	5.35	15.62	10.21	9.16	7.55
5.90	6.53	5.31	4.85	4.99	5.23	4.46	5.25	4.34	6.66
12.79	8.93	8.24	5.74	8.08	7.50	10.13	9.22	8.16	8.72
8.04	7.22	7.69	10.03	9.50	8.69	7.74	8.88	11.24	10.86
8.84	9.82	11.04	16.89	10.14	9.28	11.25	12.50	13.38	14.17
J38	18.18	11.36	12.96	14.21	10.80	10.58	9.95	8.69	16.62
10.44	9.36	8.29	7.07	14.29	9.48	8.34	5.44	4.22	3.55
0.00	14.75	12.44	11.90	8.57	6.61	0.00	13.20	10.89	9.85
9.58	6.58	6.55	4.18	3.64	2.02	0.00	0.00	0.00	0.00
2.65	13.28	13.42	10.27	8.06	7.64	8.01	4.13	4.85	3.69
3.30	9.71	9.14	8.35	5.67	5.53	4.92	3.84	3.92	0.00
0.00	2.99	0.00	1.96	3.25	3.88	16.99	11.58	9.74	8.78
8.86	7.75	7.04	6.93	6.72	7.20	4.74	3.95	3.05	5.19
14.16	10.15	9.46	4.54	6.61	6.03	11.35	10.45	9.38	9.01
8.33	7.50	6.23	11.25	10.73	8.98	8.02	7.41	9.78	12.09
9.12	11.36	9.58	18.27	11.37	9.56	11.53	11.03	14.02	12.71
J39	19.43	12.62	14.22	15.47	12.06	11.84	11.21	9.95	17.88
11.70	10.62	9.55	8.32	15.55	10.74	9.60	6.70	5.47	4.81
0.00	16.01	13.70	13.15	9.83	7.87	0.00	14.45	12.15	11.11
10.84	7.84	7.81	5.44	4.90	3.27	4.30	2.50	0.00	0.00
0.00	14.54	14.67	11.52	9.31	8.90	9.27	5.39	6.11	4.94
4.46	11.01	10.74	9.60	6.98	6.83	6.22	5.14	5.22	4.13
2.85	4.36	0.00	3.25	4.53	3.14	18.25	12.84	11.04	10.08
10.16	9.05	8.34	8.23	8.02	8.51	6.04	5.15	4.34	4.45
15.42	11.45	10.77	5.83	5.87	5.29	12.66	11.75	10.68	
10.31	9.63	8.81	5.48	12.55	12.03	10.28	9.32	6.67	9.03
13.39	11.29	10.62	8.83	19.52	12.72	11.73	13.05	10.29	
13.28	11.96								
J40	21.08	14.27	15.87	17.12	13.71	13.49	12.86	11.60	19.53
13.34	12.27	11.20	9.97	17.20	12.39	11.25	8.35	8.19	7.52
5.62	17.66	15.35	14.80	11.48	9.52	5.88	16.10	13.80	12.76
12.48	9.49	7.98	7.09	5.97	4.92	7.02	4.33	3.09	0.00
0.00	16.19	16.32	13.17	10.96	8.71	7.99	6.90	6.96	6.16
5.40	11.04	10.77	7.69	7.01	6.86	6.26	5.17	5.25	4.16
2.88	4.39	0.00	3.28	0.00	0.00	19.90	14.05	11.08	10.11
10.20	9.08	8.37	8.26	8.05	8.54	6.07	4.36	4.37	3.66
16.63	11.48	10.80	6.21	5.08	4.50	12.69	11.78	10.71	
10.34	9.66	8.84	4.69	12.59	12.06	10.31	9.36	5.88	8.24
13.42	10.50	9.83	8.04	17.50	11.93	10.94	12.26	9.50	12.49
11.17									
J41	15.41	8.60	13.57	13.61	12.99	12.48	11.85	12.17	5.82
9.91	11.26	10.19	10.55	5.88	8.96	8.70	9.78	11.35	13.85
13.94	3.95	4.46	4.41	6.32	8.51	13.40	2.40	4.21	4.94
8.58	7.23	8.09	9.76	10.95	11.51	11.00	12.17	13.60	14.98
16.46	0.00	1.92	4.65	7.06	7.24	7.95	9.76	9.09	10.64
11.99	7.12	6.56	6.84	7.67	11.32	11.58	12.57	13.76	13.03
15.23	15.16	15.68	15.63	16.92	17.68	4.32	4.94	7.21	8.40
7.21	8.71	9.57	10.08	9.58	10.36	12.34	17.63	16.72	18.99
4.14	6.70	8.40	13.63	20.42	19.83	8.76	9.48	12.98	12.88
13.48	15.16	20.03	9.03	11.18	12.42	13.40	17.18	17.04	
10.12	13.41	15.46	23.38	12.24	13.38	14.92	16.49	18.61	
18.81	19.60								
J42	14.05	7.23	12.20	12.24	11.62	11.69	11.76	12.31	5.96
10.52	11.39	10.32	10.69	6.02	9.09	8.83	9.92	11.49	13.98
14.08	4.09	4.59	4.55	6.45	8.64	13.54	0.00	0.00	5.08
5.75	7.37	8.23	9.89	11.09	11.64	11.13	12.31	13.73	15.12

16.59	1.92	0.00	0.00	7.19	7.37	5.31	9.90	9.22	10.78
12.13	5.75	5.20	5.48	6.30	6.88	9.50	12.70	10.77	13.17
15.37	15.29	15.81	15.77	17.06	17.82	5.63	3.57	5.84	7.03
5.84	7.34	8.20	8.71	8.21	8.99	10.97	17.76	16.86	19.13
5.45	5.33	7.03	12.26	20.55	19.97	7.48	8.20	11.69	11.60
12.20	13.88	20.16	7.74	9.90	11.13	12.12	15.90	15.76	
8.83	12.13	14.17	18.82	10.87	12.10	13.64	15.20	17.33	17.52
18.32									
J43	12.61	5.79	10.76	10.80	10.18	10.25	10.32	9.10	9.28
9.08	5.95	7.11	7.48	8.30	5.60	5.33	6.71	8.28	10.77
10.87	6.99	5.30	4.75	3.26	5.44	10.33	0.00	0.00	0.00
0.00	4.31	5.17	6.69	7.88	8.44	7.92	9.10	10.52	11.91
13.38	4.65	0.00	0.00	4.28	4.31	3.87	6.69	5.36	7.57
8.92	0.00	3.76	4.04	4.86	5.44	8.06	9.54	9.33	9.96
12.16	12.08	12.61	12.56	13.85	14.61	6.58	0.00	4.40	5.59
4.40	5.90	6.76	7.27	6.77	7.55	9.53	12.65	13.65	15.92
4.71	3.89	5.59	10.82	16.25	16.76	6.04	6.76	10.25	10.16
10.76	12.44	16.95	6.30	8.46	9.69	10.68	14.46	14.32	
7.39	10.69	12.73	17.38	9.43	10.66	12.20	13.76	15.89	16.08
16.88									
J44	10.14	5.39	6.34	7.60	6.11	5.45	6.26	6.79	7.37
4.23	3.64	4.73	4.97	6.39	3.28	3.02	4.18	5.92	8.41
8.51	8.84	6.02	5.47	1.88	2.35	7.96	5.51	4.46	3.43
0.00	0.00	2.13	3.13	3.88	4.22	5.56	5.00	8.16	9.54
11.02	7.37	5.73	4.29	0.00	0.00	0.00	2.30	1.95	2.98
3.76	3.30	2.09	2.37	2.73	3.19	3.91	4.71	8.27	5.75
7.71	10.27	8.16	8.11	9.40	12.25	8.46	4.01	2.82	4.54
2.74	3.21	4.02	3.59	3.80	4.61	8.48	11.59	10.46	13.56
6.59	5.21	4.54	9.76	13.49	14.40	6.43	6.52	8.70	9.36
9.96	11.24	13.15	6.33	8.22	9.45	9.88	14.21	14.07	7.17
10.44	12.49	17.13	10.71	10.41	11.95	13.52	15.64	15.84	
16.63									
J45	10.29	5.54	6.49	7.75	6.26	5.59	6.40	6.94	7.52
4.38	3.78	4.88	5.12	6.53	3.43	3.17	4.33	6.06	8.56
8.65	8.99	6.17	5.62	2.03	2.50	8.11	5.65	4.61	3.57
0.00	0.00	0.00	3.28	3.62	3.96	5.71	4.73	5.98	9.69
8.72	7.52	7.65	4.50	0.00	0.00	0.00	0.00	0.00	2.71
3.49	3.95	1.98	1.63	2.47	2.93	3.64	4.45	6.97	5.48
7.45	8.97	7.89	7.85	9.14	9.94	9.10	4.65	3.46	3.46
2.21	2.95	3.76	3.33	3.54	4.35	7.17	10.28	9.16	11.25
7.23	5.86	5.19	8.46	12.18	12.09	7.08	6.33	7.40	8.05
8.65	9.94	11.85	6.98	7.48	8.40	8.58	13.16	13.02	7.81
9.39	11.44	15.64	11.35	9.38	10.90	12.49	14.59	14.81	15.60
J46	10.94	7.00	7.14	8.40	6.91	6.25	7.05	7.59	8.17
5.03	4.44	5.53	5.77	7.19	4.08	3.82	4.98	6.72	9.21
9.30	9.64	6.82	6.27	2.68	3.15	8.76	6.31	5.26	4.22
0.00	2.07	2.21	3.93	3.51	3.85	6.36	4.62	5.86	7.12
7.99	6.69	5.32	3.88	0.00	0.00	0.00	0.00	0.00	2.60
2.93	2.87	0.00	0.00	0.00	2.29	2.79	3.72	6.38	4.76
6.73	8.38	7.17	8.88	10.16	9.22	8.04	3.59	2.39	2.18
1.31	2.36	3.18	2.74	2.95	3.59	6.59	9.70	8.57	11.05
6.17	4.78	4.11	7.87	11.60	11.97	6.00	6.08	6.81	7.47
8.07	9.35	11.26	5.90	7.78	7.82	7.99	12.58	12.44	6.73
8.81	10.86	15.50	10.29	8.80	10.32	11.90	14.01	14.22	15.02
J47	12.20	7.58	8.41	9.66	6.95	6.73	6.10	4.92	9.43
6.58	5.51	4.43	3.30	8.45	5.63	4.49	2.53	3.16	6.59

6.68	10.97	8.67	8.12	3.94	2.76	6.14	9.42	7.11	6.08
4.91	2.15	0.00	0.00	1.60	2.12	2.80	2.89	4.13	5.39
6.90	9.51	9.64	6.49	2.43	0.00	0.00	0.00	0.00	0.00
1.67	4.73	3.05	2.26	1.63	0.00	0.00	2.63	4.23	3.66
5.63	5.53	6.07	6.03	7.32	8.12	13.22	5.43	4.25	3.85
3.21	3.34	2.61	2.15	2.29	2.53	5.17	8.02	7.12	9.43
8.01	6.16	5.48	6.46	10.85	10.27	7.37	6.46	5.40	6.05
6.65	7.94	10.47	7.27	6.74	6.40	6.58	11.16	11.02	8.10
7.39	9.44	13.82	14.49	7.38	8.90	10.49	12.59	12.81	13.60
J48	11.73	6.98	7.93	9.19	6.73	6.51	5.89	5.82	8.96
5.82	5.29	4.22	4.20	7.98	4.87	4.28	3.43	4.05	7.48
7.58	10.70	7.61	7.06	3.47	2.55	7.04	7.10	6.05	5.02
3.05	1.86	1.18	0.00	2.49	2.83	3.69	3.61	4.85	6.11
6.94	9.24	9.37	6.22	1.95	0.00	0.00	0.00	0.00	1.37
1.72	4.38	2.71	0.00	0.00	0.00	0.00	2.67	4.28	3.71
5.67	5.58	6.12	6.07	7.36	8.17	9.54	5.09	3.90	3.50
2.86	2.99	2.66	2.20	2.34	2.57	5.22	8.06	7.16	9.48
7.67	6.05	5.36	6.50	10.90	10.32	7.25	6.37	5.44	6.10
6.70	7.98	10.51	7.15	6.78	6.44	6.62	11.21	11.07	7.98
7.44	9.48	13.86	11.79	7.43	8.95	10.53	12.64	12.85	13.65
J49	12.75	8.46	8.95	10.21	7.59	7.37	6.74	5.67	9.98
7.25	6.17	5.10	3.68	9.00	5.89	5.32	2.52	2.99	5.77
5.86	11.85	9.55	9.00	4.49	3.58	5.32	10.30	7.99	6.95
4.08	3.03	1.97	1.04	0.00	1.70	2.63	2.47	3.71	4.97
6.16	10.39	10.52	7.37	2.98	2.71	2.65	0.00	1.37	0.00
0.00	5.41	3.73	2.93	2.29	1.79	0.00	1.89	3.50	2.93
4.90	4.80	5.34	5.30	6.58	7.39	10.56	6.11	4.92	5.45
3.88	4.01	3.28	2.82	2.96	3.19	4.30	7.29	6.39	8.70
8.69	6.83	6.14	5.59	10.12	9.54	8.03	7.12	6.06	6.72
7.32	7.07	9.73	7.93	7.40	7.06	7.24	10.92	11.25	8.76
8.05	9.67	13.09	12.84	8.04	9.13	11.15	14.54	13.47	14.26
J50	13.53	9.80	9.73	10.99	9.25	9.02	8.40	6.58	10.76
8.88	7.80	6.73	4.49	9.78	6.67	6.15	3.33	3.23	5.37
5.47	13.20	10.89	10.34	5.27	4.42	4.93	11.64	9.33	8.30
4.19	3.81	2.75	2.20	0.00	0.00	2.87	2.08	3.30	4.46
5.40	11.73	11.86	8.71	3.76	3.49	2.93	1.67	1.72	0.00
0.00	5.40	3.59	2.93	2.26	2.13	0.00	0.00	2.73	0.00
4.13	4.03	4.58	4.53	5.82	6.62	10.55	6.10	4.92	5.42
4.03	4.40	3.25	2.79	2.93	3.16	3.54	6.65	5.62	7.93
8.68	6.80	6.11	4.82	9.36	8.78	8.00	7.09	6.03	6.69
7.12	6.30	8.97	7.90	7.37	7.03	6.82	10.16	10.48	8.73
8.02	8.90	12.32	12.81	8.01	8.36	10.33	12.05	13.44	14.23
J51	14.26	7.45	9.65	12.46	11.84	11.90	11.98	9.96	10.94
7.54	6.94	7.90	8.14	9.96	6.58	6.32	7.35	9.08	11.57
11.67	12.41	8.41	7.86	5.18	5.66	11.13	7.89	6.85	5.81
0.00	4.43	5.29	6.29	7.90	7.67	8.72	8.44	9.70	11.02
11.05	7.56	6.19	0.00	3.28	3.92	2.84	4.70	3.87	5.98
7.33	0.00	0.00	3.03	4.38	4.51	4.77	6.25	6.03	6.87
8.18	8.04	9.44	8.53	9.82	12.28	8.92	0.00	0.00	2.30
3.71	2.60	3.47	3.98	3.47	4.26	6.24	9.35	8.22	10.70
7.04	0.00	0.00	7.52	11.25	11.62	4.20	4.28	6.46	7.12
7.72	9.00	10.91	4.09	5.98	7.21	7.64	11.97	11.83	4.93
8.20	10.25	14.90	7.50	8.17	9.71	11.28	13.40	13.60	14.39
J52	13.70	6.89	8.22	11.90	11.28	7.32	7.67	8.06	10.38
6.11	5.51	6.00	6.24	9.40	5.15	4.89	5.45	7.19	9.68
9.78	9.29	7.90	7.35	3.75	4.23	9.23	7.38	6.34	5.30

2.23	3.04	3.40	4.40	4.62	4.96	6.83	5.74	6.98	10.74
10.77	6.57	5.20	3.76	2.21	1.98	0.00	3.04	2.69	3.72
3.57	0.00	0.00	0.00	1.53	1.99	3.04	3.99	5.76	5.12
7.91	7.76	9.17	8.25	9.54	12.00	7.93	3.48	0.00	0.00
0.00	1.73	2.55	2.12	2.33	2.97	5.96	9.07	7.95	10.42
6.06	4.68	4.01	7.24	10.97	11.34	5.90	5.12	6.18	6.84
7.44	8.72	10.64	5.80	6.27	7.19	7.37	11.95	11.81	6.63
8.18	10.23	14.87	10.18	8.17	9.69	11.28	13.38	13.60	14.39
J53	11.90	7.06	8.11	9.37	7.73	7.21	6.88	7.28	9.14
6.00	5.40	5.22	5.46	8.15	5.05	4.78	4.67	6.40	8.89
8.99	10.61	7.79	7.24	3.64	3.54	8.45	7.27	6.23	5.19
2.04	2.25	2.61	3.62	3.84	4.18	6.04	4.95	6.20	7.45
7.70	6.75	5.38	3.94	2.13	1.87	0.00	2.26	0.00	2.93
2.95	2.95	0.00	0.00	0.00	1.64	2.83	3.78	5.55	4.47
7.70	7.55	8.96	8.04	9.33	8.93	8.10	3.65	2.47	2.04
0.00	1.53	2.34	1.91	2.12	2.76	5.75	8.86	7.74	10.21
6.23	4.59	3.90	7.04	10.76	11.13	5.79	4.91	5.98	6.64
7.23	8.52	10.43	5.69	6.06	6.98	7.16	11.74	11.60	6.52
7.97	10.02	14.67	10.35	7.96	9.48	11.07	13.18	13.39	14.18
J54	12.33	7.98	8.53	9.79	8.57	7.64	7.72	6.54	9.56
6.42	5.83	6.05	4.92	8.57	5.47	5.21	4.15	4.78	8.20
8.30	12.59	8.21	7.66	4.07	4.38	7.76	7.69	6.65	5.61
2.88	2.67	2.71	2.87	3.21	3.55	4.42	4.33	5.68	7.00
7.03	7.66	6.29	4.85	2.55	2.29	0.00	1.63	0.00	1.92
2.26	3.87	1.53	0.00	0.00	0.00	1.19	2.13	4.33	3.79
5.76	6.33	7.74	6.82	8.11	8.26	9.02	4.57	3.38	0.00
0.00	0.00	0.00	0.00	1.65	1.89	4.53	7.64	6.52	8.99
7.15	4.87	4.18	5.82	9.54	9.91	6.07	5.82	4.75	5.41
6.01	7.30	9.21	5.97	6.10	5.76	5.94	10.52	10.38	6.80
6.75	8.80	13.45	10.88	6.74	8.26	9.85	11.95	12.17	12.96
J55	13.43	10.94	9.63	10.89	8.50	8.28	7.66	6.48	10.66
8.14	7.06	5.99	4.86	9.68	6.57	6.05	4.09	4.71	8.14
8.24	12.53	10.23	9.68	5.17	4.32	7.70	10.98	8.67	7.63
3.47	3.70	2.65	2.81	3.15	3.49	4.36	4.27	5.46	6.77
6.80	11.06	6.89	5.45	3.65	3.39	2.21	0.00	0.00	1.79
2.20	4.54	2.00	1.54	0.00	0.00	0.00	1.59	3.78	3.57
5.93	5.79	7.19	6.28	7.57	8.03	9.61	5.16	4.57	3.61
2.22	2.58	0.00	0.00	1.11	0.00	3.99	7.10	5.98	8.45
7.74	4.98	4.30	5.27	9.00	9.37	6.19	5.28	4.21	4.87
5.47	6.75	8.67	6.09	5.56	5.22	5.40	9.98	9.84	6.92
6.21	8.26	12.90	11.00	6.20	7.72	9.31	11.41	11.63	12.42
J56	13.68	11.19	9.89	11.14	8.76	8.54	7.91	6.74	14.69
8.40	7.32	6.25	5.11	13.70	6.82	6.30	3.38	4.75	6.78
6.87	12.79	10.48	9.93	5.42	4.57	6.33	11.23	8.93	7.89
4.09	3.96	2.91	2.25	3.06	2.87	4.40	3.64	4.81	6.13
6.16	11.32	11.45	8.09	3.91	3.64	2.90	0.00	0.00	0.00
0.00	4.80	3.05	2.14	1.19	0.00	0.00	0.00	2.60	2.92
4.89	5.20	5.34	5.69	6.98	7.39	12.25	7.80	4.83	3.86
2.47	2.84	1.69	1.23	1.37	0.00	3.40	6.52	5.39	7.86
10.38	5.24	4.55	4.69	8.41	8.79	6.44	5.54	4.47	5.13
5.73	6.17	8.08	6.34	5.81	5.47	5.65	10.24	10.10	7.17
6.47	8.51	12.25	11.25	6.46	7.98	9.56	11.67	11.88	12.68
J57	14.63	12.69	11.98	13.23	9.82	9.60	8.97	7.71	15.64
9.46	8.38	7.31	6.09	13.32	8.50	7.37	4.46	3.80	5.79
5.89	13.77	11.47	10.92	6.37	5.63	5.35	12.22	9.91	8.87
4.91	5.60	3.86	3.20	2.11	0.00	3.45	2.65	3.83	5.14

5.17	12.30	12.44	9.29	4.86	4.59	3.72	2.78	2.70	1.89
0.00	6.29	4.00	3.09	2.13	1.59	0.00	0.00	0.00	0.00
3.91	4.25	5.66	4.74	6.03	6.40	13.75	9.29	6.32	5.36
3.42	4.33	2.64	2.18	2.32	2.55	0.00	5.57	4.44	6.91
11.87	6.73	6.05	3.74	7.46	7.84	7.94	7.03	5.42	6.08
6.04	5.22	7.13	7.83	6.76	6.42	5.74	9.14	9.40	8.67
6.84	7.82	11.30	12.75	7.41	7.28	9.25	10.97	12.83	13.63
J58	19.29	12.47	13.17	17.49	11.02	10.79	10.17	8.91	15.96
10.65	9.57	8.50	7.28	14.98	9.70	8.56	5.66	5.00	5.91
6.01	14.96	12.66	12.11	7.83	6.83	5.47	13.41	11.10	10.07
8.35	6.80	5.31	4.40	3.31	2.47	4.64	2.77	3.93	5.25
5.28	13.50	13.63	9.37	6.32	6.05	5.33	4.23	4.30	3.56
2.73	6.08	5.81	5.61	3.78	3.24	2.60	0.00	0.00	0.00
0.00	0.00	3.67	2.76	4.05	5.29	13.53	9.08	6.11	5.14
5.23	4.12	3.41	3.29	3.08	3.57	0.00	0.00	3.85	6.10
11.66	6.52	5.83	3.52	6.65	7.02	7.72	6.81	5.75	6.41
5.82	5.00	6.31	7.62	7.09	6.75	5.52	8.32	9.18	8.45
6.62	7.60	10.48	12.53	7.73	7.06	9.03	10.76	13.16	13.95
J59	17.66	10.84	12.44	13.70	10.29	10.06	9.44	8.17	16.10
9.92	8.84	7.77	6.55	13.78	8.96	7.83	4.93	4.27	4.78
4.88	14.23	11.93	11.38	8.05	6.10	4.34	12.68	10.37	9.33
5.95	6.07	4.74	3.67	2.73	0.00	3.91	0.00	0.00	4.13
4.17	12.77	12.90	9.75	5.75	5.48	4.76	3.66	3.73	2.93
0.00	6.91	5.12	4.46	3.77	3.63	3.02	0.00	0.00	0.00
0.00	0.00	3.21	2.29	3.58	5.39	12.08	7.63	6.94	5.98
6.06	4.95	4.76	4.30	4.44	4.67	3.48	4.29	3.38	5.63
10.21	7.35	6.67	4.77	6.18	6.55	8.55	7.65	6.58	7.24
7.07	6.25	5.85	8.45	7.93	7.72	6.76	8.93	11.29	9.29
7.87	8.84	11.09	13.37	8.57	8.31	10.27	12.54	12.40	14.22
J60	19.80	12.99	14.59	15.84	12.43	12.21	11.58	10.32	18.25
12.07	10.99	9.92	8.69	15.92	11.11	9.97	7.07	5.84	5.18
5.28	16.38	14.07	13.52	10.20	8.24	4.74	14.82	12.52	11.48
11.20	8.21	6.70	5.81	4.69	3.64	4.67	0.00	0.00	2.72
2.90	14.91	15.04	11.89	9.68	7.43	6.71	5.62	5.68	4.88
4.12	8.15	7.88	7.68	5.73	5.58	4.98	3.89	0.00	0.00
0.00	0.00	0.00	0.00	2.40	4.13	15.60	11.15	8.18	7.21
7.30	6.19	5.48	5.36	5.15	5.64	3.18	3.10	2.20	4.45
13.73	8.59	7.90	3.69	5.00	5.37	9.79	8.88	7.82	7.75
7.06	6.24	4.67	9.69	9.16	7.71	6.76	6.67	9.04	10.52
7.86	8.84	8.84	14.60	9.80	8.30	10.27	10.29	13.28	11.97
J61	21.27	14.46	14.49	15.74	12.33	12.11	11.48	10.22	17.95
11.96	10.89	9.81	8.59	16.97	11.01	9.87	6.97	5.74	5.08
5.18	16.28	13.97	13.42	10.10	8.14	4.64	14.72	12.42	11.38
10.34	8.11	6.57	5.71	4.56	3.51	4.57	2.76	2.97	4.13
4.32	14.81	14.94	11.79	9.58	9.01	8.35	5.49	5.56	4.76
3.99	8.06	7.79	7.59	6.35	5.81	5.23	4.28	0.00	0.00
0.00	0.00	0.00	0.00	0.00	4.23	15.52	11.06	8.09	7.13
7.21	6.10	5.39	5.28	5.07	5.55	3.09	0.00	0.00	5.03
13.64	8.50	7.82	4.37	5.58	5.95	9.70	8.80	7.73	7.36
6.68	5.85	5.25	9.60	9.08	7.33	6.37	7.25	9.62	10.44
7.48	8.45	9.42	14.51	9.72	7.92	9.88	10.87	12.01	12.55
J62	22.68	15.87	15.03	16.29	12.87	12.65	12.02	10.76	18.69
12.51	11.43	10.36	9.14	16.37	11.55	10.42	7.51	6.29	5.63
6.03	16.82	14.52	13.97	10.64	8.68	6.29	15.27	12.96	11.92
11.75	8.66	7.14	6.25	5.13	4.08	5.12	3.30	0.00	0.00
0.00	15.35	15.49	12.34	10.13	7.88	7.16	6.06	6.13	5.33

4.56	9.47	9.20	9.00	6.17	7.22	5.42	4.34	3.68	3.21
0.00	0.00	0.00	0.00	0.00	0.00	16.93	12.47	9.50	8.54
8.62	7.51	6.80	6.69	6.48	6.97	4.50	3.57	2.67	3.43
15.05	9.91	9.23	4.16	4.85	4.27	11.12	10.21	9.14	8.21
7.53	6.71	4.47	11.01	10.49	8.18	7.23	5.65	8.02	11.85
8.33	9.60	7.82	15.93	9.76	8.77	10.74	9.27	12.26	10.95
J63	21.74	14.93	14.98	16.24	12.83	12.60	11.98	10.71	18.42
12.46	11.38	10.31	9.09	17.44	11.51	10.37	7.46	6.24	5.58
5.68	16.77	14.47	13.92	10.60	8.64	5.14	15.22	12.91	11.87
10.81	8.61	7.09	6.21	5.09	4.04	5.07	3.25	1.95	3.11
3.30	15.31	15.44	12.29	10.08	7.83	8.82	6.01	6.08	5.28
4.51	8.53	8.26	8.06	6.12	6.28	5.70	4.75	2.74	2.27
0.00	0.00	0.00	0.00	1.66	2.80	15.99	11.53	8.56	7.60
7.68	6.57	5.86	5.75	5.54	6.02	3.13	2.36	1.46	3.71
14.11	8.97	8.28	2.95	4.26	4.63	10.17	9.27	8.20	7.01
6.32	5.50	3.93	10.07	9.55	6.97	6.02	5.94	8.30	10.91
7.12	8.10	8.10	14.98	8.55	7.56	9.53	9.55	12.54	11.23
J64	23.03	16.21	16.27	17.53	14.12	13.89	13.27	12.00	19.71
13.75	12.67	11.60	10.38	18.73	12.79	11.66	8.75	7.53	6.87
6.97	18.06	15.76	15.21	11.88	9.93	6.43	16.51	14.20	13.16
12.10	9.90	8.38	7.50	6.37	5.33	6.36	4.54	3.24	4.40
0.00	16.60	16.73	13.58	11.37	9.12	10.10	7.30	7.37	6.57
5.80	9.82	9.55	9.35	7.41	7.57	6.99	6.04	4.02	3.56
2.40	0.00	0.00	1.66	0.00	0.00	17.27	12.82	9.85	8.89
8.97	7.86	7.15	7.03	6.83	7.31	3.14	0.00	0.00	0.00
15.40	10.26	9.57	2.96	2.99	3.36	11.46	10.56	9.49	7.02
6.33	5.51	2.66	11.36	8.90	6.98	6.03	4.67	7.03	12.19
7.13	8.11	6.83	16.27	8.56	7.57	9.54	8.28	11.28	9.96
J65	22.32	15.50	17.11	18.36	14.95	14.72	14.10	12.84	20.76
14.58	13.50	12.43	11.21	18.44	13.63	12.49	9.59	8.36	7.70
6.93	18.90	16.59	16.04	12.72	10.76	7.19	17.34	15.03	14.00
13.72	10.73	9.22	8.33	7.21	6.16	7.19	5.17	3.93	3.15
0.00	17.43	17.56	14.41	12.20	9.95	9.23	8.13	8.20	7.40
6.64	12.28	12.01	8.93	8.25	8.10	7.50	6.41	5.31	5.40
4.12	4.24	0.00	2.81	0.00	0.00	21.14	15.29	12.31	11.35
11.43	10.32	9.61	9.50	9.29	9.78	5.17	3.14	3.33	0.00
17.86	12.72	12.04	4.98	3.85	2.40	13.93	12.29	11.95	
9.04	8.36	7.54	3.47	13.19	11.05	9.86	8.05	4.66	7.02
13.46	9.28	8.60	6.82	15.69	10.71	9.72	11.04	8.27	11.26
9.95									
J66	16.77	9.96	14.92	14.97	14.35	14.41	14.49	15.89	9.54
13.25	14.71	13.90	14.26	9.60	13.18	11.49	13.50	15.07	17.56
17.66	7.67	8.17	8.13	8.88	12.22	17.12	6.11	7.92	8.66
8.47	9.60	10.46	13.47	14.67	15.22	14.71	15.89	17.31	18.69
20.17	4.32	5.63	6.58	8.45	9.09	8.04	9.87	9.52	10.24
10.53	8.48	7.92	8.20	9.03	9.61	12.23	13.71	13.49	12.08
15.64	15.50	16.90	15.99	17.28	21.40	0.00	5.23	8.57	9.76
8.57	10.06	10.93	11.44	10.93	11.72	13.70	16.81	15.69	18.16
0.00	8.06	8.82	15.06	17.68	19.43	7.47	8.19	11.68	11.59
12.19	13.87	17.56	7.73	9.89	11.12	12.11	15.88	15.74	
8.82	12.11	14.16	18.81	10.87	12.08	13.62	15.19	17.32	17.51
18.30									
J67	12.32	5.50	10.47	10.52	9.89	9.96	10.04	10.26	9.00
8.80	10.26	8.27	8.64	8.01	8.73	7.04	7.87	9.44	11.93
12.03	7.66	6.46	5.91	4.42	6.60	11.49	6.11	4.91	3.87
0.00	5.15	6.01	7.85	9.04	9.60	9.08	10.26	11.69	13.07

14.54	4.94	3.57	0.00	4.00	4.64	3.58	5.42	5.07	5.78
6.07	0.00	3.47	3.75	4.57	5.15	7.78	9.26	9.04	7.63
11.19	11.05	12.45	11.54	12.83	15.77	5.23	0.00	4.12	5.31
4.12	5.61	6.48	6.99	6.48	7.27	9.25	12.36	11.23	13.71
3.36	3.60	5.30	10.53	15.96	14.63	5.75	6.47	9.97	9.87
10.47	12.15	13.92	6.02	8.18	9.41	10.39	14.17	14.03	
7.11	10.40	12.45	17.09	9.14	10.37	11.91	13.48	15.60	15.80
16.59									
J68	14.24	7.42	9.19	12.43	11.81	8.29	11.95	9.50	10.91
7.08	6.48	7.44	7.68	9.93	6.13	5.86	6.89	8.62	11.11
11.21	9.82	8.87	8.32	4.73	5.20	10.67	8.35	7.31	6.27
2.84	3.97	4.83	5.84	7.92	7.68	8.26	8.46	9.72	11.04
11.07	7.10	5.73	4.29	2.82	3.46	2.39	4.24	3.41	4.61
7.35	0.00	0.00	2.57	3.40	4.53	4.78	6.26	6.05	6.88
8.20	8.05	9.46	8.54	9.83	12.30	8.46	4.01	0.00	0.00
2.94	2.62	3.48	3.99	3.49	4.27	6.25	9.37	8.24	10.72
6.59	2.99	2.32	7.54	11.26	11.64	4.21	4.29	6.48	7.14
7.74	9.02	10.93	4.11	6.00	7.23	7.66	11.99	11.85	4.94
8.22	10.27	14.91	9.01	8.19	9.73	11.30	13.42	13.62	14.41
J69	15.54	8.72	13.69	13.73	13.11	13.18	13.25	8.86	12.21
7.57	6.98	6.80	7.04	11.23	6.62	6.36	6.25	8.66	10.75
10.84	13.69	9.68	9.13	5.22	5.12	10.30	9.16	8.12	7.08
4.60	3.83	4.19	5.19	6.97	6.73	8.30	7.51	8.77	10.08
10.12	8.42	7.05	5.61	3.71	3.44	2.18	3.83	3.49	4.10
6.40	2.32	0.00	2.03	0.00	2.39	2.89	5.31	5.10	5.93
7.25	7.10	8.51	7.59	8.88	11.34	9.78	5.33	0.00	0.00
0.00	0.00	2.53	1.97	2.54	3.32	5.30	8.41	7.29	9.76
7.91	2.76	0.00	6.59	10.31	10.68	3.97	4.05	5.53	6.19
6.78	8.07	9.98	3.87	5.75	6.53	6.71	11.29	11.15	4.70
7.52	9.57	14.22	8.78	7.51	9.03	10.62	12.73	12.94	13.73
J70	12.25	7.59	8.45	9.71	8.52	7.55	7.67	8.07	9.48
6.34	5.74	6.00	6.25	8.49	5.39	5.12	5.45	7.19	9.68
9.78	10.00	8.13	7.58	3.99	4.33	9.24	7.61	6.57	5.53
2.57	3.04	3.40	4.40	4.62	4.96	6.83	5.74	9.02	10.34
10.37	7.28	5.91	4.47	2.55	2.21	1.31	3.04	2.70	3.72
4.19	3.48	0.00	0.00	0.00	2.14	2.63	3.58	5.35	6.19
7.50	7.35	8.76	7.85	9.13	11.60	8.64	4.18	3.00	0.00
0.00	0.00	2.04	1.71	1.92	2.56	5.56	8.67	7.54	10.02
6.76	4.39	3.71	6.84	10.57	10.94	5.59	4.72	5.78	6.44
7.04	8.32	10.23	5.49	5.86	6.79	6.96	11.55	11.41	6.33
7.78	9.82	14.47	10.41	7.77	9.29	10.87	12.98	13.19	13.99
J71	15.84	9.02	9.19	14.04	13.42	8.29	7.96	8.36	12.52
7.07	6.48	6.30	6.54	11.53	6.12	5.86	5.75	7.59	9.68
9.78	13.99	9.98	9.43	4.72	4.62	9.23	9.47	8.43	7.39
3.54	3.33	3.69	4.69	5.90	5.66	7.24	6.44	7.70	9.02
9.05	8.73	7.36	5.92	3.21	2.94	2.28	3.33	2.99	3.97
5.33	2.63	1.72	1.53	0.00	2.51	2.76	4.24	4.03	4.86
6.18	6.03	7.44	6.52	7.81	10.27	10.08	5.63	2.66	0.00
0.00	0.00	0.00	1.97	0.00	2.25	4.23	7.35	6.22	8.69
8.21	3.07	0.00	5.52	9.24	9.62	4.27	3.39	4.46	5.12
5.72	7.00	8.91	4.17	4.54	5.46	5.64	10.23	10.09	5.00
6.45	8.50	13.15	9.08	6.45	7.97	9.55	11.66	11.87	12.67
J72	16.71	9.89	10.02	14.90	14.28	9.33	8.70	7.52	13.38
7.91	7.32	7.04	5.90	12.40	6.96	6.70	5.13	5.76	9.09
9.19	14.86	10.85	10.30	5.56	5.36	8.65	10.33	9.29	8.25
4.37	4.16	3.70	3.86	4.20	4.54	5.40	5.31	7.11	8.43

8.46	9.59	8.22	6.78	4.04	3.78	3.11	2.61	2.66	2.90
3.25	3.49	2.56	2.36	0.00	0.00	1.69	2.64	3.44	4.28
5.59	5.44	6.85	5.94	7.22	9.69	10.95	6.50	3.53	2.56
1.98	0.00	0.00	0.00	0.00	1.18	3.65	6.76	5.63	8.11
9.08	3.93	3.25	4.93	8.66	9.03	5.14	4.23	3.87	4.53
5.13	6.41	8.32	5.04	5.21	4.88	5.05	9.64	9.50	5.87
5.87	7.92	12.56	9.95	5.86	7.38	8.96	11.07	11.28	12.08
J73	13.37	10.12	9.58	10.83	8.99	8.77	8.14	6.97	13.61
7.47	6.87	6.48	5.34	12.63	6.51	6.53	4.58	5.20	8.63
8.73	13.02	9.26	8.71	5.11	4.80	8.19	11.47	7.70	6.66
3.93	4.19	3.14	3.30	3.64	3.98	4.84	4.75	6.11	7.42
7.45	11.55	7.34	5.90	3.60	3.34	2.67	2.06	2.10	2.34
2.69	3.72	2.12	1.92	0.00	0.00	1.13	2.08	3.58	4.22
5.73	5.58	6.99	6.08	7.36	8.68	10.07	5.62	3.76	1.97
1.54	1.46	0.00	0.00	0.00	0.00	3.79	6.90	5.77	8.25
8.20	4.16	3.48	5.07	8.80	9.17	5.37	4.46	4.01	4.67
5.27	6.55	8.46	5.27	5.35	5.02	5.19	9.78	9.64	6.10
6.01	8.06	12.70	10.18	6.00	7.52	9.10	11.21	11.42	12.22
J74	16.71	9.89	14.86	14.91	9.23	9.00	8.38	7.20	13.39
7.68	7.78	6.71	5.58	12.40	6.72	6.77	4.81	5.44	8.87
8.96	13.25	10.85	10.30	5.32	5.04	8.42	10.34	9.30	8.26
4.14	4.43	3.37	3.54	3.87	4.22	5.08	4.99	7.12	8.43
8.46	9.60	8.23	6.79	3.81	3.55	2.88	2.29	2.34	2.58
2.93	3.50	2.33	2.13	1.65	1.11	1.37	2.32	3.45	4.28
5.60	5.45	6.86	5.94	7.23	9.69	10.95	6.50	3.53	2.56
1.75	0.00	0.00	0.00	0.00	0.00	3.65	6.76	5.64	8.11
9.08	3.94	3.25	4.93	8.66	9.03	5.14	4.24	3.87	4.53
5.13	6.42	8.33	5.04	5.22	4.88	5.06	9.64	9.50	5.87
5.87	7.92	12.56	9.95	5.86	7.38	8.97	11.07	11.29	12.08
J75	17.50	10.68	10.39	15.70	9.46	9.24	8.61	7.44	14.18
9.10	8.02	6.95	5.82	13.19	7.33	7.01	5.05	5.67	9.18
9.28	13.49	11.64	11.09	5.93	5.27	8.74	11.94	10.09	9.05
4.74	4.66	3.61	3.77	4.11	5.16	5.31	5.94	7.20	8.52
8.55	10.39	9.02	7.58	4.41	4.15	3.48	2.53	2.57	2.81
3.16	4.29	2.93	2.73	1.89	0.00	0.00	2.55	3.53	4.36
5.68	5.53	6.94	6.02	7.31	9.78	11.74	7.29	4.32	3.35
2.35	2.33	1.18	0.00	0.00	0.00	3.74	6.85	5.72	8.20
9.87	4.73	4.04	5.02	8.75	9.12	5.93	5.03	3.96	4.62
5.22	6.50	8.41	5.83	5.30	4.96	5.14	9.73	9.59	6.66
5.96	8.00	12.65	10.74	5.95	7.47	9.05	11.16	11.37	12.17
J76	19.44	12.63	17.60	17.64	11.82	11.60	10.97	9.71	16.12
11.46	10.38	9.31	8.09	15.14	10.36	9.37	6.47	5.81	6.46
6.56	15.77	13.59	13.04	8.96	7.63	6.02	14.22	12.03	10.99
8.51	7.61	6.24	5.21	4.11	3.88	5.95	4.14	4.72	5.88
6.06	12.33	10.96	9.52	7.45	7.18	6.52	5.16	5.21	4.37
3.54	6.23	5.96	5.76	4.52	3.98	3.41	0.00	0.00	2.58
3.87	2.82	4.35	3.13	3.14	5.17	13.69	9.24	6.26	5.30
5.39	4.27	3.56	3.45	3.24	3.73	0.00	2.90	2.56	4.25
11.82	6.67	5.99	0.00	4.80	5.17	7.88	6.97	5.90	4.88
4.19	3.37	4.46	7.78	7.25	4.84	3.89	6.47	7.55	8.61
4.99	5.97	8.63	12.69	6.42	5.43	7.40	10.09	9.53	10.32
J77	22.56	15.74	16.98	20.75	14.82	14.60	13.97	12.71	19.23
14.46	13.38	12.31	11.08	18.25	13.50	12.36	9.46	8.23	7.57
8.82	18.77	16.46	15.91	12.59	10.63	9.08	17.21	14.91	13.87
11.62	10.60	9.09	8.20	7.08	6.03	7.06	5.25	3.95	5.03
4.62	17.30	17.43	12.63	10.56	10.30	9.63	8.01	8.07	7.27

6.51	9.34	9.08	8.88	7.64	7.09	6.52	5.57	0.00	4.26
3.10	0.00	3.58	2.36	0.00	3.03	16.80	12.35	9.38	8.41
8.50	7.39	6.67	6.56	6.35	6.84	2.90	0.00	0.00	0.00
14.93	9.79	9.10	0.00	0.00	3.03	10.99	10.08	9.02	6.77
6.09	5.27	0.00	10.89	8.66	6.74	5.79	3.57	5.93	11.07
6.89	7.51	5.73	15.80	8.32	7.33	9.30	7.18	10.18	8.86
J78	21.45	14.63	16.07	19.64	13.92	13.69	13.07	11.80	18.12
13.55	12.47	11.40	10.18	17.14	12.60	11.46	8.55	7.33	6.67
6.77	17.86	15.56	15.01	11.69	9.73	6.23	16.31	14.00	12.97
10.51	9.70	8.18	7.30	6.18	5.13	6.16	4.34	3.05	4.20
4.39	16.40	16.53	13.38	11.17	9.19	8.52	7.10	7.17	6.37
5.61	8.23	7.97	7.77	6.53	5.98	5.41	4.46	3.83	3.36
2.20	0.00	2.68	1.46	0.00	3.33	15.69	11.24	8.27	7.30
7.39	6.27	5.56	5.45	5.24	5.73	2.56	0.00	0.00	0.00
13.82	8.68	7.99	2.38	2.96	3.33	9.88	8.97	7.91	6.43
5.75	4.93	2.62	9.78	8.32	6.40	5.45	4.63	6.99	10.61
6.55	7.53	6.79	14.69	7.98	6.99	8.96	8.25	11.24	9.92
J79	23.91	17.09	18.42	19.67	16.26	16.04	15.41	14.15	20.58
15.90	14.82	13.75	12.52	19.60	14.94	13.80	10.90	9.68	9.01
8.25	20.21	17.90	17.35	14.03	12.07	8.51	18.66	16.35	15.31
12.97	12.04	10.53	9.64	8.52	7.47	8.50	6.48	5.24	4.46
4.05	18.74	18.87	15.72	13.51	11.64	10.98	9.45	9.51	8.71
7.95	10.69	10.42	10.23	8.98	8.44	7.87	6.92	6.08	5.61
4.45	5.01	3.44	3.71	0.00	0.00	18.15	13.70	10.73	9.76
9.85	8.73	8.02	7.91	7.70	8.19	4.25	0.00	0.00	0.00
16.28	11.13	10.45	4.07	0.00	0.00	12.34	11.37	10.36	
8.12	7.44	6.62	2.55	12.27	10.13	8.09	7.14	3.74	6.10
12.54	8.36	7.68	5.90	14.77	9.79	8.80	10.12	7.35	10.35
9.03									
J80	14.90	8.09	13.06	13.10	12.48	12.55	12.62	12.85	11.58
11.38	12.85	10.86	11.22	10.60	11.31	9.62	10.46	12.03	14.52
14.62	7.48	7.98	7.94	7.01	9.18	14.07	5.93	7.49	6.45
6.60	7.73	8.59	10.43	11.62	12.18	11.67	12.84	14.27	15.65
17.13	4.14	5.45	4.71	6.58	7.22	6.17	8.00	7.65	8.37
8.66	6.61	6.05	6.33	7.16	7.74	10.36	11.84	11.63	10.21
13.78	13.63	15.04	14.12	15.41	18.36	0.00	3.37	6.70	7.89
6.70	8.20	9.06	9.57	9.07	9.85	11.83	14.94	13.82	16.29
0.00	6.19	7.89	13.12	17.23	17.21	7.02	7.74	11.23	11.14
11.74	13.42	17.11	7.28	9.44	10.67	11.66	15.43	15.30	
8.37	11.66	13.71	18.36	11.73	11.64	13.18	14.74	16.87	17.06
17.86									
J81	13.79	6.97	11.94	11.99	11.37	11.43	11.51	11.73	10.47
10.27	11.73	9.74	10.11	9.49	10.20	8.24	9.34	10.91	13.41
13.50	11.94	7.93	7.39	5.90	8.07	12.96	7.42	6.38	5.34
5.22	6.35	7.21	9.32	8.37	8.14	10.55	8.91	10.17	11.49
11.52	6.68	5.31	3.87	5.20	5.84	4.76	6.16	6.03	6.45
7.80	0.00	4.76	4.56	4.85	4.98	5.24	6.72	6.50	7.34
8.65	8.51	9.91	9.00	10.29	12.75	8.03	3.58	2.97	2.77
4.18	3.07	3.94	4.45	3.94	4.73	6.71	9.82	8.69	11.17
6.16	0.00	0.00	7.99	11.72	12.09	0.00	4.36	6.93	7.59
8.19	9.47	11.38	3.91	6.07	7.30	8.11	12.06	11.92	5.00
8.29	10.34	14.98	7.03	8.26	9.80	11.37	13.49	13.69	14.48
J82	15.47	8.65	13.62	13.67	13.04	13.11	13.19	11.22	12.14
11.95	8.20	9.16	9.40	11.16	7.84	7.58	11.02	12.59	15.08
15.18	13.62	9.61	9.06	6.44	6.92	14.64	9.10	8.06	7.02
4.56	5.69	6.55	7.55	7.70	7.47	12.23	8.24	9.50	10.82

10.85	8.35	6.99	5.55	4.54	5.18	4.10	5.49	5.35	5.78
7.13	0.00	4.01	3.89	4.18	4.31	4.56	6.05	5.83	6.67
7.98	7.83	9.24	8.33	9.62	12.08	8.82	5.26	2.32	0.00
3.51	0.00	3.27	3.78	3.27	4.05	6.04	9.15	8.02	10.50
7.84	0.00	0.00	7.32	11.46	11.42	0.00	0.00	5.47	5.37
5.97	7.65	11.34	1.79	3.67	4.91	5.89	9.67	9.53	2.62
5.90	7.94	12.59	4.85	5.87	7.41	8.97	11.10	11.29	12.09
J83	20.73	13.91	18.88	18.93	13.11	12.89	12.26	11.00	17.41
12.74	11.67	10.60	9.37	16.42	11.64	10.65	7.75	7.09	8.06
8.15	17.06	14.87	14.32	10.24	8.92	7.61	15.50	13.32	12.28
9.79	8.89	7.53	6.49	5.40	5.16	6.73	5.73	4.54	5.69
5.88	13.61	12.25	10.81	8.73	8.47	7.80	6.45	6.49	5.65
4.83	7.52	7.25	7.05	5.81	5.27	4.69	3.74	3.53	3.33
3.69	4.25	4.17	2.95	2.96	4.99	14.97	10.52	7.55	6.58
6.67	5.56	4.85	4.73	4.53	5.01	0.00	0.00	2.38	4.07
13.10	7.96	7.27	0.00	4.61	4.99	9.16	7.12	5.65	3.99
3.31	0.00	4.28	8.01	5.87	3.96	3.00	6.29	6.67	8.29
4.11	5.08	8.45	10.52	5.53	4.55	6.51	8.24	8.64	9.44
J84	23.95	17.13	18.46	19.71	16.30	16.08	15.45	14.19	20.62
15.94	14.86	13.79	12.57	19.64	14.98	13.85	10.94	9.72	9.06
8.29	20.25	17.95	17.40	14.07	12.11	8.55	18.70	16.39	15.35
13.01	12.08	10.57	9.68	8.56	7.51	8.54	6.52	5.28	4.50
4.09	18.78	18.92	15.77	13.56	11.31	10.58	9.49	9.56	8.75
7.99	10.73	10.47	10.27	9.60	8.48	8.85	6.96	6.12	6.76
4.49	5.05	3.49	3.75	2.49	2.50	18.19	13.74	10.77	9.80
9.89	8.78	8.07	7.95	7.74	8.23	4.29	0.00	2.45	0.00
16.32	11.18	10.49	4.11	0.00	1.75	12.38	11.47	10.41	
8.16	7.48	6.66	0.00	12.28	9.82	8.13	7.18	3.43	5.80
12.24	8.05	7.38	5.59	17.19	9.48	8.72	10.69	7.05	10.04
8.72									
J85	24.83	18.01	24.51	25.77	22.36	22.13	21.51	20.24	28.17
21.99	20.91	19.84	18.62	25.85	21.04	19.90	17.05	10.51	9.85
9.09	26.30	24.00	23.45	20.13	18.17	9.34	24.75	22.44	21.40
13.89	18.14	18.11	15.80	9.36	8.31	9.34	7.32	6.08	5.30
4.88	24.84	24.97	21.82	19.61	19.19	11.90	10.29	10.35	9.55
8.79	11.61	11.35	11.15	10.40	9.36	8.79	7.84	7.00	6.53
5.37	5.93	4.28	4.63	3.37	2.40	19.48	14.62	11.65	10.68
10.77	9.66	8.94	8.83	8.62	9.11	5.17	3.14	3.33	0.00
17.20	12.06	11.37	4.99	3.11	0.00	12.89	11.54	11.29	
9.04	8.36	7.54	2.72	12.44	10.30	9.11	8.06	3.91	6.27
12.71	8.53	7.85	6.07	14.94	9.96	8.97	10.29	7.53	10.52
9.20									
J86	15.95	9.13	14.10	14.14	13.52	13.59	13.66	13.89	12.62
12.42	13.89	11.90	12.26	11.64	12.36	9.43	11.50	13.07	15.56
15.66	14.10	10.09	9.54	8.05	10.22	15.12	9.57	8.53	7.49
6.41	7.54	8.40	11.47	9.55	9.32	12.71	10.09	11.35	12.67
12.70	8.76	7.46	6.02	6.39	7.03	5.95	7.34	7.20	7.62
8.98	4.13	5.86	5.74	6.03	6.16	6.41	7.90	7.68	8.51
9.83	9.68	11.09	10.17	11.46	13.65	7.47	5.74	4.16	3.95
5.36	4.25	5.12	5.62	5.12	5.90	7.89	11.00	9.87	12.73
7.02	0.00	0.00	8.53	11.15	12.90	0.00	1.66	5.15	5.06
5.66	7.34	11.03	0.00	3.36	4.59	5.58	9.35	9.21	2.31
5.58	7.63	12.28	4.96	5.56	7.09	8.66	10.79	10.98	11.78
J87	16.42	9.60	14.57	14.61	13.99	14.06	14.13	14.36	13.09
12.89	14.36	12.37	12.74	12.11	12.83	9.37	11.97	13.54	16.03
16.13	14.57	10.56	10.01	8.52	10.69	15.59	10.05	9.00	7.96

6.34	7.47	8.33	11.94	8.91	8.67	13.18	9.45	10.71	12.02	
12.06	9.23	7.93	6.49	6.32	6.96	5.89	6.70	6.58	6.98	
8.34	4.07	5.32	5.12	5.41	5.52	5.77	7.25	7.04	7.87	
9.19	9.04	10.45	9.53	10.82	12.47	7.94	6.21	4.10	3.88	
4.74	3.63	4.47	4.98	4.48	5.26	7.24	10.14	9.23	11.55	
7.49	4.48	0.00	7.35	9.97	11.72	1.35	0.00	0.00	3.88	
4.48	6.16	9.85	0.00	0.00	3.41	4.40	8.17	8.03	0.00	
4.40	6.45	11.10	3.96	4.38	5.91	7.48	9.61	9.80	10.59	
J88	19.67	12.85	17.82	17.87	17.24	12.10	11.47	10.30	16.35	15.42
11.54	10.88	9.81	8.67	15.36	10.59	9.87	7.91	9.29	11.38	
11.48	17.82	13.81	13.26	9.18	8.13	10.93	13.30	12.26	11.22	
8.73	7.52	6.47	6.63	7.60	7.36	8.93	8.14	9.40	10.72	
10.75	12.55	11.19	9.75	7.67	7.41	6.74	5.39	5.43	5.67	
6.02	6.46	6.19	5.99	4.75	4.21	4.46	5.94	5.73	6.56	
7.88	7.73	9.14	8.22	9.51	11.97	12.03	9.46	6.49	5.52	
5.61	4.50	3.79	3.67	3.47	3.95	5.93	9.05	7.92	10.39	
12.04	6.90	6.21	5.83	9.68	11.32	5.45	0.00	0.00	0.00	
3.39	4.64	9.56	4.99	0.00	0.00	3.31	7.89	7.75	5.29	
4.11	6.16	10.81	7.52	4.11	5.63	7.21	9.32	9.53	10.33	
J89	20.60	13.79	18.76	18.80	18.18	18.25	12.18	11.00	17.28	16.36
12.24	11.58	10.51	9.38	16.30	11.29	10.57	8.61	10.00	10.99	
11.09	18.75	14.75	14.20	9.89	8.84	10.54	14.23	13.19	12.15	
9.44	8.23	7.17	7.33	8.30	8.07	9.64	8.84	8.54	9.70	
9.89	13.42	12.12	10.68	8.38	8.11	7.45	6.09	6.14	6.38	
6.72	7.16	6.89	6.69	5.45	4.91	5.17	6.65	6.43	7.27	
7.69	7.34	8.18	6.96	6.97	8.99	12.13	10.40	7.19	6.23	
6.31	5.20	4.49	4.38	4.17	4.66	5.11	6.72	6.38	8.07	
11.68	7.60	6.92	3.94	7.92	8.99	5.54	4.19	0.00	0.00	
0.00	2.74	7.80	5.08	0.00	0.00	0.00	6.12	5.98	5.36	
2.35	4.48	9.05	7.59	3.22	3.63	5.39	7.56	9.01	9.81	
J90	21.20	14.39	19.36	19.40	18.78	18.85	12.78	11.60	17.88	16.96
12.84	12.18	11.11	9.98	16.90	11.89	11.17	9.21	9.34	10.31	
10.40	19.35	15.35	14.80	10.49	9.44	9.86	14.83	13.79	12.75	
10.04	8.83	7.77	7.93	7.65	7.41	8.98	7.98	7.86	9.02	
9.20	14.02	12.72	11.28	8.97	8.71	8.05	6.69	6.73	6.98	
7.08	7.76	7.49	7.29	6.05	5.51	5.76	5.99	5.78	7.02	
7.01	6.66	7.49	6.27	6.28	8.31	12.72	10.99	7.79	6.83	
6.91	5.80	5.09	4.98	4.77	5.25	4.43	6.04	5.70	7.39	
12.28	8.20	7.51	3.26	7.00	8.31	6.14	4.79	3.15	0.00	
0.00	0.00	6.88	5.68	3.54	0.00	0.00	5.20	5.06	5.96	
2.63	3.48	8.13	8.19	3.50	2.94	4.91	6.64	7.04	7.83	
J91	22.23	15.42	20.38	20.43	14.61	14.39	13.76	12.50	18.91	17.98
14.25	13.17	12.10	10.88	17.93	13.15	12.16	9.25	8.59	9.56	
9.65	18.56	16.38	15.83	11.75	10.42	9.11	17.01	14.82	13.78	
11.30	10.39	9.03	7.99	6.90	6.66	8.24	7.23	7.11	8.27	
8.46	15.12	13.75	12.31	10.23	9.97	9.31	7.95	7.99	7.15	
6.33	9.02	8.75	8.55	7.31	6.77	6.19	5.24	5.03	6.28	
6.26	5.91	6.75	5.53	5.53	7.56	13.85	12.02	9.05	8.09	
8.17	7.06	6.35	6.24	6.03	6.51	3.68	5.29	4.95	6.64	
14.60	9.46	8.77	0.00	7.40	7.56	7.27	5.92	4.44	2.79	
0.00	0.00	6.86	6.81	4.67	2.75	0.00	5.60	0.00	7.09	
0.00	0.00	8.52	9.32	4.33	3.34	5.31	7.03	7.44	8.23	
J92	24.09	17.28	19.27	22.29	17.12	16.89	16.27	15.00	20.77	19.85
16.75	15.67	14.60	13.38	19.79	15.80	14.66	11.75	10.53	9.87	
9.10	21.06	18.76	18.21	14.89	12.93	9.36	19.51	17.20	16.16	
13.16	12.90	11.38	10.50	9.38	8.33	9.36	7.34	6.10	5.32	

4.90	19.60	19.73	14.17	12.10	11.83	11.17	10.30	10.37	9.57
8.80	10.88	10.61	10.41	9.17	8.63	8.06	7.11	6.26	5.80
4.64	5.20	4.30	3.90	2.63	3.31	17.64	13.88	10.91	9.95
10.03	8.92	8.21	8.10	7.89	8.38	4.44	0.00	2.60	2.39
16.46	11.32	10.64	4.25	0.00	2.57	11.05	9.70	9.43	7.88
6.91	6.81	0.00	10.59	8.45	7.26	6.61	2.06	4.43	10.87
6.69	6.01	4.23	13.10	8.11	7.13	8.44	5.68	8.67	7.36
J93	16.44	9.62	14.59	14.64	14.02	14.08	14.16	14.38	13.12
12.92	14.38	12.39	12.76	12.13	12.85	9.40	11.99	13.56	16.05
16.15	14.59	10.58	10.03	8.54	10.72	15.61	10.07	9.03	7.99
6.38	7.51	8.37	11.97	9.60	9.36	13.20	10.14	11.40	12.72
12.75	9.26	7.96	6.52	6.36	7.00	5.93	7.39	7.27	7.67
9.03	4.11	6.01	5.81	6.10	6.21	6.46	7.94	7.73	8.56
9.88	9.73	11.14	10.22	11.51	13.16	7.96	6.23	4.14	3.92
5.43	4.32	5.16	5.67	5.17	5.95	7.93	10.83	9.92	12.24
7.51	4.52	1.82	8.05	10.66	12.41	0.00	0.00	4.66	4.57
5.17	6.85	10.54	0.00	2.85	4.10	5.09	8.87	8.73	0.00
5.37	6.84	11.79	3.28	4.40	6.30	7.48	10.30	9.80	10.60
J94	17.66	10.85	15.81	15.86	15.24	15.30	15.38	15.60	14.34
14.14	15.60	13.62	13.98	13.36	14.07	9.73	13.21	14.78	17.28
17.37	15.81	11.81	11.26	9.77	11.94	16.83	11.29	10.25	9.21
7.59	7.20	7.56	8.19	9.16	8.92	14.43	9.70	10.96	12.28
12.31	10.48	9.18	7.74	7.57	6.82	6.15	6.95	6.86	7.23
7.58	5.31	5.60	5.40	5.69	5.77	6.02	7.50	7.29	8.12
9.44	9.29	10.70	9.78	9.27	11.78	9.18	7.45	5.34	4.92
5.02	3.91	4.75	5.23	5.03	5.51	7.49	9.03	8.69	10.86
8.73	5.73	3.03	6.24	9.28	11.03	2.60	0.00	0.00	0.00
3.80	5.05	9.16	2.14	0.00	0.00	3.72	7.48	7.34	0.00
3.71	5.76	10.41	5.20	3.69	5.22	6.79	8.92	9.11	9.91
J95	19.60	12.78	17.75	17.80	17.18	17.24	17.32	10.72	16.28
16.08	11.30	10.23	9.10	15.29	11.01	10.29	8.33	9.72	10.96
11.05	17.75	13.74	13.19	9.61	8.56	10.51	13.23	12.19	11.15
9.16	7.94	6.89	7.05	8.02	7.79	9.36	8.56	8.51	9.67
9.85	12.42	11.12	9.68	8.09	7.83	7.17	5.81	5.85	6.10
6.44	6.88	6.61	6.41	5.17	4.63	4.88	6.37	6.15	6.99
7.66	7.31	8.14	6.92	6.93	8.96	11.12	9.39	6.91	5.95
6.03	4.92	4.21	4.10	3.89	4.37	5.08	6.69	6.35	8.04
10.67	7.32	4.97	3.91	7.31	9.06	4.54	3.18	0.00	0.00
0.00	2.71	7.19	4.08	0.00	0.00	0.00	5.51	5.37	4.36
0.00	3.79	8.43	6.58	2.67	3.25	4.84	6.94	7.99	8.79
J96	21.13	14.31	19.28	19.32	18.70	18.77	12.70	11.52	17.80
12.76	12.11	11.03	9.90	16.82	11.81	11.09	9.13	9.04	10.00
10.10	19.28	15.27	14.72	10.41	9.36	9.56	14.75	13.71	12.67
9.96	8.75	7.70	8.44	7.34	7.11	8.68	7.68	7.55	8.71
8.90	13.94	12.64	11.20	8.90	8.63	7.97	6.61	6.66	6.90
6.77	7.68	7.41	7.22	5.97	5.43	5.69	5.69	5.47	6.72
6.71	6.36	7.19	5.97	5.98	8.00	12.65	10.92	7.71	6.75
6.84	5.72	5.01	4.90	4.69	5.18	4.12	5.74	5.40	7.08
12.20	8.12	7.44	2.95	6.70	8.01	6.06	4.71	3.08	0.00
0.00	0.00	6.58	5.60	3.46	0.00	0.00	4.90	4.76	5.88
0.00	0.00	7.82	8.11	2.91	2.64	4.61	6.33	6.74	7.53
J97	24.36	17.55	22.51	22.56	18.41	18.18	17.56	16.29	21.04
18.04	16.96	15.89	14.67	20.06	17.09	15.95	13.04	11.82	11.16
10.39	22.35	20.05	19.50	16.18	14.22	10.65	20.80	18.49	
17.46	14.55	14.19	12.67	11.79	10.67	9.62	10.65	8.63	7.39
6.61	6.19	17.18	15.88	14.44	15.66	13.23	12.56	11.59	11.66

10.86	10.09	12.28	12.01	11.81	10.57	10.03	10.95	9.06	8.22	
8.86	6.60	7.16	5.59	5.86	4.59	4.60	15.88	14.15	12.31	
11.34	11.43	10.32	9.61	9.49	9.29	9.77	6.39	3.49	4.55	
3.68	15.43	12.72	9.73	6.21	2.11	3.86	9.30	7.95	7.67	
6.12	5.16	5.62	1.99	8.84	6.70	5.51	4.86	0.00	0.00	
9.12	4.93	4.26	3.23	11.35	6.36	5.37	6.69	4.69	7.68	
6.36										
J98	24.22	17.41	22.38	22.42	21.80	21.87	21.94	15.98	20.90	19.98
20.70	19.33	18.26	14.36	19.92	16.27	18.31	13.42	14.19	13.52	
12.76	22.37	18.37	17.82	16.33	16.58	13.01	17.85	16.81		
15.77	14.41	13.20	12.15	12.16	11.06	11.98	13.01	10.99		
9.75	8.97	8.56	17.04	15.74	14.30	13.35	13.09	12.42	11.07	
11.11	11.32	10.49	12.14	11.87	11.67	10.43	9.89	10.14	9.41	
9.19	11.23	8.96	9.52	7.95	8.22	6.95	6.97	15.74	14.01	
12.17	11.20	11.29	10.18	9.47	9.35	9.15	9.63	7.84	5.86	
6.92	6.05	15.30	12.58	9.59	6.67	4.47	6.22	9.16	7.81	
7.53	5.98	5.02	0.00	4.35	8.70	6.56	5.37	4.72	0.00	
0.00	8.98	4.79	4.12	0.00	11.21	6.22	5.23	6.55	3.33	
6.32	7.33									
J99	17.27	10.46	15.42	15.47	14.85	14.91	14.99	15.22	13.95	13.02
13.75	15.21	13.23	13.59	12.97	13.68	10.24	12.82	14.40	16.89	
16.98	15.42	11.42	10.87	9.38	11.55	16.44	10.90	9.86	8.82	
7.21	8.34	9.20	12.80	10.43	10.20	14.04	10.97	12.23	13.55	
13.58	10.09	8.79	7.35	7.19	7.84	6.76	8.22	8.10	8.51	
9.86	4.94	6.84	6.64	6.93	7.04	7.29	8.78	8.56	9.40	
10.71	10.56	11.97	11.06	11.36	13.45	8.79	7.06	4.97	4.75	
6.26	5.15	6.00	6.51	6.00	6.79	8.77	11.12	10.77	12.52	
8.34	5.35	2.66	8.33	10.95	12.70	2.21	0.00	5.26	5.16	
5.76	7.14	10.83	0.00	0.00	4.39	5.68	9.15	9.01	0.00	
5.63	7.10	12.08	3.12	4.65	6.56	7.74	10.58	10.06	10.86	
J100	20.59	13.78	18.74	18.79	18.17	18.23	18.31	12.35	17.27	
16.34	17.07	18.53	11.86	10.72	16.29	12.64	11.92	9.96	10.20	
11.16	11.26	18.74	14.74	14.19	12.70	10.18	10.72	14.22		
13.18	12.14	10.78	9.57	8.52	8.68	8.50	8.27	9.84	8.83	
8.71	11.23	10.81	13.41	12.11	10.67	9.72	9.46	8.79	7.44	
7.48	7.72	7.93	8.51	8.24	8.04	6.80	6.26	6.51	6.85	
6.63	7.88	7.87	7.52	8.35	7.13	7.14	9.23	12.11	10.38	
8.54	7.57	7.66	6.55	5.84	5.72	5.52	6.00	5.28	6.89	
6.55	8.30	11.66	8.95	5.96	4.11	6.73	8.48	5.53	4.18	
3.90	2.44	2.46	0.00	6.61	5.42	2.93	0.00	0.00	4.93	
4.79	5.68	0.00	0.00	7.86	7.91	0.00	0.00	3.56	6.36	
5.69	6.49									
J101	22.86	16.05	21.01	21.06	20.44	20.50	20.58	14.36	19.54	
18.61	19.34	20.80	13.88	12.74	18.56	14.65	13.93	11.83	11.18	
12.14	12.24	21.01	17.01	16.46	14.97	12.20	11.69	16.49		
15.45	14.41	12.79	11.59	10.54	10.58	9.48	9.24	10.82	9.81	
9.69	10.55	10.14	15.68	14.38	12.94	12.77	11.47	10.81	9.45	
9.50	9.73	8.91	10.51	10.25	10.06	8.81	8.27	8.53	7.82	
7.61	8.86	8.84	8.49	9.54	8.11	8.12	8.55	14.38	12.65	
10.54	9.59	9.68	8.56	7.85	7.74	7.53	8.02	6.26	7.44	
7.53	7.63	13.93	10.93	8.23	5.09	6.05	7.80	7.80	6.45	
5.92	4.37	3.44	0.00	5.93	6.88	5.20	3.76	0.00	4.26	
4.12	7.14	0.00	0.00	7.18	9.37	3.14	0.00	0.00	5.69	
4.48	5.76									
J102	27.24	20.42	25.39	25.43	20.63	20.40	19.78	18.51	23.91	
22.99	20.26	19.18	18.11	16.89	22.93	19.31	18.17	15.26	14.04	

13.38	12.61	24.57	22.27	21.72	18.40	16.44	12.87	23.02	
20.71	19.68	17.34	16.41	14.89	14.01	12.89	11.84	12.87	
10.85	9.61	8.83	8.41	23.11	18.75	17.31	17.88	15.63	14.91
13.81	13.88	13.08	12.31	15.06	14.79	14.59	13.93	12.90	13.17
11.28	10.44	11.08	8.82	9.38	7.81	8.08	6.81	6.82	18.76
17.03	15.09	14.13	14.21	13.10	12.48	12.37	12.16	12.65	8.61
5.71	6.77	5.90	18.31	15.50	12.60	8.43	4.33	6.08	12.17
10.82	10.55	9.00	8.03	8.49	4.21	11.71	9.57	8.38	7.73
3.18	0.00	11.99	7.80	7.13	0.00	14.22	9.23	8.24	8.26
0.00	5.65	4.34							
J103	19.34	12.52	17.49	17.54	16.92	16.98	17.06	17.28	16.02
15.09	15.82	17.28	15.29	15.66	15.03	15.75	13.52	14.89	16.46
18.95	19.05	17.49	13.48	12.93	11.44	13.62	18.51	12.97	
11.93	10.89	11.06	12.48	13.34	14.87	16.06	12.39	16.10	
17.28	18.71	20.09	15.77	12.23	10.86	9.42	11.03	11.68	10.62
10.41	10.30	10.70	12.05	7.91	10.51	8.84	9.12	9.23	9.49
10.97	10.76	11.59	12.91	12.76	14.17	13.25	13.55	15.64	
10.87	9.13	7.16	6.95	8.46	7.34	8.19	8.70	8.19	8.98
10.96	13.31	12.97	14.72	11.71	7.49	4.85	10.53	13.14	
14.89	4.40	4.68	7.45	7.35	7.95	9.33	13.02	3.25	5.30
6.58	7.88	11.35	11.21	3.08	7.83	9.29	14.27	0.00	6.85
8.75	9.59	12.78	11.89	12.69					
J104	20.41	13.60	18.57	18.61	17.99	18.06	18.13	12.33	17.09
16.17	16.89	18.35	11.84	10.70	16.11	16.82	11.89	9.94	11.32
13.41	13.50	18.56	14.56	14.01	12.52	10.16	12.96	14.04	
13.00	11.96	10.34	9.55	8.50	8.66	9.63	9.39	10.96	10.17
10.14	12.66	12.24	13.23	11.93	10.49	10.32	9.44	8.77	7.42
7.46	7.70	8.05	8.06	8.22	8.02	6.78	6.23	6.49	7.97
7.76	8.59	9.30	9.76	9.78	8.56	8.57	10.65	11.93	10.20
8.10	7.55	7.64	6.53	5.82	5.70	5.49	5.98	6.71	8.32
7.98	9.73	11.49	8.48	5.78	5.54	8.16	9.91	5.35	4.00
3.88	3.22	3.50	4.35	8.04	4.43	2.75	2.61	2.91	6.36
6.22	4.69	0.00	3.14	9.28	6.92	0.00	0.00	3.24	7.79
6.05	6.84								
J105	22.07	15.26	20.22	20.27	19.65	19.71	19.79	13.83	18.75
17.82	18.55	20.01	13.34	12.20	17.77	14.12	13.40	11.30	10.64
11.60	11.70	20.22	16.22	15.67	14.18	11.66	11.16	15.70	
14.66	13.62	12.26	11.05	10.00	10.04	8.94	8.71	10.28	9.27
9.15	11.67	11.25	14.89	13.59	12.15	11.20	10.94	10.27	8.92
8.96	9.20	8.37	9.99	9.72	9.52	8.28	7.74	7.99	7.29
7.07	8.32	8.31	7.96	8.79	7.57	7.58	9.67	13.59	11.86
10.02	9.05	9.14	8.03	7.32	7.20	7.00	7.48	5.72	7.33
6.99	8.74	13.14	10.43	7.44	4.55	7.17	8.92	7.01	5.66
5.38	3.83	2.90	3.36	7.05	6.35	4.41	3.22	2.60	5.37
5.23	6.61	0.00	0.00	8.30	8.83	0.00	0.00	0.00	6.80
4.10	4.89								
J106	23.50	16.68	21.65	21.70	21.07	21.14	21.22	15.41	20.17
19.25	19.98	21.44	14.92	13.79	19.19	15.70	14.98	13.02	12.61
13.57	13.67	21.65	17.64	17.09	15.60	13.25	13.13	17.13	
16.09	15.05	13.43	12.64	11.58	11.74	10.91	10.68	12.25	
11.24	11.12	12.71	12.29	16.31	15.02	13.58	13.40	12.52	
11.86	10.50	10.55	10.79	10.34	11.15	11.30	11.10	9.86	9.32
9.58	9.26	9.04	10.29	10.27	9.92	10.76	9.54	9.55	10.71
15.02	13.29	11.18	10.64	10.72	9.61	8.90	8.79	8.58	9.07
7.69	9.30	8.96	9.78	14.57	11.56	8.87	6.52	8.21	9.96
8.43	7.08	6.97	5.39	4.87	5.32	8.09	7.52	5.84	4.78

4.57	6.41	6.27	7.78	3.56	0.00	8.24	9.62	3.24	0.00
0.00	7.79	3.31	4.10						
J107	25.79	18.98	23.95	23.99	23.37	23.44	23.51	19.88	22.47
21.55	22.27	20.55	19.48	18.26	21.49	20.67	19.54	16.63	15.41
14.75	13.98	23.94	19.94	19.39	17.90	17.81	14.24	19.42	
18.38	17.34	15.99	17.78	13.72	15.37	14.25	13.20	14.24	
12.22	10.98	10.20	9.78	18.61	17.31	15.87	14.92	14.66	14.00
12.64	12.68	14.45	13.68	13.71	13.44	13.24	12.00	11.46	11.71
10.98	10.76	12.45	10.18	10.74	9.18	9.45	8.18	8.19	17.32
15.59	13.74	12.78	12.86	11.75	11.04	10.93	10.72	11.20	9.98
7.08	8.14	7.27	16.87	14.15	11.16	8.24	5.69	7.44	10.73
9.38	9.10	7.56	6.59	7.05	5.57	10.27	8.13	6.94	6.29
4.25	3.33	10.55	6.36	5.69	0.00	12.78	7.79	6.80	7.92
0.00	5.31	4.00							
J108	25.80	18.98	23.95	24.00	23.37	23.44	23.52	17.71	22.48
21.55	22.28	23.74	17.22	16.09	21.49	18.00	17.28	15.32	16.71
17.79	17.02	23.95	19.94	19.39	17.90	15.55	17.28	19.43	
18.39	17.35	15.73	14.94	13.88	14.04	15.01	14.78	16.35	
15.26	14.02	13.24	12.82	18.62	17.32	15.88	15.70	14.82	
14.16	12.80	12.85	13.09	13.43	13.45	13.60	13.40	12.16	11.62
11.88	13.36	13.14	13.98	13.23	13.79	12.22	12.49	11.22	11.23
17.32	15.59	13.48	12.94	13.02	11.91	11.20	11.09	10.88	11.37
9.81	10.12	11.18	10.31	16.87	13.86	11.17	8.64	8.74	10.49
10.73	9.38	9.27	7.52	6.99	7.45	8.62	9.82	8.14	8.03
6.69	7.59	6.32	10.08	5.69	4.49	5.63	11.92	6.05	4.09
3.30	5.18	0.00	0.00						
J109	26.60	19.78	24.75	24.80	24.17	24.24	24.32	18.51	23.27
22.35	23.08	24.54	18.02	16.89	22.29	18.80	18.08	16.12	17.51
16.48	15.71	24.75	20.74	20.19	18.70	16.35	15.97	20.23	
19.18	18.15	16.53	15.74	14.68	14.84	15.81	15.58	15.97	
13.95	12.71	11.93	11.51	19.41	18.12	16.68	16.50	15.62	
14.96	13.60	13.65	13.89	14.23	14.25	14.40	14.20	12.96	12.42
12.68	14.16	13.94	14.18	11.92	12.48	10.91	11.18	9.91	9.92
18.12	16.39	14.28	13.74	13.82	12.71	12.00	11.89	11.68	12.17
10.61	8.81	9.87	9.00	17.67	14.66	11.97	9.44	7.43	9.18
11.53	10.18	10.07	8.32	7.79	8.25	7.31	10.62	8.94	8.83
7.49	6.28	7.20	10.88	6.49	5.76	4.32	12.71	6.84	4.89
4.10	3.87	0.00	0.00;						

Parameters

A(J) Amount of waste generated in a collection point j per week (mt per week)

/

J0 0

J1 2.72055981688407

J2 2.05422256292366

J3 0.26082343940736

J4 1.87335959399155

J5 2.63108024278082

J6 1.84480228310753

J7 3.39451235374689

J8 1.70011190796185

J9 1.70582337013865

J10 2.6044267526224

J11 1.56874827789537

J12 3.06324754749228

J13 3.14320801796753

J14 1.15181153898871
J15 1.12515804883029
J16 2.38548736917827
J17 3.44020405116132
J18 1.54399860846255
J19 0.721548055002844
J20 2.00853086550924
J21 0.74820154516126
J22 2.28458487072141
J23 2.42165996296469
J24 1.35552035662803
J25 2.08468369453328
J26 2.73388656196328
J27 2.33027656813583
J28 1.71343865304105
J29 1.22034908511035
J30 1.64490110691941
J31 0.365533579315425
J32 0.0475955181400293
J33 1.35742417735364
J34 1.39740441259126
J35 2.93759537960261
J36 0
J37 2.31885364378223
J38 3.52206834236217
J39 1.42976936492648
J40 1.53257568410894
J41 1.08517781359267
J42 0.58447296275956
J43 3.31074424182044
J44 1.26604078252478
J45 0.50451249228431
J46 2.02756907276525
J47 2.80242410808492
J48 1.58397884370017
J49 1.55351771209056
J50 2.40833321788548
J51 2.50542807489114
J52 2.03328053494205
J53 1.22034908511035
J54 2.74340566559129
J55 2.57586944173838
J56 1.43167318565208
J57 1.77055327480909
J58 2.4445058116719
J59 2.35502623756865
J60 2.05422256292366
J61 1.98378119607642
J62 3.44020405116132
J63 0.401706173101847
J64 1.97426209244841
J65 2.21604732459976
J66 0.314130419724193
J67 0.078056649749648
J68 0.285573108840176
J69 2.71484835470727

J70 2.19129765516695
 J71 3.43449258898451
 J72 1.97045445099721
 J73 2.51304335779355
 J74 2.22366260750217
 J75 0.759624469514867
 J76 2.276969587819
 J77 3.4192620231797
 J78 1.22606054728715
 J79 2.35312241684305
 J80 0.3255533440778
 J81 1.41073115767047
 J82 2.78148208010331
 J83 2.17987473081334
 J84 0.0951910362800586
 J85 0.380764145120234
 J86 3.30312895891803
 J87 1.99520412043003
 J88 3.21936084699158
 J89 2.9242686345234
 J90 2.70532925107926
 J91 2.4426019909463
 J92 2.06754930800287
 J93 1.65061256909622
 J94 2.73579038268888
 J95 2.4387943494951
 J96 1.15371535971431
 J97 0.529262161717126
 J98 0.778662676770879
 J99 1.90572454632677
 J100 2.93759537960261
 J101 3.2574372615036
 J102 2.67867576092085
 J103 0.721548055002844
 J104 2.74340566559129
 J105 2.67867576092085
 J106 1.26794460325038
 J107 0.91002630683736
 J108 0.930968334818973
 J109 0.607318811466774/

Dr(j) distance driven within a collection point j when visited (km)
/

J0 7.806561138
 J1 84.7771685703816
 J2 22.4408639638444
 J3 40.7087127388016
 J4 58.623442985928
 J5 19.0059961637097
 J6 13.5757115455069
 J7 65.5537296271118
 J8 22.5292161054204
 J9 26.5456244716062
 J10 28.9877989805519
 J11 15.0016081140899
 J12 21.721138472811

J13 43.7024864180746
J14 7.89043806207928
J15 12.4233424202365
J16 22.5024121711349
J17 42.4168509904452
J18 23.8046732944066
J19 1.20588114637912
J20 19.914955411013
J21 12.4357303953535
J22 21.495224222442
J23 18.7629479478928
J24 14.1295280950636
J25 23.4303401087344
J26 29.8724331165194
J27 14.330149481628
J28 12.5086319652618
J29 19.0073391627677
J30 34.4046606152408
J31 10.5181435819631
J32 20.3744242405263
J33 26.2745101209697
J34 12.9128771424067
J35 26.1826668992866
J36 0
J37 16.8901495784724
J38 35.2599199928332
J39 15.1113942826428
J40 31.5265912109697
J41 20.751501125591
J42 21.847796700889
J43 44.3576478472594
J44 8.77439923321376
J45 8.9154888092912
J46 16.1775789684594
J47 26.997643952722
J48 23.2861200863318
J49 6.67502814552604
J50 17.3302128575186
J51 39.3566737605072
J52 12.113870226402
J53 6.34815894122996
J54 21.3950159250266
J55 15.0299554247476
J56 11.376945573948
J57 18.3305163071859
J58 29.65223853454
J59 26.0418598814703
J60 17.4384873665721
J61 19.3531120899135
J62 27.0436266557194
J63 5.096894928277
J64 25.0148004140066
J65 24.2409488726716
J66 45.8684356086624
J67 6.86002610765064
J68 4.28235763665256

J69 5.59175692247694
J70 5.21003762001956
J71 8.38763538371541
J72 1.49855571620418
J73 2.77089668156836
J74 2.24783357430626
J75 10.5454632582198
J76 18.6764379824092
J77 36.4389901045187
J78 8.97126148156332
J79 24.2409488726716
J80 28.6168649848914
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