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Development of a Novel Food Waste Collection Kiosk and Waste-to-Energy Business Model

Matthew Franchetti

Mechanical, Industrial and Manufacturing Engineering Department, The University of Toledo, 2801 W. Bancroft St., Toledo, OH 43606, USA; matthew.franchetti@utoledo.edu; Tel.: +1-419-530-8051

Academic Editor: Witold-Roger Poganietz
Received: 8 July 2016; Accepted: 24 August 2016; Published: 29 August 2016

Abstract: The U.S. generates more than 37 million metric tons of food waste each year, and over 95% of it is disposed of at U.S. landfills. This paper describes the development of a novel food waste collection kiosk and business model called "Greenbox" that will collect and store food waste from households and restaurants with incentives for user participation to spur food waste-to-energy production in a local community. Greenbox offers a low-cost collection point to divert food waste from landfills, reduce greenhouse gases from decomposition, and aid in generating cleaner energy. A functional prototype was successfully developed by a team of engineering students and a business model was created as part of a senior design capstone course. Each Greenbox unit has the potential to reduce 275 metric tons of food waste per year, remove 1320 kg of greenhouse gases, and create 470,000 liters of methane gas while providing a payback period of 4.2 years and a rate of return of 14.9%.

Keywords: food waste; waste-to-energy; waste collection

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1. Introduction and Problem Statement

1.1. Overview

Currently, the U.S. generates more than 37 million metric tons of food waste each year and over 95% of it is disposed into landfills [1]. This equates to over 90 kg of food waste each year for every man, woman, and child in the U.S. Landfill disposal of food waste is problematic because as it decomposes, it generates methane gas (a greenhouse gas 25 times more potent than CO_2) and occupies space in the natural environment that may be used for other purposes [2]. Recent research indicates that methane has more significant short-term implications to climate change than previously known [3]. The goals of this research were to develop a novel and sustainable solution to reduce the landfill disposal of food waste and to convert the food waste into "green" energy. This paper describes an approach that was developed by a group of upper-level Bachelor of Science engineering students with funding from the U.S. Environmental Protection Agency (EPA)'s P3 Program [4]. The student team developed a food waste collection kiosk (named "Greenbox") with the following objectives: (1) to develop a functional Greenbox food waste collection unit that would be installed in northwest Ohio by the end of the one year grant period; (2) to estimate food waste volumes, collection processes, waste-to-energy potential, and financial performance for each Greenbox unit; and (3) to formulate incentive and award structures to promote the adoption of Greenbox by households and restaurants in a given community (for this project, Toledo, OH, USA). The purpose of Greenbox will be to gather and consolidate large amounts of food waste from households and restaurants that will then be transported to large-scale anaerobic digesters to convert the food waste into energy.

The project closely relates to pollution prevention (P2) in that it promotes the use of nontoxic organic food waste as the feedstock to generate energy versus more toxic fossil fuels. Additionally, the project promotes the use of materials (food waste in this case) versus placing them into the waste stream. From a sustainability standpoint, capturing food waste sent to U.S. landfills and diverting it to waste-to-energy may generate over five million metric tons of methane gas in the United States [1]. This may provide an opportunity and an alternative source of energy which would decrease the need for fossil fuels and energy facilities by utilizing food waste, and may prevent 33 million metric tons of CO_2 per year [1]. Also, food waste-to-energy technologies such as anaerobic digestion (AD) can reduce waste residue by up to 90%, and this product may be used in value-added ways such as fertilizers [1].

1.2. Literature Review Summary

Currently, in regards to diverting food waste from landfills, several challenges exist that are related to supply chain, technical, and economic constraints. From a supply chain standpoint, several solid waste management strategies can be used for managing food waste in the food system, but their implementation depends on local factors; strategies must also be modified or designed to accommodate local needs and unique circumstances [5]. Additionally, the infrastructure required to convert large amounts of food waste to energy are still being developed and not fully realized in the U.S., especially from a collection standpoint [6]. This research will fill this gap. From a technical standpoint, the current organic waste-to-energy technologies typically involve AD [7]. AD is typically used for agricultural and municipal wastewater sludge, but has not had wide application for household and restaurant food waste due to slower hydrolysis during the first step of the process [8]. The slower hydrolysis process for food waste versus wastewater and sludge is related to the thicker cell walls of the food waste particles. From an economic standpoint, this hydrolysis delay makes anaerobic digestion for food wastes less desirable from a time and cost standpoint. Additionally, low landfill disposal costs in the U.S. also contribute to the low waste-to-energy diversion rates [9]. *The development of a user friendly collection kiosk for food waste that provides incentives is a key to successfully overcoming the techno-economic challenges of food waste division*. Recently, several new technologies have emerged that have very strong promise for alleviating these constraints. In recent years, the application of AD for the treatment of organic waste has grown significantly and the amount of anaerobically digested substrate from waste has increased at an annual growth rate of 25% [10]. Specifically, by speeding up the hydrolysis process for food wastes, it will significantly increase the appeal and cost benefit of anaerobic digestion for these materials and aid in the diversion of these materials from US landfills and the associated greenhouse gas emissions. Several recent studies have been conducted to address organic waste-to-energy and to address the food waste problem in the U.S. [11–15]. From a technical standpoint, to speed up the hydrolysis process, the sonication of food waste has been explored recently [16–19] in addition to the thermal treatment of food waste [20–24]. These studies primarily focus on the chemical processes and "proof of concept" analyses, but do not fully explore the techno-economic nor environmental impacts of utilizing these technologies related specifically to food waste at local or region-specific levels, nor do they incentivize reduction from an economic standpoint. This study aimed at filling this knowledge gap as well.

From a sustainability standpoint, the collection of the 37 metric tons of food waste and the conversion of this waste-to-energy may generate over 5 million metric tons of methane gas in the U.S. [1]; a new source of alternative energy may be possible, decreasing the need for fossil fuels. Several current and relevant approaches exist to address the food waste problem, as highlighted below, but many involve donation centers or curbside collection programs that target large waste generators. From a food donation center standpoint, many soup kitchens and charitable organizations exist across the U.S. to collect and distribute edible excess food. Based on the hierarchy of food waste management established by the EPA and displayed in Figure 1, these outlets should remain the first option [1].

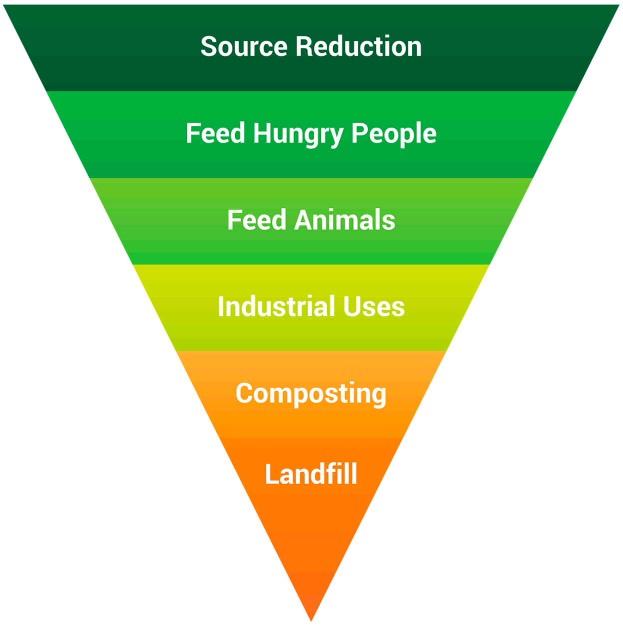

Figure 1. U.S. Environmental Protection Agency (EPA) Food Recovery Hierarchy [6].

Several existing methods for food waste collection are utilized in the U.S. For example, Philly Compost, operating in Philadelphia, PA, is a locally owned business that provides curbside food waste collection and composting services [25]. The City of Princeton, NJ, offers a curbside food waste collection system [26] that started in 2011. Both the Philly Compost and City of Princeton system utilize curbside collection totes as displayed in Figure 2.

Figure 2. Food Waste Collection Tote [25].

Currently, most food waste and organic waste collection systems in the U.S. require the use of these curbside collection totes. The curbside collection programs significantly drive up collection costs in terms of vehicle use, maintenance, labor, and fuel, and in many cases create poor economics to justify food waste collection by public or private groups. Greenbox will help to significantly reduce the high costs associated with curbside collection programs by creating single collection points while creating incentives for users to participate in the program. Novel approaches are required to address the food waste problem in the U.S., as indicated by the high levels of food waste generation (37 million metric tons per year in the U.S.) and low diversion rates of less than 5% [1].

In terms of feasibility, Greenbox applies a similar approach to the Redbox® (Outerwall, Inc., Bellevue, WA, USA) kiosk in terms of design, function, and location.

In addition, Greenbox integrates an incentive structure similar to Recycle Bank ® (RecycleBank, New York, NY, USA). Recycle Bank® is a recycling rewards program that works closely with municipalities' curbside collection programs to collect common household items such as plastics, papers, metals, and glass. Currently, Redbox® has over 35,000 kiosks in the U.S. [27,28] and reported annual revenue of $1.97 billion from 775 million rentals in 2013 [29]. In terms of feasibility, these numbers demonstrate a high adoption and acceptance rate for community-based kiosk systems in the U.S. Recycle Bank® has been operating for over 10 years, and in 2013 reported that their community-based incentive recycling program recycled an estimated 768,000 tons across the U.S. [30,31]. By combining and adapting the successful efforts of Redbox® and Recycle Bank®, a new system can be developed to tackle the food waste problem in U.S. while simultaneously providing a non-fossil-fuel-based energy source for anaerobic digesters operating in the U.S. At the present time, anaerobic digester infrastructure exists in the U.S. to process food waste collected via curbside or drop-off programs, allowing for the rapid proliferation of new collection systems. Currently, 87 large-scale (over 50 MW capacities) waste-to-energy facilities operate in the U.S.; these facilities process less than 10% of available municipal solid waste and less than 3% of food waste [32]. Large-scale waste-to-energy facilities are beginning to gain traction in the U.S., such as U.S. retail giant, Kroger's (NYSE:KR) 55,000 ton per year anaerobic digestion food waste-to-biogas facility in Compton, California [6].

1.3. Research Objectives

The goal of this research was to explore novel food waste collection systems and processes that would encourage and incentivize households and businesses to reduce food waste entering U.S. landfills. The research project involved the following objectives: (1) to develop a functional food waste collection unit; (2) to estimate food waste volumes, collection processes, waste-to-energy potential, and financial performance for each unit; and (3) to formulate incentive and award structures to promote the adoption by households and restaurants in a given community based on user feedback (for this project, Toledo, OH, USA).

2. Material and Methods

The development and fabrication of the Greenbox unit and the associated business plan was funded by the EPA's P3 Program [4]. The grant provided $15,000 for the student team to develop the unit and to travel to Washington DC to present the project at the U.S. Science and Engineering Festival in April 2016. The Greenbox unit was created as a joint upper-level Bachelor of Science engineering students design project between the Mechanical, Industrial, and Manufacturing Engineering Department and the Electrical Engineering and Computer Science Department in the College of Engineering (COE) at the University of Toledo (UT). The COE at UT has over a 15 year history of successfully completing industry and community-based senior design projects [33]. Students had full access to the COE's dedicated Senior Design Clinic.

The method utilized for this study focused on answering the research questions discussed in the Introduction section. These research questions hinged upon developing a functional prototype, estimating food waste volumes, and creating an incentive structure. The first step for the research team was to develop functional specifications for the unit based on literature reviews and feedback from potential users. Feedback from potential users was collected via an online survey tool to determine what percentage of potential users would use the system and if the users preferred bags or plastics containers for the food waste. The survey was emailed to a total of 300 University of Toledo students, family, and friends based on contact information collected from the student team. A sample size of 300 was selected based on the population city for the City of Toledo, USA (280,000), a 95% confidence interval, and a 5.5% margin of error. The survey questions were formed by the student team based on a literature review and an internet search of similar surveys for benchmarking purposes. The survey contained a total of four multiple choice questions administered via an online survey platform named Survey Monkey. The questions were: (1) Do you currently compost or collect food waste? (2) Would you consider collecting food waste in your home and transporting it to a local drop-off center without incentives? (3) Would you consider collecting food waste in your home and transporting it to a local drop-off center with incentives, such as gift cards and other perks? (4) If you were to collect food waste in your home, would you prefer to use a zip lock bag or plastic container? The respondents were provided with an internet link to complete the survey. The data was analyzed by calculating the total number of responses and then dividing the number in each category by the total to determine the relative frequency of each category.

Once specifications were determined from the survey results, including food waste reduction amounts and environmental benefits, the team developed alternative designs and utilized a quality deployment function to select the final design. The team then began to purchase materials and assemble the prototype. The team then developed a financial plan and incentive structure related to the commercialization of the Greenbox units.

The timeline provided in Table 1 lists the chronological events for the student team to accomplish the goals of the project. The project began in January 2016 and ended in May 2016 over a 16 week timeframe that aligned with the spring semester schedule at UT.

Table 1. Project Timeline.

Tasks	Week															
Develop a Functional Food Waste Collection Unit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Complete literature review	█	█														
Conduct market survey			█	█												
Finalize design and bill of materials					█	█	█									
Conduct FEA, functional, and Safety analyses							█	█	█							
Assemble the unit										█	█	█	█			
Test the unit														█	█	█
Estimate Volumes, Collection Processes, and Financial Performance																
Determine food waste generation rates per household			█	█												
Determine drop off and collection processes					█	█										
Estimate energy potential in the collected food waste							█	█	█	█						
Perform financial analyses											█	█	█	█	█	█
Formulate Incentive and Award Structures to Promote the Adoption																
Determine an incentive structure for users											█	█	█			
Perform financial analyses											█	█	█	█	█	█

3. Results and Discussion

During the design phase of the Greenbox prototype, the team proposed three different designs. The designs all had the same basic function of storing food waste that could be easily dropped off by the user. The three designs included a rotary shredder, compactor, and a bin-holder. A quality deployment function called the house of quality (Table 2) was performed to determine the best design based on the team's most important constraints. The constraints measured included: safety, reliability, maintenance cost, complexity, logistics, security, and material cost.

Table 2. House of Quality.

Constraint	Rating	Rotary	Compactor	Bin
Safety	10	8	7	10
Odor	7	9	10	10
Logistics	8	10	10	10
Operational Cost	8	8	6	10
Reliability	9	9	7	10
Environmental Impact	9	6	6	7
Rodent Control	7	10	10	9
Maintenance	8	5	7	10
Weight	6	5	5	6
Size	6	4	4	4
Material Cost	6	5	8	9
Security	9	7	7	7
Temp/Moisture	7	10	10	10
Complexity	7	5	7	10
Appearance	7	7	7	7
TOTAL	–	931	844	992

The first design, a rotary shredder, would have provided an internal measuring scale to track the amount of food waste delivered by each user. The waste was to be placed in the Greenbox, weighed, released into the machine, and shredded by a hammer mill. The shredded and near-pureed food waste would then be stored in the bottom of the unit until a collection truck would suck the mixture out to empty the Greenbox. This design provided a great way to maximize internal space, as the shredded mixture would fill out the box; however, several factors steered the team away from this design. First, the high operational costs to run potentially two motors for the hammer mill did not prove to be a sustainable plan for Greenbox operators. Second, the internal measuring scale provided no check on participant misuse; thus, the user could have tried to place rocks or metal into the unit to gain more points towards rewards. Doing this could have damaged the internal machinery and allowed for fraudulent points towards rewards.

The second design assessed was similar in setup to design one, however, instead of a shredder, the internal mechanical component was a compactor. The initial process would be the same, having the food waste weighed for reward distribution, however, after being released from the scale, the waste would drop onto a platform. Below the platform was the compacting mechanism, which would compact the food up against a metal sheet that would close when the compactor was triggered. This design provided great internal space optimization; however, again, due to high operational costs and potential participant misuse, the compactor design was dismissed.

After detailed analysis with the house of quality, the Greenbox unit design shown in Figure 3 was selected.

The team developed a budget of approximately $3800 to create one Greenbox prototype unit as displayed in Table 3. Most of the cost was related to the cost of materials and labor to create the metal shell of the unit. Additional costs included the $755 bin to store the food waste within the Greenbox unit, $32 solenoid to lock the food waste deposit hatch when not in use, the $435 touch screen, the $99 printer, the $37 Raspberry Pi 2 programming unit, and a $249 sensor to indicate when the unit is full and needs to be collected.

Figure 3. Final Greenbox Rendering.

Table 3. Greenbox Fabrication Budget.

Item	Cost
Food Collection Bin	$755
Box Fabrication	$2,250
Solenoid Locking Mechanism	$32
Touch Screen	$435
Printer	$100
Raspberry Pi Circuit Board	$37
Sensor	$249
TOTAL	$3,858

From a technical aspects point of view, the Greenbox design has many positive characteristics. The most important factor in the design is safety. Contrary to the first two designs, there are no moving parts inside of the Greenbox that can harm the user or the environment. This simple but effective design helps decrease maintenance cost, operational cost, as well as user abuse and misuse. This design is also very reliable and doesn't allow for any major failures to keep it from functioning properly. The negative technical aspects of the Greenbox design include the collection of food waste in plastic bags as well as the breakdown of the waste in the bag before it can be discarded. This issue is hard to avoid with any design and will have to be dealt with. Another issue is users abusing the Greenbox by dumping garbage or trash into the kiosk to collect incentives. This issue could not be avoided in any of the design alternatives; however, the bin design allows for misuse to be taken care of at the sorting facility after collection at the Greenbox. Greenbox will provide decomposable storage bags to users to minimize messes and odors for the users as well. Greenbox will automatically notify the hauler when it is full to schedule a pick up (this will minimize transportation). The disposal storage bags will be provided via a dispenser mechanism attached to the Greenbox unit.

In order to verify that the prototype Greenbox unit would be structurally safe, a finite element analysis (FEA) study was conducted. The main parameters studied were the deflection and stress that would occur of a force applied downward on the top of the box. This case applies if a heavy person were to stand on top of the Greenbox. To set up the FEA, a force of 135 kg was distributed over an area roughly the size of a person. Also, the bottom face of the Greenbox was fixed to the ground, which is a safe assumption due to friction. After setting these conditions, the material to be untreated sheet steel, and a few other parameters, the Autodesk software gave a result shown in the Figure 4.

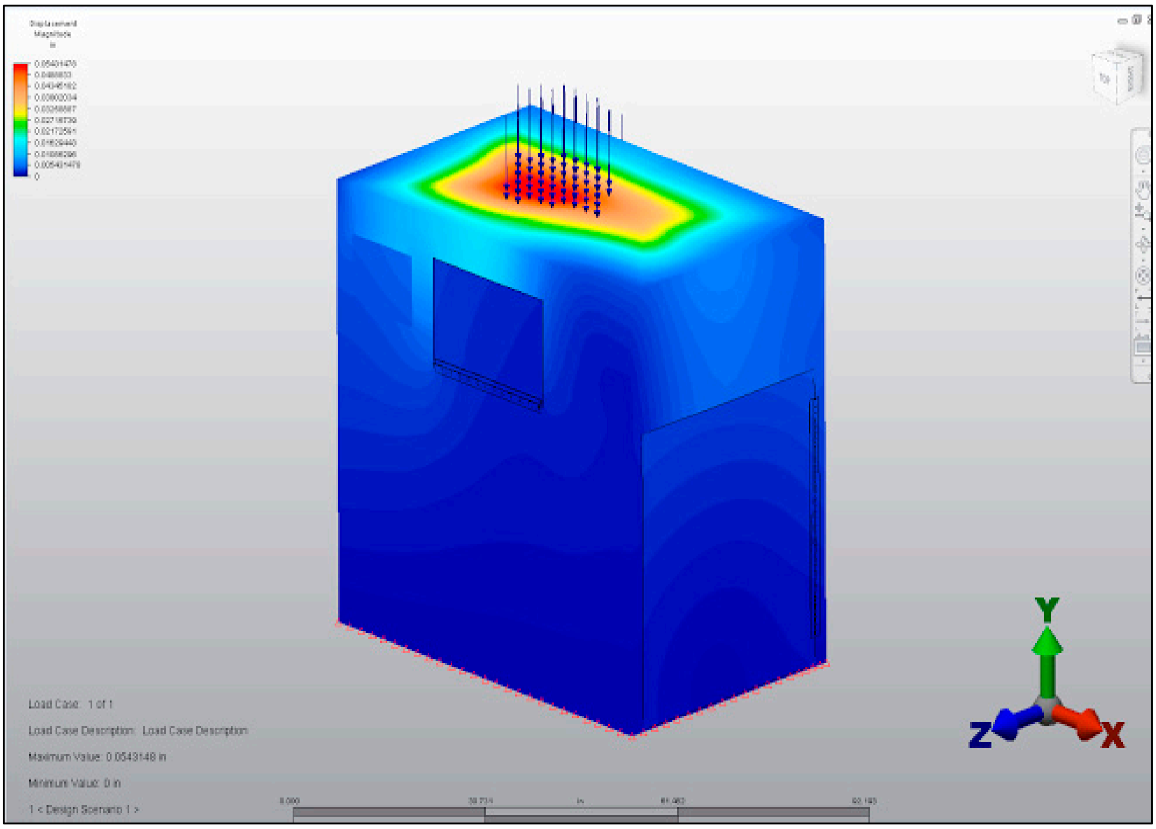

Figure 4. Stress and Deflection finite element analysis (FEA).

The result was even better than anticipated. It was determined that this force of 135 kg only caused the top of the box to deflect 1.27 mm. Using the Von Mises stress analysis, which is relatively conservative, the minimum factor of safety calculated was 2.35. These results are within the range of what the group decided was a safe design. Some of the largest concerns of Greenbox taken into design consideration were ease of use, distributing the bags evenly in the bin, tipping force, and cleanliness of the collection bin.

A tip force analysis was performed on Greenbox to ensure that the unit would be safe around public misuse. To calculate tip force, first the weight of the empty unit, only including an empty bin, was calculated and found to be 375 kg. An empty unit was analyzed as it will be the lightest, and thus, the easiest to tip over as the worst case scenario. Next, the unit was analyzed to determine where the worst case scenario force would be placed to tip the unit over. It was determined that at the front or rear of the unit, the critical tip force would occur, as the unit is deeper than it is wide. The weight of the unit was taken as a point force at the center of the box, so the tip force was calculated assuming a center of mass directly halfway in between the face and rear of the unit. This distance was divided by two to achieve the "x-value" of the analysis. Taking the critical tip force to be applied horizontally at the maximum height of the unit, 2.54 m., and the minimum tip force was found to be 121.6 kg. The calculation can be seen in Figure 5.

$$Shell = \frac{[2(67.11 * 67.25) + 2(67.11 * 43.28) + 2(67.25 * 43.25)]in^2}{144in^2} * 4.375\frac{lbs}{ft^2}$$

$$Shell = 708\ lbs$$

$$Total\ Weight\ Empty = (bin + Shell + Misc) = (95 + 628 + 25)$$

$$Total\ Weight\ Empty = 828\ lbs$$

$$F_{tip} = \frac{x * F_N}{h} = \frac{(1.813\ ft.) * (828\ lbs)}{(5.593\ ft.)}$$

$$\boldsymbol{F_{tip}} = \mathbf{268\ lbs.}$$

Figure 5. Force to Tip Calculations.

Greenbox will also take advantage of existing food waste diversion tools; specifically, tools developed by the EPA. The most widely utilized food waste diversion calculator developed by the U.S. EPA estimates the cost competitiveness of alternatives to food waste disposal, including source reduction, donation, composting, and recycling of yellow grease [1]. Greenbox will leverage the EPA calculator to help address collection issues and to provide a robust strategy for understanding and quantifying food waste collection and technical strategies from a combined environmental, economic, and process efficiency perspective that accurately models net energy gains and financial returns.

Greenbox provides a touchscreen user-interface that will allow participants to log their contributions to the program. Once the information is entered in, the user will be prompted to use a present-time printed label to adhere to their recyclable plastic bag of food waste. The user will then be able to open the bin and into it, place their contribution. When the bin is shut, the bag of food waste will drop into the unit. An angled plate will be utilized through attached torsional springs to produce an equally distributed pile of bags. When the waste accumulates to two-thirds the storage capacity, a sensor within the unit will alert a driver within the pickup service to come and remove the food waste. Once the service associate removes the bin, he or she will replace it with an empty, clean bin through a rail system on the bottom of the Greenbox. After the service driver secures the bin and locks the unit, the food waste will be taken to a service site to be weighed, scanned, and prepared for a collection company to take it away.

A functional Greenbox prototype was successfully created in spring 2016 and is pictured in Figure 6. This section provides details regarding the financial analysis/business plan and environmental benefits.

Figure 6. Final Prototype.

3.1. Financial Analysis

The average life cycle of a self-service kiosk is approximately 6.5 years [34]. Greenbox specifically is expected to have a lifespan of at least 7 years with an internal rate of return (IRR) of 14.9%. The payback period for a single Greenbox is 4.2 years. This is calculated taking into consideration that the Greenbox will have a revenue of about $2300 per year from food waste sales, an initial investment of $10,000, and a yearly cost of $2500 including maintenance and transportation. The payback period and IRR are indicative of a strong financial outlook and will produce a positive investment. These figures are displayed in Table 4.

Table 4. Financial Analysis.

Cost/Revenue Line Item	Cost
Cost of Greenbox	−$10,000
Implementation cost	−$2,000
Total Initial Cost	−$12,000
Annual revenue from sale of food waste	$6,875
Annual maintenance cost	−$2,500
Annual rewards costs as incentives	−$1,500
Total annual revenue	$2,875
Payback period (years)	4.2
Internal rate of return (IRR)	14.9%

From a financial perspective, Greenbox will offer positive economic returns. In terms of the short-term costs of creating the first prototype and implementing Greenbox via the COE Senior Design Project, the research team anticipates a cost of $3858, primarily for materials as discussed previously in Table 3. Maintenance costs of approximately $2500 per year are anticipated for electricity and to clean, repair, and inspect Greenbox. Additionally, a minimal annual cost is expected per year to provide reward incentives to users, and the research team anticipates that companies will be pleased to donate rewards based on the "green" appeal of Greenbox. Participation in Greenbox from restaurants and supermarkets will be a way for those entities to enhance their own brand while increasing business. In terms of revenue, the team anticipates an annual revenue of $2300 from the sale of food waste to large organic waste-to-energy companies. This was calculated by multiplying the annual food waste collected from each Greenbox unit by the price per ton paid by the large organic waste-to-energy companies. It is anticipated that each Greenbox unit will collect 50 households' food waste, equating to 753 kg of food waste per day (converted to 275 metric tons per year) and the food waste will be sold at $30 per ton to the local large organic waste-to-energy companies. These facilities would then process it through an anaerobic digester to produce $40 worth of usable energy (at $0.073 per kWh).

To increase the usage of Greenbox and engage users, an incentive structure will be created that rewards users for depositing food waste into Greenbox similar to the Recycle Bank® reward system. The rewards will include gift cards and/or discount coupons to local restaurants and shops as displayed in Table 5.

Table 5. Sample Greenbox Incentive Structure.

Reward	Pounds of Food Waste Required
Green food waste tote bag	10
Buy one get one free at Sofie's Ice Cream	15
50% off at Ted's Diner	20
One free car wash at Express Wash	25
Free magazine subscription to Green Life	40
Free cell phone charger	50

Potential businesses that will offer these gift cards and/or discount coupons will be engaged by student teams to encourage their participation. From an end user standpoint, Greenbox will track a user's usage of the system in terms of food waste reduction, greenhouse gas mitigation, and green energy production to track an individual user's environmental protection efforts. Furthermore, Greenbox will provide convenient decomposable storage bags to users to reduce the mess and odor of the food waste in their homes and cars. In all, 95 people responded to the survey, and of the respondents, 90% indicated they take efforts to reduce waste, 50% would participate without rewards, and 70% would participate with or without rewards. Additionally, 57% preferred bags to store the food waste versus plastic containers. The survey results discussed in the Methods section correspond with the use of bags to store the food waste and that a reward structure will increase participation.

From an economic standpoint, Greenbox and the increased AD of the food waste will result in several benefits for the individual end user and society in general. From the end user point of view, he or she will receive a gift card or discount coupon for utilizing Greenbox and reducing food waste sent to landfills, which will create a sense of goodwill for users. From a society and community point of view, Greenbox and the increased AD of the food waste will result in a low-cost energy source that is not based on fossil fuels and reduction in waste hauling costs for transporting the food waste to landfills. For example, in northwest Ohio, one ton of municipal solid waste (which includes 95% of food waste generated) costs about $60 to dispose of at a local landfill. A major hurdle in justifying cost of food waste-to-energy programs is the high cost of collection, usually done via a curbside collection program [6]; Greenbox will significantly reduce collection costs by consolidating food waste in one centralized collection point for the hauler and food waste-to-energy facility.

In terms of long-term costs, once the units are mass produced professionally on a large scale, the research team anticipates a manufacturing cost of $10,000 per unit and a $2000 implementation cost from a manufacturing organization. Annual maintenance and operational costs of approximately $2500 per year are anticipated for electricity and to clean, repair, and inspect Greenbox. The student team plans to investigate companies willing to donate rewards based on the "green" appeal of Greenbox, so the cost of incentives will be minimal (similar to the Recycle Bank® model). In terms of revenue, the team anticipates annual revenue of $6875 from the sale of the food waste to large organic waste-to-energy companies. The $6875 was calculated by multiplying the annual food waste collected by each Greenbox unit by the price per ton paid by the large organic waste to energy companies. It is anticipated that each Greenbox unit will collect 753 kg of food waste per day (converted to 275 metric tons per year) and sell the food waste at $25 per ton to the local large organic waste to energy companies. Twenty-five dollars per ton represents cost of the energy generated from the food waste versus the cost to purchase the energy from the local utility in Ohio. As displayed previously in Table 4, the payback period for each Greenbox unit is 4.2 years and the internal rate of return (IRR) is 14.9% over the 7 year life of each Greenbox unit. Both the payback and IRR indicate a strong financial long term investment.

3.2. Environmental Benefit Analysis

Greenbox will significantly promote sustainable environmental protection, economic prosperity, and social benefit for users, communities, and the U.S. Greenbox will have several positive impacts on the environment by diverting food waste. Figure 7 displays the logistical model for the system. From an environmental benefit perspective, users of the system will deposit food in the Greenbox collection kiosks, preventing this waste from entering U.S. landfills. Food waste will then be transported from the Greenbox units to a local anaerobic digestion facility to create a source of green energy and reduce greenhouse gas emissions from the food waste decomposing in landfills.

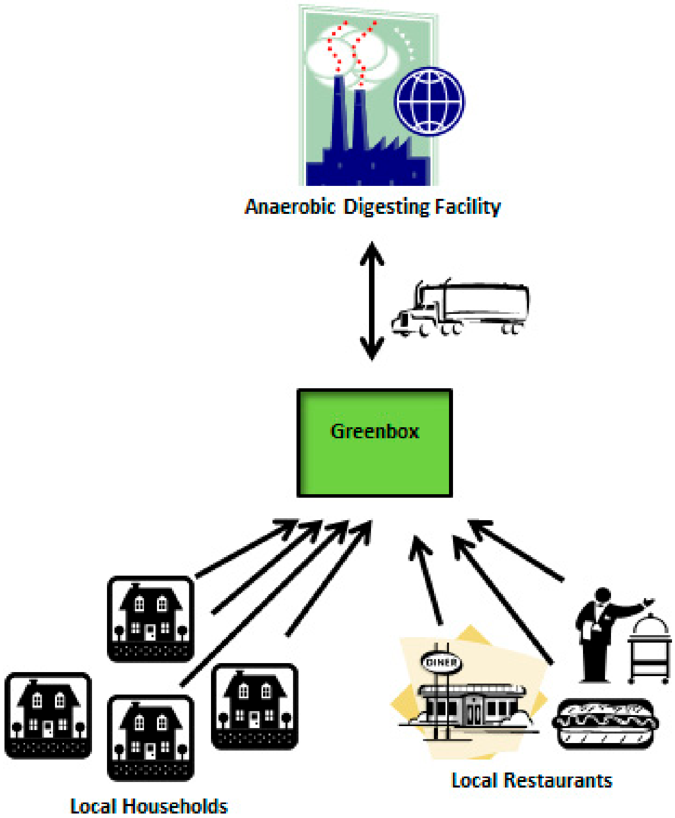

Figure 7. Transportation Network.

First and foremost, Greenbox will address the 37 million metric ton per year food waste problem in the U.S. As stated earlier, each Greenbox unit is anticipated to collect 76 tons of food waste per year; each Greenbox unit will reduce 275 metric tons entering U.S. landfills per year. Developing Greenbox will help to overcome common obstacles to food waste collection through consolidating food waste into a form deliverable to large energy firms while providing incentives to users in the form of rewards. Greenbox will be a low-cost alternative which will help divert food waste from landfills, reduce greenhouse gases from decomposition, and aid in generating cleaner energy. Annually, this will translate into 76 tons less of organic waste in U.S. landfills and the mitigation of 780 million cubic liters of methane gas generated from the waste decomposing in the landfills (Moriarty, 2016). Reducing methane gas emissions is especially important when compared to other greenhouse gases, because pound for pound it is 25 times more potent than CO_2. Additionally, each Greenbox unit will be responsible for generating 40,000 kWh from the conversion of the food waste to energy at a local anaerobic digestion facility based on the annual amount of 275 metric tons collected [35]. This will reduce the U.S.'s reliance on fossil fuel, diminish fossil fuel consumption, and help move the country closer towards energy independence. In terms of the local environment, Greenbox will directly offer the food waste reduction and energy benefits to the local area as the Greenbox units and anaerobic digestion facility will be community driven. Negative environmental impacts will not be shifted to another locality or media, as the organic food waste is being directly diverted from landfills, reducing space requirements and the associated greenhouse gas emissions. Over the entire lifecycle, the transportation of the food waste from a Greenbox unit to the anaerobic digestion facility is assumed to be neutral compared with landfill disposal, as the transportation resources (trucks, fuel, etc.) are currently required to transport the food waste to the landfill from homes and restaurants. This transportation will be shifted to a route from Greenbox to the anaerobic digestion facility.

In terms of output measures from the development and implementation of Greenbox, the project team expects:

- The diversion of 275 metric tons of food waste from U.S. landfills per year;
- The mitigation of 1320 kg of greenhouse gas by removing the food waste from landfills;
- The generation of 470,000 liters of "green" energy from the food waste (in the form of methane gas) that will reduce the reliance on more harmful energy sources such as coal and oil;
- A pathway to cleaner, healthier communities with a reduction in unwanted food waste, contributions to climate change mitigation, and the generation of green energy; and
- The development of a competitive business model that will require a $12,000 initial investment per unit and provide a 4.2 year payback period and 14.9% rate of return.

In terms of transferability and scalability, Greenbox will be designed as a "franchise" type of business opportunity that could be applied anywhere in the U.S. near an organic waste-to-energy facility. Currently, 87 large-scale (over 50 MW capacities) waste-to-energy facilities operate in the U.S.; these facilities process less than 10% of available municipal solid waste and less than 3% of food waste [32]. For an initial investment of $12,000, a Greenbox unit can be produced and installed in any community. Annually, this will translate into a reduction of 275 metric tons of organic waste in U.S. landfills and the mitigation of 1320 kg of greenhouse gas generation from the waste decomposing in the landfills; these values are based on figures developed by Scharff and Jacobs for food waste-to-energy [36]. Additionally, each Greenbox unit will be responsible for generating over 470,000 liters of methane gas from the conversion of the food waste to energy at a local anaerobic digestion facility, again using figures developed by Scharff and Jacobs [36].

4. Conclusions

The objective of this project was to design a proof-of-concept for the Greenbox unit, which will collect and store food waste from homes and restaurants. The goal is to consolidate food waste and make it available to collection companies as a waste-to-energy feedstock. Collection companies typically use the food waste, an organic substance, in AD to harness the primary byproducts: methane gas and liquid effluent. This will be done via a community-based rewards system, encouraging people to participate in the program and direct their food waste in a positive direction.

From a user point of view, Greenbox will provide meaningful environmental and economic benefits as confirmed by the survey results discussed in the Methods section; 90% of respondents were concerned about environmental protection and 70% indicated that they would use the system. Specifically, from an environmental standpoint, Greenbox will reduce the amount of food waste entering U.S. landfills, reduce the greenhouse gas emissions associated with the food waste rotting in landfills, and lead to cleaner environments. As cited earlier, each man, woman, and child in the U.S. generates over 90 kg of food waste each year and less than 3% of food is being diverted [1]; if Greenbox could capture a small portion of this food waste, significant environmental protection could occur. For example, for every metric ton of food waste diverted, Greenbox and the increased AD of the food waste will result in the mitigation of 4.8 kg of greenhouse gas, 1755 cubic liters of methane gas (alternative energy), and one less metric ton of food waste in a U.S. landfill [36]. This study demonstrated a novel student driven solution to the ongoing environmental problem of food waste from and environmental and economics perspective This model provides a novel solution to the food waste problem in the U.S. by creating the first reward-based food waste collection kiosk coupled with a franchisee business model to promote usage. These novel aspects may appeal to both environmentally conscious conversationalists and finically savvy investors.

The primary limitations of this study involve the geographical region study. The data and survey results are specific to the Midwest USA, but the research team believes the model may apply well to other regions in the U.S. Additionally, the financial calculations and costs related to energy, transportation, and disposal represent figures in the Midwest U.S. as well. Future research in this field would include expanding the model to other regions in the U.S. and world. Additional future research would include studying the post-implementation results and actual benefits.

Acknowledgments: The research team would like to acknowledge the US EPA for funding for this project. The project was funded through the EPA P3 Program (grant number SU835999).

Conflicts of Interest: The author declares no conflict of interest.

References

1. US EPA. Basic Information about Food Waste. Available online: http://www.epa.gov/osw/conserve/materials/organics/food/fd-basic.htm (accessed on 26 November 2014).
2. US EPA. Landfill Methane Outreach Program. 2011. Available online: http://www.epa.gov/lmop/basic-info/index.html (accessed on 27 November 2014).
3. Wedderburn-Bisshop, G.; Longmire, A.; Rickards, L. Neglected transformational responses: Implications of excluding short lived emissions and near term projections in greenhouse gas accounting. *Int. J. Clim. Chang. Impacts Responses* **2015**, *7*, 11–27. [CrossRef]
4. US EPA P3 Program. People, Prosperity and the Planet (P3) Student Design Competition. Available online: https://www.epa.gov/P3 (accessed on 15 May 2016).
5. Evans-Cowley, J.S.; Arroyo-Rodríguez, A. Integrating food waste diversion into food systems planning: A case study of the Mississippi Gulf Coast. *J. Agric. Food Syst. Community Dev.* **2013**, *3*, 1–19. [CrossRef]
6. Varrasi, J. Beyond Waste to Energy. ASME. Available online: http://www.asme.org/kb/news---articles/articles/renewable-energy/beyond-waste-to-energy (accessed on 27 November 2014).
7. Ward, A.J.; Hobbs, P.J.; Holliman, P.J.; Jones, D.L. Review: Optimisation of the anaerobic digestion of agricultural resources. *Bioresour. Technol.* **2008**, *99*, 7928–7940. [CrossRef] [PubMed]
8. Elbeshbishy, E.; Nakhla, G. Comparative study of the effect of ultrasonication on the anaerobic biogradablity of food waste in single and two-stage systems. *Bioresour. Technol.* **2011**, *102*, 6449–6457. [CrossRef] [PubMed]
9. Cleary, J. The incorporation of waste prevention activities into life cycle assessments of municipal solid waste management system: Methodological issues. *Int. J. Life Cycle Assess.* **2010**, *15*, 579–589. [CrossRef]
10. Buffiere, P.; Mirquez, L.D.; Steyer, J.P.; Bernet, N.; Delgenes, J.P. Anaerobic digestion of solid wastes needs research to face an increasing industrial success. *Int. J. Chem. React. Eng.* **2008**, *6*. [CrossRef]
11. Han, S.K.; Kim, S.H.; Kim, H.W.; Shin, H.S. Pilot scale two-stage process: A combination of acidogenic hydrogenesis and methanogensis. *Water Sci. Technol.* **2005**, *52*, 131–138. [PubMed]
12. Ke, S.Z.; Shi, Z.; Fang, H.H.P. Application of two phase anaerobic degradation in industrial waste water treatment. *Int. J. Environ. Pollut.* **2005**, *23*, 65–80. [CrossRef]
13. Mohareb, A.; Warith, M.; Diaz, R. Modeling greenhouse gas emissions for municipal solid waste management strategies in Ottawa, Ontario, Canada. *Resour. Conserv. Recycl.* **2008**, *52*, 1241–1251. [CrossRef]
14. Muhle, S.; Balsam, I.; Cheeseman, C.R. Comparison of carbon emissions associated with municipal solid waste management in Germany and the UK. *Resour. Conserv. Recycl.* **2010**, *54*, 793–801. [CrossRef]
15. Pimenteira, C.A.P.; Pereira, A.S.; Oliveria, L.B.; Rosa, L.P.; Reis, M.M.; Henriques, R.M. Energy conservation and CO_2 emission reductions due to recycling in Brazil. *Waste Manag.* **2004**, *24*, 889–897. [CrossRef] [PubMed]

16. Aldin, S.; Elbeshbishy, E.; Nakhla, G.; Ray, M. Modeling the effect of sonication on the anaerobic digestion of biosolids. *Energy Fuels* **2010**, *24*, 4703–4711. [CrossRef]
17. Bougrier, C.; Carrère, H.; Delgenès, J.P. Solubilization of waste-activated sludge by ultrasonic treatment. *Chem. Eng. J.* **2005**, *106*, 163–169. [CrossRef]
18. Khanal, S.K.; Grewell, D.; Sung, S.; Leeuwen, J.V. Ultrasound applications in wastewater sludge pretreatment: A review. *Crit. Rev. Environ. Sci. Technol.* **2007**, *37*, 277–313. [CrossRef]
19. Kobus, Z.; Kusinska, E. Influence of physical properties of liquid on acoustic power of ultrasonic processor. *Teka Komisji Motoryzacji I Energetyki Rolnictwa* **2008**, *8*, 71–78.
20. Gavala, H.N.; Yenal, U.; Skiadas, I.V.; Westermann, P.; Ahring, B.K. Mesophilic and thermophilic anaerobic digestion of primary and secondary sludge: Effect of pre-treatment at elevated temperature. *Water Res.* **2003**, *37*, 4561–4572. [CrossRef]
21. Neyens, E.; Baeyens, J. A review of thermal sludge pre-treatment processes to improve dewaterability. *J. Hazard. Mater. B* **2003**, *98*, 51–67. [CrossRef]
22. Valo, A.; Carrère, H.; Delgenès, J.P. Thermal, chemical and thermo-chemical pretreatment of waste activated sludge for anaerobic digestion. *J. Chem. Technol. Biotechnol.* **2004**, *79*, 1197–1203. [CrossRef]
23. Xuan, Y.; Pingfang, H.; Xiaoping, L.; Yanru, W. A review on the dewaterability of bio-sludge and ultrasound pretreatment. *Ultrason. Sonochem.* **2004**, *11*, 337–348.
24. Zupancic, G.D.; Ros, M. Heat and energy requirements in thermophilic anaerobic sludge digestion. *Renew. Energy* **2003**, *28*, 2255–2267. [CrossRef]
25. Philly Compost. Organics Recycling & Food Waste Collection Services. Available online: http://www.phillycompost.com/Home.html (accessed on 27 November 2014).
26. Princeton's Curbside Food Waste Program. Available online: http://www.princetonnj.gov/curbside-organics.html (accessed on 27 November 2014).
27. Redbox Automated Retail, LLC. Available online: http://www.redbox.com/ (accessed on 26 November 2014).
28. Redbox Facts. Available online: http://www.redbox.com/facts (accessed on 26 November 2014).
29. Yahoo Finance. Outerwall Inc. Announces 2013 Fourth Quarter and Full Year Results. Available online: http://finance.yahoo.com/news/outerwall-inc-announces-2013-fourth-211300355.html (accessed on 26 November 2014).
30. Recycle Bank. Available online: https://www.recyclebank.com/ (accessed on 26 November 2014).
31. Recycle Bank—About Us. Available online: https://www.recyclebank.com/about-us (accessed on 26 November 2014).
32. Messenger, B. Kroger Opens a Food Waste to Biogas Anaerobic Digestion Plant, Waste Management World. 2013. Available online: http://www.waste-management-world.com/articles/2013/05/video--kroger-opens-food-waste-to-biogas-anaerobic-digestion-pla.html (accessed on 26 November 2014).
33. Franchetti, M.; Hefzy, H.; Pourazady, M.; Smallman, C. Framework for implementing engineering senior design capstone courses and design clinics. *J. STEM Educ.* **2012**, *13*, 25–40.
34. Kiosk Marketplace. Is a Kiosk or Tablet Best for Self-Service Registration? Available online: http://www.kioskmarketplace.com/blogs/is-a-kiosk-or-tablet-best-for-self-service-registration/ (accessed on 22 March 2016).
35. Moriarty, K. *Feasibility Study of Anaerobic Digestion of Food Waste in St. Bernard, Louisiana*; National Renewable Energy Laboratory: Golden, CO, USA, 2016.
36. Scharff, H.; Jacobs, J. Comparison of methane emission models and measurements. In Proceedings of the Sardinia, Tenth International Waste Management and Landfill Symposium, Cagliari, Italy, 3–7 October 2005.