# Optimizing UC Berkeley's Plastics Recycling Facility

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## ABSTRACT

Plastic pollution is becoming a major environmental concern due to inadequate handling and disposal procedures associated with the end-life of plastic material. As recyclables have become an international commodity, with many of the exports going to China and East Asia, many negative social impacts are associated with this recycling industry. Local, circular economies with identified end-life uses for plastic materials must be established domestically in order to sustain the plastic materials economy. UC Berkeley students have created a recycling research facility with the assistance of staff and faculty from multiple campus departments. This facility will process all waste within the facility grounds, an innovative approach to waste materials management. In this study, I perform a systems analysis of the UC Berkeley Plastic's Recycling Facility Project, identifying the relative economic successes and stakeholder benefits associated with this program. Using optimization to evaluate economic gain, I identified that a positive revenue (considering variable production costs) could be attained, considering waste audit data and total work hours available. The optimal solution for handling 121.4 tons of recycling waste generated in 2018 at UC Berkeley was to recycle all waste into circular economy projects, rather than landfill. I conducted interviews with key stakeholders, identifying the many non-economic benefits of the project, such as research connections between staff and students, an interdisciplinary approach to sustainability, and innovative materials management protocols. This system analysis serves as a model for domestic waste management operations, with many economic and social benefits associated from the establishment of a closed-loop, local, circular economy-focused plastics recycling system.

## KEYWORDS

Waste management, optimization, waste systems analysis, materials management, circular economy

## INTRODUCTION

Plastics are a very diverse group of materials that are mechanically preferable for consumer applications: they are lightweight, easily molded, and durable. 4% of the world's oil and gas production is used as a feedstock for plastic materials, and another 3-4% is used in the production of this material. disposable packaging and short-lived products are often made of plastic, creating a need for alternative methods of handling accumulating plastic debris in landfills and natural habitats (Day 1981). Recycling is commonly used to reduce the environmental impacts associated with plastic waste, but the industrial methods involved in processing of plastic material have negative environmental impacts (Hopewell et al. 2009). Measurements of various plastic waste recycling methods and the environmental impacts associated with them could help determine best practices for plastic waste processing. In doing this life cycle analysis, I identify the environmental impacts of mechanical recycling and conventional recycling locally.

In a study done in 2003 by Arena et al., life cycle analysis of plastic waste disposal showed that recycling products and creating a new end product from recycled inputs is in fact less energy intensive than creating new virgin products when comparing the disposal processes of combustion, mechanical recycling, and conventional recycling. Mechanical recycling is a process that involves processing plastic material for the creation of end products on site. Chemical Recycling, or conventional recycling, is a commercial process used to turn plastic waste into a plastic oil via depolymerization using a two-step process: a mechanical processing component followed by a combination of chemical inputs (Arena et al. 2003). Depolymerization is done at very high temperatures, thus requiring a high energy and water input associated with the process, which in turn releases many greenhouse gas emissions as a result. While technically feasible, chemical recycling processes were also found to be very uneconomic as a result of the low price of petrochemical stock and insignificant subsidies combined with a high technology cost (Dodbiba 2006). Some plastics, such as PET and polyolefins, can be chemically recycled with minimal impact, but mechanical recycling processes tend to create products that are more permanently recyclable, creating a circular economy(Hopewell et al. 2009). Mechanical recycling requires nearly half of the overall energy demand for the production of new end products from recycled materials versus the production of end products from virgin (Arena et al. 2003). Compared to chemical recycling, mechanical recycling tends to be the most environmentally preferable, as it has been measured to consume the least amount of water and energy produce the least amount of associated greenhouse gas emissions and excess waste. The negative environmental impacts associated with mechanical recycling are scrap waste and energy consumption (Arena et al. 2003).

Little research has been done on the applicability of a plastic mechanical recycling system on a university campus. There are currently materials recovery facilities at University of Colorado Boulder, Middlebury College, University of California Merced, and the University of Pennsylvania. None, however, are entirely student-led or focused on identifying long-term circular solutions for plastic waste. The Zero Waste Research Center at UC Berkeley is working to create the first university research facility focused on identifying solutions for plastic waste and pollution by recycling plastic waste via research projects and cross-departmental collaboration focused on mechanical recycling and minimally-impactful recycling processes. As student lead, I have been in charge of identifying funding opportunities, working with administrators, and identifying on-campus and local solutions to impose a circular economy for the plastic waste. With this facility, we can effectively recycle more plastic locally, if solutions are identified. Currently, we have secured partnerships with Unifi to create Cal Athletics apparel from recycled PET water bottles and the College of Engineering at UC Berkeley to create recycled 3D printer filament.

However, the necessary fiscal and labor inputs to construct this facility may cause too many drawbacks to construct such a student-sovereign waste research operation. In this study, I will be attempting to answer the central question: What are the economic benefits of this mechanical recycling facility on a university campus? My sub questions are: 1) What is the relative value and composition of the incoming recycling waste stream generated by the UC Berkeley campus? 2) Considering the costs and benefits of a closed-loop recycling system that creates end products for revenue, what is the optimal use of UC Berkeley's recyclable waste resources in the creation of various end products? And 3) What are the intangible benefits associated with this project?

**Systems Engineering Models used in Waste Management System Analysis**

Specific outlook-forward analysis techniques can be used to create and establish new facilities, purchase new technologies, and compare management options. These analysis techniques are called systems engineering models, and attempt to turn a large problem into small, hierarchically arranged problems that can be solved more easily, leading to a final combined solution to the larger problems. Some general models include: cost-benefit analysis, optimization models, simulation models, forecasting models, and integrated modeling systems. Cost-benefit analysis is one of the most commonly used economic outlook techniques, and assesses the positive and negative economic and physical effects independently of each production process, allowing well defined cost-benefit analyses to translate environmental aspects into economic terms (Pires et al. 2011). Simulation models are used to trace lengthy chains of continuous or discrete events, based on cause-and-effect relations describing the operations in complex systems. These models help investigate the dynamic behavior of complex systems (Pires et al. 2011). Some solid waste management models that have been developed using simulation philosophy include GIGO, EcoSolver IP-SSK, and TASAR. One model, SWIM, is a computer program that attempts to create a system map of waste generation and management from user-inputted data of waste collections and pricing. This is done through computer-generated demand models (demand for certain waste collection services, waste generation), supply (system operating characteristics, physical systems, and participation), and impact models (environmental and economic impacts) (Wang et al. 1996)

**Systems Analysis Models used in Waste Management Analysis**

System Analysis Models are used to evaluate the performance of existing systems and their relation to original project objectives and environmental regulations. Improvements are made in areas that each model identifies as lacking. The generalized modelling approaches for system analysis include management information systems/expert systems, scenario development, material flow analysis/life cycle assessment, risk assessment, environmental impact assessment, strategic environmental assessment, socioeconomic assessment, and sustainable assessment (Pires et al. 2011).

Socioeconomic assessment and sustainable assessment refer to analysis of systems using computer algorithms and joint datasets. Socioeconomic assessment uses computer-based algorithms that apply market-based or policy regulations to current waste management practices to propose changes to existing operations. Socioeconomic assessments are used to model producer-responsibility schemes and deposit-refund schemes for waste haulers. Sustainable assessment refers to the use of integrated modelling techniques to show sustainability implications (Pires et al. 2011). An example of sustainable assessment is Chang et al. 2008 for landfill siting, where researchers combined GIS data, LCA information, an optimization model, and an environmental impact assessment to explain an integrated methodology for choosing a long-term sustainable site for a landfill in south Texas (Chang et al. 2008). Integrated modelling systems can reduce the variability in the results of the model as there are more parameters influencing the outcomes.

Comparative analysis is used to compare multiple waste systems qualitatively and draw conclusions from the differences found between various waste management systems. One such framework is the Integrated Solid Waste Management (ISWM) framework proposed by Wilson et al. in 2012. In a comparison of 20 municipal solid waste systems internationally, the research team investigated the following qualities of each waste management system: user and provider inclusivity, waste generation and composition, environmental and public health impact, financial sustainability, and institutional coherence. It was found that this analysis framework provided beneficial information into not only the performance of physical systems but also key governance implications between waste management systems (Wilson et al. 2012). Comparative analysis creates a model that allows for lessons to be learnt from other waste management systems.

**Models used in European Waste Processing Systems**

Different models are used for different objectives for forecasting predictions for waste management decisions. In Europe, waste management decisions can be generalized into modelling decisions made about: municipal solid waste (MSW), residual/mixed waste, biodegradable municipal waste (BMW), and packaging waste. MSW and residual/mixed waste management modelling include objectives of using modelling to better understand environmental impact, siting implications, and collect information on flows of waste. Packaging waste management modelling aims to understand the environmental impact of packaging waste and processing, evaluate comparatively other solid waste management streams, and to better understand certain aspects of collection, processing, or production. BMW waste management systems utilize modeling to better understand the pollutants from biodegradable waste, understand the source of the waste, and to compare system outputs with substitute products. The distinction between system analysis modelling and systems engineering modelling remains true for European municipalities: engineering methods are used before the creation of a system, and analysis methods are used to review to progress and impact of and existing system. LCA, sustainable assessment, and decision support systems were the most commonly used systems analysis models and forecast and optimization modelling was used most in systems engineering modelling (Pires et al. 2011).

## METHODS

### Optimization Model and Waste Calculator for UC Berkeley Campus

I created a linear programming model for the optimization of uses for each plastic resin, set to an identify an optimal solution for an objective of maximizing the sum of all end product profit value. This model was created with Majdi Abou Najm, Professor at UC Davis, and based on his 2002 master's project entitled "Computer-based interface for an integrated solid waste management optimization model". I used fixed rates, which are found using waste audit data, processing constraints, and relative costs and benefits associated with each item to identify pounds of material to use for each item, considering the cost associated with the production of each decision variable. I present a calculator which created to input waste audit data and total waste generation, per day, to calculate the estimated amount of plastic that will be inputted as feedstock, which will change the coefficients depending on this number.

### Study Site and UC Berkeley Plastic Recycling Waste Calculator

For this analysis, I used the UC Berkeley Plastics Recycling Facility Project as a system to analyze. This project, started in 2015 by the Zero Waste Research Center, aims to find local solutions to commonly discarded plastic waste. This calculator was created using proportions of waste calculated from waste audit data. This calculator returns tons of waste for each waste type, as identified before, considering an input of total waste generation per day (X). $\alpha$ represents proportion of waste that is recyclable, whereas $1-\alpha$ represents the proportion of total waste generation that is non recyclable (sorted landfill). Thus, total recyclable waste in the UC Berkeley waste stream:

Tons recycling waste that is actually recyclable (not contaminants) generated / day = $X\alpha$

$\alpha$ proportion differentiates non-recyclable and recyclable waste in the recycling bin, $\boldsymbol{\beta}_{\text{material}}$ represents the proportion of each material type, $\gamma_{\text{plastic resin}}$ represents the proportion of materials used from each material type sorted. Finally, $\phi_{\text{plastic resin, use}}$ is a variable representation of the proportion of plastic resin to be used for each use. So, to find total tonnage that is #1 PET plastic, given a total recycling waste generation amount, this would be:

Total waste that is #1 Plastic, given X lbs waste generated = $X\alpha\boldsymbol{\beta}_{\text{plastic}}\gamma_{\text{1 PET}}$

And, for example, to find total waste of the recycling that is paper:

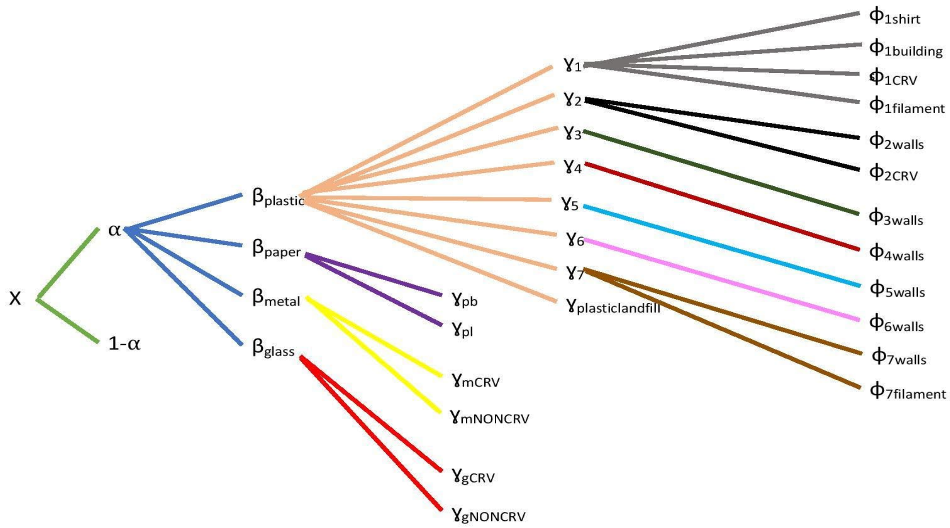
Total waste in recycling waste that is paper / day = $X\alpha\boldsymbol{\beta}_{\text{paper}}$

The constraints on these proportional measurements:

$$\sum\gamma_{\text{all plastic resin}} = 1$$
$$\sum\boldsymbol{\beta}_{\text{all material types}} = 1$$

The tree-thinking for the division of these rates, in terms of separating measurements for total recycling waste generated (Figure 1).

**Figure 1: Tree-thinking diagram for optimization decision variables.** Each decision variable represents a use for each material type. These options were identified with the ZWRC team and are the current methods of processing campus plastic waste.




The user inputs waste audit rates for each identified material type. Different rates can be measured, and more variables can be added for the material use of interest (i.e. one can define variables using this same method for paper, given they have a usage). The calculator was created to find materials generation to make a limit on the amount of end products that can be created.

**Table 1. Waste Audit Measurements Performed on Cans and Bottles Co-mingled Recycling, UCB Waste Audit.** Data was collected with the assistance of 3 student staff on April 15. Overall, 220 pounds of recycling waste was sorted.

| Measured Material | Description |
|---|---|
| TOTAL WEIGHT OF TOTER, FULL | Weight of Total Full, with all waste inside |
| TOTAL WEIGHT OF TOTER EMPTY | Weight of empty toter |
| TOTAL RECYCLING WASTE IN TOTER (X) | Weight of toter full - weight of empty toter. Total waste in toter. |
| Non-recyclable | Non-recyclable contaminants in recycling bin |
| Recyclable | All recyclable materials weight added |
| Paper | All recyclable paper waste in cans and bottles bins |
| Glass | All recyclable glass waste in cans and bottles bin |
| Plastic | All plastic waste in can and bottles bin |
| Metal (aluminum) | All recyclable metal and aluminum waste in the cans and bottles bin |
| #1 resin, PET | All PET Plastic Weight in Bin |
| #2 resin, HDPE | All HDPE Plastic Weight in Bin |
| #3 resin, PVC | All PVC Plastic Weight in Bin |
| #4 resin, LDPE | All LDPE Plastic Weight in Bin |
| #5 resin, PP | All PP Plastic Waste in Bin |
| #6 resin, PS | All PS Plastic Waste in Bin |
| #7 resin, PLA | All PLA Plastic Waste in Bin |

## Analysis: Optimization of Recycling Plastic Materials on the UC Berkeley campus

The Objective of the Plastics Recycling Facility is to maximize profit, considering all costs and revenues associated with the creation of each material. Thus, the objective function for this optimization problem is:

Maximize \$ / day = ∑ revenues from production of all end products - ∑ costs from production of all end products - fixed costs

The variable costs and benefits for the production of each of the identified (Table 2). Fixed costs are assumed to be accounted for in operational budgeting. For this analysis I only consider the variable costs of each production item as the program's operational budget is replenished annually.

**Table 2. Costs and Benefits associate with each cost (Variable Costs).** These values were estimated with the assistance of key project stakeholders. All costs and benefits are normalized by pound, as optimization requires all variables be in a similar unit.

| **Decision Variable** | **Pounds of Plastic per product** | **Cost of production per pound of plastic** | **Benefit of production per pound of plastic (retail savings)** | **Source** |
|---|---|---|---|---|
| #1 PET plastic for Unifi Shirts | .14 pounds of PET / unit | \$.37 | \$15 savings per pound | John Bissigniano, Unifi |
| #1 PET plastic for CRV | 1 lb / unit | \$ 0 | \$1.25 / pound | Calrecycle |
| #1 PET plastic for 3D Printer Filament | 2.2 lb/ unit | \$4 / kg | \$6.18 savings / kg spool | Filabot Extruders, Lauren Irie. Cost of 5 kg of virgin plastic resin at ⅓ of kg in spool plastic resin being used in feedstock being virgin material. 5 kg of plastic resin is \$60. |
| #1 PET for building components | 50 lb/ unit | \$0 as we already have equipment purchased | \$5 / pound | Prof. Ronald Rael |
| #2 HDPE for CRV refund | 1 lb / unit | \$0 | \$1.25 / pound | Calrecycle |
| #2 HDPE for building components | 50 lb/ unit | \$0 as we already have equipment purchased | \$5 / pound | Prof. Ronald Rael |

| | | | | |
|---|---|---|---|---|
| #3 PVC for building components | 50 lb/ unit | $0 as we already have equipment purchased | $5 / pound | Prof. Ronald Rael |
| #4 LDPE for building components | 50 lb/ unit | $0 as we already have equipment purchased | $5 / pound | Prof. Ronald Rael |
| #5 PP for building components | 50 lb/ unit | $0 as we already have equipment purchased | $5 / pound | Prof. Ronald Rael |
| #6 PS for building components | 50 lb/ unit | $0 as we already have equipment purchased | $5 / pound | Prof. Ronald Rael |
| #7 PLA/Other for filament | 2.2 lb/ unit | $4 / kg | $6.18 savings / kg spool | Filabot Extruders, Lauren Irie. Cost of 5 kg of virgin plastic resin at ⅓ of kg in spool plastic resin being used in feedstock being virgin material. 5 kg of plastic resin is $60. |
| #7 PLA/Other for building components | 50 lb/ unit | $0 as we already have equipment purchased | $5 / pound | Prof. Ronald Rael |
| Landfill Plastic (Plastic Contaminants) | 1 lb / unit | $49 / ton average, 2.4 cents per pound | No benefit | Lin King |

We are constrained by a budget, the law of conservation of mass (cannot use the same amount of material twice, cannot use more than amount of waste generated), and processing capacity.

*Law of Conservation of Mass*

We cannot create more end products for materials that are not generated. Thus, we can constrain the amount waste to be used in each end product as:

$$\phi_{1\ \mathrm{PET,\ Buildings}} + \phi_{1\ \mathrm{PET,\ Filament}} + \phi_{1\ \mathrm{PET,\ CRV}}\ \phi_{1\ \mathrm{PET,\ shirts}} \leq \mathrm{X}\alpha\boldsymbol{\beta}_{\mathrm{plastic}}\gamma_{1\ \mathrm{PET}}$$

…

And so on for each $\phi_{\text{plastic resin, use}}$, where the sum of all tons of plastic resin in each type plastic used must be less than or equal total amount of plastic generated from that type.

*Processing Capacity Constraint*

We can only process as much waste and create as many end products in a day given the amount of person hours available. Thus, we can constrain the amount of person hours available to work on the project by:

Total Employee Work Hours Available $\leq$ (Time required to sort per pound of PET and construct walls, as indicated in interviews)$\phi_{1\text{ PET, Buildings}}$ + (time required to sort per pound of PET and create filament, as indicated in interviews)$\phi_{1\text{ PET, Filament}}$ + (time required to sort pound of PET and transport to facility, in minutes) $\phi_{1\text{ PET, CRV}}$ + (time required to sort pound of PET and send to Unifi to create shirts, in minutes)$\phi_{1\text{ PET, shirts}}$

This is done for each $\phi_{\text{plastic resin, use}}$, where the sum of all work hours for each use of each type plastic used must be less than or equal total number of work hours available.

Based on previous waste audit time measurements, we calculated the time it would take to create end products with plastic resins. Average sorting time of the mixed recyclables was 27 minutes per average of 49.4 pounds of recycling waste, or 0.54 min per pound of recycling waste. This will be fixed for each processing decision. 3D Printer Filament takes our 3D Printer Filament Associate an average of 10 minutes to make 1 kg, or 4.5 minutes per pound of plastic to process. Buildings take about 45 minutes to make, according to Ronald Rael, or 0.18 min / pound. Unifi estimates that shirts take 30 minutes to create, or 0.12 minutes per pound to process. Finally, CRV programs take 30 minutes to drive to the CRV program and back, with recyclables, equating to a processing time of 30 min per maximum of 500 pounds that can fit in the vehicle. Thus, CRV programs take .06 min per pound of waste to process. Landfilling plastic takes 30 minutes to drive to Keller Canyon Landfill, with an equivalent load capacity, making the time to process landfilled plastic to be .06 min per pound of plastic. Currently, we have 2 staff available to work 10 hours /

week, or 520 hours / week each / year. Thus, total work hours available is 1040 hours/year, or 62400 minutes.

### Interviews of Key Project Personnel

I conducted 10 interviews with stakeholders in the UC Berkeley Recycling Facility Project (Table 3). I will be asking a standardized questionnaire (5 questions) about the sustainability implications of this project (questions still being developed), which I will review with Professor Kate O'Neill to find common trends in the responses. These questions will ask personnel to consider the tangible benefits (economic and environmental) and the intangible benefits (student-faculty relationships, campus ownership of waste) of this project. I will also allow respondents to add additional information and recommendations they may have for the project. These responses will be used to as evidence for the resulting optimization problem, and will be used to show the relative cost-effectiveness of the UC Berkeley Recycling Research Facility Project.

**Table 3: Contacts for the Plastics Recycling Facility Interviews**

| Contact Name | Contact Email | Position/Title | Relationship to UC Berkeley Plastics Recycling Facility Project |
|---|---|---|---|
| Sharon Daraphonhdeth | sdara@berkeley.edu | Supervisor of SERC | Project Staff Supervisor |
| Lin King | ltking@berkeley.edu | Campus Refuse and Recycling Services Manager | Project Staff Supervisor |
| Tarek Zohdi | zohdi@berkeley.edu | College of Engineering, Grant Manager, Materials Research | Faculty Project Lead |
| Ronald Rael | rrael@berkeley.edu | Materials Research, Plastic Structures | Faculty Project Partner |
| Scott Shackleton | scotts@berkeley.edu | Richmond GBC Supervisor | Administrative Project Lead and Dean of Capital Projects at UCB |

# RESULTS

## UC Berkeley Recycling Waste Audit

A waste audit of select recycling bins from campus buildings was performed on April 8-13, 2019. Waste audits were performed for 3 hours per day by student volunteers. Students recorded weight of each material type and contaminants, and further analyzed the recyclable waste for the amount of plastic that can be used in for each decision. These measured weights can be divided by the total waste generated in its more general material category to get a proportion that represents material type per total waste generated (Table 4) (i.e. to get a proportion to represent the amount of PET recycled in a recycling waste stream, you divide weight of PET recycled / total plastic waste recycled).

**Table 4: Average Waste Audit Results - Rates of Material Type in Recycling Container.** To find proportion of each recyclable materials, the measured weights were divided by the total amount of recyclable (non-landfilled) waste. To find the proportion of each plastic resin, the measured weights were divided by the total amount of measured plastic in each bin.

| | **Mulford** | **Wurster** | **Latimer** | **Etcheverry** | **AVERAGE (TO BE USED IN CALCULATOR)** |
|---|---|---|---|---|---|
| **Measured Material Description** | **Proportion of Weight Category** | **Proportion of Weight Category** | **Proportion of Weight Category** | **Proportion of Weight Category** | **Proportion of Weight Category** |
| TOTAL WEIGHT OF TOTER, FULL | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| TOTAL WEIGHT OF TOTER EMPTY | 0.31 | 0.44 | 0.34 | 0.50 | 0.40 |
| TOTAL RECYCLING WASTE IN TOTER (X) | 0.69 | 0.56 | 0.66 | 0.50 | 0.60 |
| Non-recyclable | 0.01 | 0.42 | 0.05 | 0.28 | 0.19 |
| Recyclable | 0.99 | 0.58 | 0.95 | 0.78 | 0.82 |
| Paper | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 |
| Glass | 0.59 | 0.55 | 0.78 | 0.03 | 0.48 |
| Plastic | 0.19 | 0.39 | 0.14 | 0.54 | 0.32 |
| Metal (aluminum) | 0.08 | 0.06 | 0.04 | 0.43 | 0.15 |
| Plastic Material, #1 resin | 0.64 | 0.35 | 0.53 | 0.39 | 0.48 |
| Plastic Material, #2 resin | 0.11 | 0.35 | 0.39 | 0.37 | 0.31 |
| Plastic Material, #3 resin | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Plastic Material, #4 resin | 0.16 | 0.12 | 0.08 | 0.11 | 0.11 |
| Plastic Material, #5 resin | 0.06 | 0.06 | 0.00 | 0.05 | 0.04 |
| Plastic Material, #6 resin | 0.02 | 0.00 | 0.00 | 0.08 | 0.02 |
| Plastic Material, #7 resin | 0.02 | 0.12 | 0.00 | 0.00 | 0.03 |

### Optimization of UC Berkeley's Recycling Waste Stream

Using the fixed variables from the measured averages in the waste audit, these variables were added as coefficients in each of the constraints. The amount of recycling waste generated by UC Berkeley in 2017 was 121.64 tons, so for this optimization, we will use 121.64 tons as our X, and the time period for this optimization will be one year.

The resulting amounts of resource constraints using 121.64 tons as X (total waste generated) and a time period of one year (Table 5). Total work hours for one year is two students at 10 hours per week each. Students work 52 weeks out of the year, so the total amount of work hours available is 1040 hours.

**Table 5: Resource Generation for 2018 Recycling Waste Generation.** The example total waste generated used in this calculator is the total amount of comingled bottles and cans generated at UC Berkeley in 2018.

| **Incoming Waste Generated (Pounds)** | | 243280 | In Tons = 121.4 |
|---|---|---|---|
| **Measured Material Description** | **Proportion of Waste Stream** | **Total Waste Generated of each Material Type, Based on Waste Audit Data, pounds** | **Total Waste Generated of each Material Type, Based on Waste Audit Data, tons** |
| Non-recyclable | 0.19 | 46434.49 | 23.22 |
| Recyclable | 0.82 | 200224.40 | 100.11 |
| Paper | 0.00 | 455.06 | 0.23 |
| Glass | 0.48 | 97030.24 | 48.52 |
| Plastic | 0.32 | 63295.46 | 31.65 |
| Metal (aluminum) | 0.15 | 30818.52 | 15.41 |
| Plastic Material, #1 resin | 0.48 | 30296.67 | 15.15 |
| Plastic Material, #2 resin | 0.31 | 19391.74 | 9.70 |
| Plastic Material, #3 resin | 0.00 | 0.00 | 0.00 |
| Plastic Material, #4 resin | 0.11 | 7249.03 | 3.62 |
| Plastic Material, #5 resin | 0.04 | 2752.64 | 1.38 |
| Plastic Material, #6 resin | 0.02 | 1496.50 | 0.75 |
| Plastic Mateiral, #7 resin | 0.03 | 2108.88 | 1.05 |

The optimal solution for 121.4 tons of recycling waste generated in 2018, using the waste audit results as fixed coefficients is to use 15.14 tons of #1 plastic for the creation of T-shirts, 9.69 tons of #2 plastic for building components, 3.62 tons of #4 plastic for building components, 1.37 tons of #5 plastic for building components, .74 tons of #6 plastic for building components, 1.05 tons of #7 plastic for filament. There was no PVC generation as no PVC was found in the recycling bin waste audits. Finally, the amount of contaminants for 121.64 tons of recycling waste annually is 23.21 tons of non-recyclable items sorted out, per year. All work hours were used in this analysis, and a revenue of $608,655.38 / year was identified from the costs and the benefits of the creation of each item.

### Interviews with Key Project Personnel

All interviews were successfully conducted with the identified key personnel. Common themes faculty and staff identified was a drive toward sustainability in their research and work, general support for the project, and an explanation of intangible (non-economic) benefits of the project. All interviews took place during the month of April and were completed either in-person or via email. Faculty identified how circular economies benefit their respective departments. Staff, on the other hand, explained how circular economies benefit budget and university operations.

## DISCUSSION

Results showed that there was an optimal strategy for managing the incoming recyclable waste stream at UC Berkeley, using the Plastics Recycling and Research Facility as a model. An analysis of the UC Berkeley waste stream indicates that the relative quality of UC Berkeley's recyclables is variable by each department on the UC Berkeley campus. The closed-loop, circular economy model of using waste resources in the creation of various end products is a model that can be used to work towards local solutions for the current stockpiling of plastic waste as a result of National Sword Policy. There are many social or intangible benefits associated with this project, including influencing faculty research programs towards sustainability goals, interdisciplinary campus partnerships, and the establishment of a circular economy on the UC Berkeley campus.

This study can inform waste management officials at municipalities and campus communities on how to optimize the use of recyclables to produce a circular waste economy.

## UC Berkeley Recycling Waste Quality

The waste audit performed at UC Berkeley Zero Waste Research Center showed relatively differing qualities of waste streams from different campus departments. In a waste audit done at University of British Columbia over the course of 3 days, recyclables accounted for nearly 24% of the total solid waste weight (Felder 1999). a comparison of the waste composition of three municipal neighborhoods in New York City indicated similar results to our waste audit. The more participation in recycling programs that a suburb had, the more recyclables were in the waste stream. Overall, the audit of NYC suburbs found that glass was the majority of weight in the recycling waste stream, concurrent with our measurements (Apahale et al. 2015). The recycling participation within the College of Natural Resources was described by Kate O'Neill as "very good, but there are still many single-use containers used in events and gatherings". This can explain the relative cleanliness, but heavy weight, of the recyclables measured from Mulford Hall. Professor Tarek Zohdi explains the College of Engineering's efforts toward increased recycling participation as a "relatively basic understanding, and some people give more effort than others. I do not think people really understand how their waste impacts everyone else" . The College of Natural Resources had 99% of waste discarded in the recycling bin being recyclables when compared to the amount of 78% clean recyclables generated by the College of Engineering. The higher contamination rate in the College of Engineering is a result of a lack of awareness for recycling programs. This data allows us to prioritize educational programs in efforts of educating those who need to improve their waste stream quality. To achieve a higher quality waste stream with more recyclables that can be used in the creation of end products, it may be beneficial to first target communities with high recycling participation rates.

## Linear Programming Optimization of UC Berkeley's Plastic Recycling Facility

The model found an optimal solution for the use of the plastic materials in the creation of various end products. This model attempts to capture regional-scale integrated solid waste management problems, as large scale systems can be optimized to maximize cost-savings in an entire collection system (Abou Najm 2002). With an objective of maximizing the profit from facility operation, the most optimal solution for X tons of waste generated was to (list all optimal solutions, #1-7 plastic). Because contamination rates were accounted for, 23.21 tons of this waste is to be landfilled, as not all recyclable waste that is generated will be usable in the creation of end products. The shirt production was the most optimal use of #1 plastic due to the relative rates of return from the production per pound of this item. The most optimal use 9.69 tons of #2 plastic was to building components, due to relatively low rate of return of profit for CR program.

a sensitivity analysis of this model, using a community in Northern Lebanon as an example, found that increased overall waste generated increased recycling returns, as a result of more waste reaching the facilities for processing. This provided a larger stock, which allowed for more money to be generated from operation. Landfilling was found to be a competitive option in the optimization of Northern Lebanon waste collection systems. This is because processing facilities in Northern Lebanon were not the ultimate waste disposal location; as operational costs increased, landfilling became more optimal (Abou Najm et al. 2002). To favor recycling solutions in the UC Berkeley Plastics Recycling Facility over landfilling solutions, greater waste generation and reduced operational costs will maximize the revenue associated with the creation of end products from recycled campus waste. This is because more materials are available to use to generate profit and reduced operational costs reduce the impact of fixed costs in this model's objective function.

**Intangible Benefits of the UC Berkeley Plastics Recycling Facility**

Key project stakeholders identified various intangible, non-economic benefits associated with the UC Berkeley Plastics Recycling Facility. Professor Kate O'Neill responded that the UC Berkeley Plastics Recycling Facility provided introductory technical career opportunities to UC Berkeley students, which is not very common on UC campusesProfessor Kate O'Neill also stated that this project has influenced her research to include waste and international relations throughout her involvement with this project, a passion which has led her to write an informative waste-transfer mechanisms book entitled *Waste* (O'Neill 2019). Dean Scott Shackleton reports that this project has provided the College of Engineering with a unique perspective on sustainability: "This program has allowed the College of Engineering to engage in sustainability as it relates to efficiency and low impact mechanical engineering." In an interview analysis investigating a recent cultural shift towards sustainable design in construction engineers, it was identified that influential power of various stakeholders and economic awareness of sustainability resulted in more environmentally-preferable construction methods (Yip Robin et al. 2009).

Sharon Daraphondeth reports that the benefits that students experience with this project include research opportunities, growing sense of place with the university, and increased communication across departments and campus communities. A student-led zero waste program was implemented at Massey University in New Zealand, which created paid research associate positions, with some support from facilities staff and senior management. Lin King, Cal Zero Waste Manager, states that the student efforts and advocacy towards zero waste has assisted his programs through volunteer support, campus administration pressure, and funding support. All of these structural linkages were identified as necessary in the success of a zero waste program, which the UC Berkeley Plastics Recycling Facility appears to succeed in (Mason et al. 2003).

**Limitations of Optimization in Waste Management**

There are some limitations of using optimization as a solution for waste management solutions. Optimization is considered a systems engineering model of analysis for waste management. Many of these quantitative-based models can only reflect part of impact factors, leaving the remaining uncertainties out of the calculations. Because all of our costs and benefits were collected by interviews and personal considerations of my colleagues, this may not represent the realistic cost of the production of these items. We are basing our estimates off of self-measured production operations, which could be cheaper or more expensive for other parties, depending on their institutional context for the use of the end products. Most systems engineering models also fail to account for dynamics, thus complex models that are difficult to understand and need large datasets such as optimization models are required.

Systems engineering models also fails to provide visualization of an inputted system, as they are focused on quantitative outcomes rather than methodological improvements (Huang et al. 2003). In one model using optimization and inexact mixed integer linear programming to predict long-term planning of integrated solid waste management systems, industrial waste and "littered" or "lost" waste is not accounted for, and all waste is assumed to be handled (Huang et al. 2005).

Thus, if these assumptions are consistent when the UC Berkeley Plastics Recycling Facility is operational, then this optimization model will be close to accurate. However, creating such a facility may be a learning process from construction to processing all of campus waste, indicating that there may be some inaccuracies from the optimal solution identified. Finally, we did not account for fixed costs in this analysis, which are assumed to be accounted for by our operational budget that is replenished. This is not the case with most MRFs, so fixed costs should be normalized across all costs to account for electrical, staff salary, and incidentals.

**Local, Circular Waste Economy as a benefit for University Campuses**

Due to the relative cost-effectiveness and social (non-economic) benefits associated with the UC Berkeley Plastics Recycling Facility, this model can be applied to other similarly-sized campuses to provide a sustainable waste management solution for plastic recyclables and other reclaimable waste resources. Through linear programming, an optimal solution to maximize profit can be identified for an incoming stream of waste, given detailed waste audit values. Constraints and objectives can be modified to account for distance traveled, various labor and processing constraints, and other operational costs that were not previously identified in the construction of this research facility. The social benefits of this project include student research positions, faculty-staff and student relationships, and an interdisciplinary approach to sustainability on the UC Berkeley campus. This is observed in the changes in sustainability culture of faculty research and facility operations. This model can be applied, with similar planning and structural linkages, at other universities, potentially resulting in a cost-savings method for handling campus waste resources.

**Future Implications and Research Priorities**

I was interested in identifying the best way to recycle plastic material, as I see many problems with the overall efficiency and energy requirements of conventional recycling procedures. Across the United States, we are experiencing a stall in plastic waste recycling due to the National Sword Policy. The National Sword Policy was a push by the Chinese government to advocate for a cleaner country by restricting the imports of contaminated recycling from Western countries. This impacted the United States greatly as China imposed a .5% contamination limit, decreased from the prior limitation of 10%, for which the United States generates too contaminated of waste streams for any exports to be taken. Due to the National Sword Policy, I could expect to see more incineration and landfilling procedures for plastic waste domestically on a large scale. The United States must handle the waste that is no longer being sent overseas, as it is stockpiling in recycling facilities across the nation (CalRecycle, "National Sword"). There is a need to identify methods to recycle plastic waste domestically, as the current procedures that are commonly practiced in recycling do not reclaim the highest resource value from plastic waste material. Disassembly of products is well understood to be needed to make recycling economically and environmentally viable, and as a result, multiple recycling methodologies have developed (Kuo 2005). This local, circular economy model for handling waste resources can be used as evidence for supporting local, domestic mechanical recycling projects that aim to obtain high resource value from plastic waste. Optimization analysis and linear programming, as well as life cycle analysis, can be used to manage the impact of integrated solid waste management systems on the environment by measuring the potential greenhouse gas emissions and energy requirements associated with the disposal of waste products (Finnveden 1999). This study identifies an optimal solution to plastic waste generated on a college campus, a solution that creates community and economic benefits from plastic waste for research-driven academic objectives.

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## APPENDIX A: UC Berkeley Recycling Waste Audit Results: Mulford Hall

**Monday April 15**

| **Toter** | Mulford | **Number of People Auditing 1** |
|---|---|---|
| **Total Time of Audit of Toter** | 40 min | **Toter Size (gal) 96 gall** |
| **Measured Material Description** | **Weight (lbs)** | **Porportion of Weight Category** |
| TOTAL WEIGHT OF TOTER, FULL | 48.3 | 1 |
| TOTAL WEIGHT OF TOTER EMPTY | 15 | 0.310559006 |
| TOTAL RECYCLING WASTE IN TOTER (X) | 33.3 | 0.689440994 |
| Non-recyclable | 0.4 | 0.012012012 |
| Recyclable | 32.9 | 0.987987988 |
| Paper | 0 | 0 |
| Glass | 19.3 | 0.58662614 |
| Plastic | 6.4 | 0.194528875 |
| Metal (aluminum) | 2.6 | 0.079027356 |
| #1 resin, PET | 4.1 | 0.640625 |
| #2 resin, HDPE | 0.7 | 0.109375 |
| #3 resin, PVC | 0 | 0 |
| #4 resin, LDPE | 1 | 0.15625 |
| #5 resin, PP | 0.4 | 0.0625 |
| #6 resin, PS | 0.1 | 0.015625 |
| #7 resin, PLA | 0.1 | 0.015625 |

**Table A1: Waste audit measurements for Mulford Hall Toter.** Data was collected on April 15, 2019. Multiple 96 gallon toters were sorted, and their respective weights were recorded. The proportion values for recyclable are based on total waste amount, whereas recyclable materials proportions is based on total amount of recyclables, and plastic proportions are based on total amount of plastic.

## APPENDIX B: UC Berkeley Recycling Waste Audit Results: Wurster Hall

**Monday April 15**

| **Toter**<br>**Total Time of Audit of Toter** | Wurster<br>30 min | **Number of People Auditing**<br>**2**<br>**Toter Size (gal) 96 gal** |
|---|---|---|
| **Measured Material Description** | **Weight (lbs)** | **Porportion of Weight Category** |
| TOTAL WEIGHT OF TOTER, FULL | 34 | 1 |
| TOTAL WEIGHT OF TOTER EMPTY | 15 | 0.441176471 |
| TOTAL RECYCLING WASTE IN TOTER (X) | 19 | 0.558823529 |
| Non-recyclable | 8 | 0.421052632 |
| Recyclable | 11 | 0.578947368 |
| Paper | 0.1 | 0.009090909 |
| Glass | 6 | 0.545454545 |
| Plastic | 4.25 | 0.386363636 |
| Metal (aluminum) | 0.7 | 0.063636364 |
| Plastic Material, #1 resin | 1.5 | 0.352941176 |
| Plastic Material, #2 resin | 1.5 | 0.352941176 |
| Plastic Material, #3 resin | 0 | 0 |
| Plastic Material, #4 resin | 0.5 | 0.117647059 |
| Plastic Material, #5 resin | 0.25 | 0.058823529 |
| Plastic Material, #6 resin | 0 | 0 |
| Plastic Mateiral, #7 resin | 0.5 | 0.117647059 |

**Table A2: Waste audit measurements for Wurster Hall Toter.** Data was collected on April 15, 2019. Multiple 96 gallon toters were sorted, and their respective weights were recorded. The proportion values for recyclable are based on total waste amount, whereas recyclable materials proportions is based on total amount of recyclables, and plastic proportions are based on total amount of plastic.

## APPENDIX C: UC Berkeley Recycling Waste Audit Results: Etcheverry Hall

**Monday April 15**

| **Toter** | Etcheverry | **Number of People Auditing 2** |
|---|---|---|
| **Total Time of Audit of Toter** | 20 | **Toter Size (gal) 96 gall** |
| **Measured Material Description** | **Weight (lbs)** | **Porportion of Weight Category** |
| TOTAL WEIGHT OF TOTER, FULL | 30 | 1 |
| TOTAL WEIGHT OF TOTER EMPTY | 15 | 0.5 |
| TOTAL RECYCLING WASTE IN TOTER (X) | 9 | 0.5 |
| Non-recyclable | 2.5 | 0.277777778 |
| Recyclable | 7 | 0.777777778 |
| Paper | 0 | 0 |
| Glass | 0.2 | 0.028571429 |
| Plastic | 3.8 | 0.542857143 |
| Metal (aluminum) | 3 | 0.428571429 |
| Plastic Material, #1 resin | 1.5 | 0.394736842 |
| Plastic Material, #2 resin | 1.4 | 0.368421053 |
| Plastic Material, #3 resin | 0 | 0 |
| Plastic Material, #4 resin | 0.4 | 0.105263158 |
| Plastic Material, #5 resin | 0.2 | 0.052631579 |
| Plastic Material, #6 resin | 0.3 | 0.078947368 |
| Plastic Mateiral, #7 resin | 0 | 0 |

**Table A3: Waste audit measurements for Etcheverry Hall Toter.** Data was collected on April 15, 2019. Multiple 96 gallon toters were sorted, and their respective weights were recorded. The proportion values for recyclable are based on total waste amount, whereas recyclable materials proportions is based on total amount of recyclables, and plastic proportions are based on total amount of plastic.

## APPENDIX D: UC Berkeley Recycling Waste Audit Results: Latimer Hall

**Monday April 15**

| **Toter**<br>**Total Time of Audit of Toter** | Latimer<br>20 | **Number of People Auditing 2**<br>**Toter Size (gal) 96 gall** |
|---|---|---|
| **Measured Material Description** | **Weight (lbs)** | **Porportion of Weight Category** |
| TOTAL WEIGHT OF TOTER, FULL | 43.5 | 1 |
| TOTAL WEIGHT OF TOTER EMPTY | 15 | 0.344827586 |
| TOTAL RECYCLING WASTE IN TOTER (X) | 28.5 | 0.655172414 |
| Non-recyclable | 1.5 | 0.052631579 |
| Recyclable | 27 | 0.947368421 |
| Paper | 0 | 0 |
| Glass | 21 | 0.777777778 |
| Plastic | 3.8 | 0.140740741 |
| Metal (aluminum) | 1.2 | 0.044444444 |
| Plastic Material, #1 resin | 2 | 0.526315789 |
| Plastic Material, #2 resin | 1.5 | 0.394736842 |
| Plastic Material, #3 resin | 0 | 0 |
| Plastic Material, #4 resin | 0.3 | 0.078947368 |
| Plastic Material, #5 resin | 0 | 0 |
| Plastic Material, #6 resin | 0 | 0 |
| Plastic Mateiral, #7 resin | 0 | 0 |

**Table A4: Waste audit measurements for Latimer Hall Toter.** Data was collected on April 15, 2019. Multiple 96 gallon toters were sorted, and their respective weights were recorded. The proportion values for recyclable are based on total waste amount, whereas recyclable materials proportions is based on total amount of recyclables, and plastic proportions are based on total amount of plastic.

# APPENDIX D: Optimization Calculator

| | Decision Variables (in pounds) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 30296.66846 | 0 | 0 | 0 | 0 | 19391.73557 | 0 | 7249.032324 | 2752.642052 | 1496.500337 | 2108.878992 | 0 | 0 | | | |
| Decision Variable Description | #1 PET plastic for Unifi Shirts | #1 PET plastic for CRV | #1 PET plastic for 3D Printer Filament | #1 PET for building components | #2 HDPE for CRV refund | #2 HDPE for building components | #3 PVC for building components | #4 LDPE for building components | #5 PP for building components | #6 PS for building components | #7 PLA/Other for filament | #7 PLA/Other for building components | Landfill Plastic (Plastic Contaminants) | | | |
| Decision Variable Symbol | ϕ1 PET, Shirts | ϕ1 PET, CRV | ϕ1 PET, Filament | ϕ1 PET, Buildings | ϕ2 PET, CRV | ϕ2 PET, Building | ϕ3 PVC, Buildings | ϕ4 LDPE Buildings | ϕ5 PP, Buildings | ϕ6 PS, Buildings | ϕ7 PLA/Other, Filament | ϕ7 PLA/Other, Buildings | ϕPlastic, Landfill | | | |
| | Constraints | | | | | | | | | | | | | Total Contribution | | Targets |
| Processing Capacity (minutes / work / week) | 0.66 | 0.6 | 2.74 | 0.72 | 0.6 | 0.72 | 0.72 | 0.72 | 0.72 | 0.72 | 2.74 | 0.72 | 0.6 | 48014.86503 | <= | 62400 |
| Capacity/Conservation of Mass (cannot process the same plastic used) | 30296.67 | 30296.67 | 30296.67 | 30296.67 | 19391.74 | 19391.74 | 0.00 | 7249.03 | 2752.64 | 1496.50 | 2108.88 | 2108.88 | 46434.49 | | | |
| | Costs and Benefits of Each Decision Variable | | | | | | | | | | | | | TOTAL COSTS AND BENEFITS | | |
| Costs per pound of production | $ 0.37 | $ - | $ 8.80 | $ - | $ - | $ - | $ - | $ - | $ - | $ - | $ 8.80 | $ - | $ 0.02 | $ 29,767.90 | | |
| Benefits | $ 15.00 | $ 1.25 | $ 14.00 | $ 5.00 | $ 1.25 | $ 5.00 | $ 5.00 | $ 5.00 | $ 5.00 | $ 5.00 | $ 14.00 | $ 5.00 | $ - | $ 638,423.88 | | |
| | | | | | | | | | | | | | TOTAL REVENUE (OBJECTIVE IS TO MAXIMIZE | $ 608,655.98 | | |

**Table A5: Optimization calculator used to find the optimal solution for handling incoming generated recycling waste.** This calculator was used in excel, and the Solver function was utilized to find an optimal solution. Constraints for this optimization problem are in the middle of the table, with the effects of completing one pound of production being listed towards the total effects. The decision variables take units of pounds, so all effects and benefits/costs are based off of a per pound measurement. The objecrtive inputted into the solver was to maximize the total revenue (costs – benefits).