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Economic and environmental analysis of extrusion processing of grains into foods and feeds

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Abstract.
One of the major problems facing our planet with such a rapidly growing population is a need for cheap and healthy food in developing countries. Although there have already been many valiant attempts at helping this crisis, a “cure-all” solution is still not likely. A common nutrient lacking from many people’s diets in developing countries is protein. One way in which this problem can be mitigated is through the use of Textured Vegetable Protein (TVP). This product is produced from the grain extrusion process, is lightweight, and carries high-protein content. It is important to analyze if this product can act as a suitable, sustainable option for protein in developing countries. In order to examine this we have focused on Brazil and Bolivia specifically. In this project, we have five scenarios and we will conduct techno-economic analysis and life cycle assessment to compare all scenarios.

Keywords. *Extrusion, food processing, grain, food, economic analysis, economic evaluation.*

Introduction

People around the world are hungry and lacking appropriate nuttitional content. One product the combats this problem is Texturized Vegetable Protein (TVP). This product is obtained through an extrusion process in which the grain is ground, mixed with water, extruded into a puffy substance, and dried. TVP can be used for animal or human consumption. TVP provides more protein to the diet of those who consume it and can be added to other food to make it last longer and give it more nutritional content.

The first focus of our project was examining extrusion in Iowa. Iowa was selected because of the agricultural production and location of our university. Four other countries were examined including: Nigeria, Cameroon, Bolivia, and Brazil. The goal of this background research was to select a pair of countries that could mutually benefit from extrusion in the area, both for the economy and the well-being of citizens.

The first thing considered were the grains grown in each country, as well as the surplus that is recognized as available. This was considered because the technology works best with certain combinations, although several types of grain can be extruded. The other main item of consideration was the amount of food available per day per person. This was a key criterion so that the partnership where extrusion could make the largest difference could be selected.

Table 1. Depicts the comparison between the four countries based on the categories of grain grown, quantity of grain grown, and the amount food available in each country for a person.

Countries & Grains				
Country	**Grains grown**	**How much?**	**Surplus?**	**kg food available/day/person**
Brazil	Soybeans, rice, wheat, corn	Soybeans – 65.7 million metric tons Rice – 11.4 million metric tons Wheat – 4.4 million metric tons Corn – 71.3 million metric tons	Soybeans – 33 million metric tons Rice – 1.3 million metric tons Wheat – 2.4 million metric tons Corn – 9.5 million metric tons	2.857
Bolivia	Soybeans	2.4 million metric tons	27, 000 metric tons	1.669
Cameroon	Corn, millet, rice	Corn – 1.6 million metric tons Millet – 98,000 metric tons Rice – 139,000 metric tons	Corn – 20 metric tons Millet – 0 Rice – 1,500 metric tons	2.098
Nigeria	Corn, Soybeans	Corn – 9.4 million metric tons Soybeans - 450,000 metric tons	Corn – minimal Soybeans – 11,000 metric tons	2.036

Brazil and Bolivia were selected because Brazil has the greatest surplus of key grains used for extrusion and Bolivia is most challenged for available food per person. The locations selected are the opportunity to make the largest impact with an extruded product. In addition, Brazil is an economic power in South America and can manufacture and develop the technology necessary for extrusion and then sell a much-needed product to their neighboring country, Bolivia.

Figure 1. Map of the Americas showing the locations selected for analysis of extrusion.

Scope

We analyzed five scenarios:

1. Extrude grain in Iowa and ship to South America (Figure 2a.)
    a. This scenario was chosen to be analyzed because Iowa has a grain surplus and the capabilities to produce an extruded product by using current manufacturing technology available in the state. The grain would then be shipped to South America to be consumed by the target market.
2. Ship grain from Iowa and extrude “on-site” (Figure 2b.)
    a. This scenario was chosen to be analyzed because Iowa has a grain surplus and Brazil has the capabilities to produce an extruded product by using manufacturing technology that is already available. The grain would then be consumed in Brazil or Bolivia.
3. Extrude in Brazil with local grains (Figure 2c.)
    a. This scenario was chosen to be analyzed because Brazil has a grain surplus and the capabilities to produce an extruded product by using manufacturing technology that is already available. The grain would then be consumed in Brazil.
4. Extrude in Brazil with local grains and ship to neighboring country, Bolivia (Figure 2d.)
    a. This scenario was chosen to be analyzed because Brazil has a grain surplus and the capabilities to produce an extruded product by using manufacturing technology that is already available. The grain would then be consumed in neighboring Bolivia.
5. Import local grain and extrude product to be consumed locally (Figure 2e.)
    a. This scenario was chosen to be analyzed because Brazil has a grain surplus and Bolivia has the capabilities to produce an extruded product by using manufacturing technology that is already available and could be further developed for economic gain and opportunity within their country. The grain would be consumed in Bolivia.

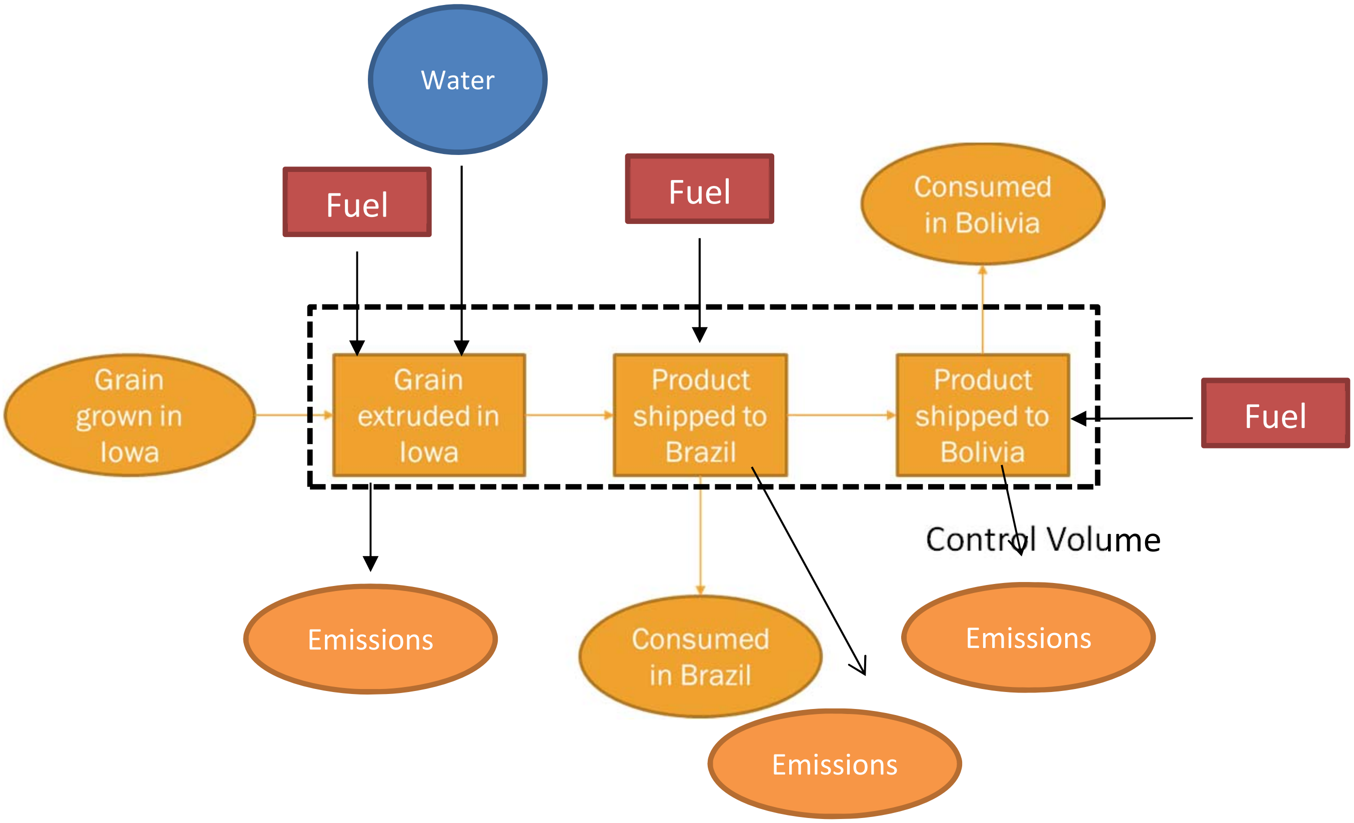

Figure 2a. Flowchart depicting the process if grain is grown and extruded in Iowa, then shipped to South America for consumption.

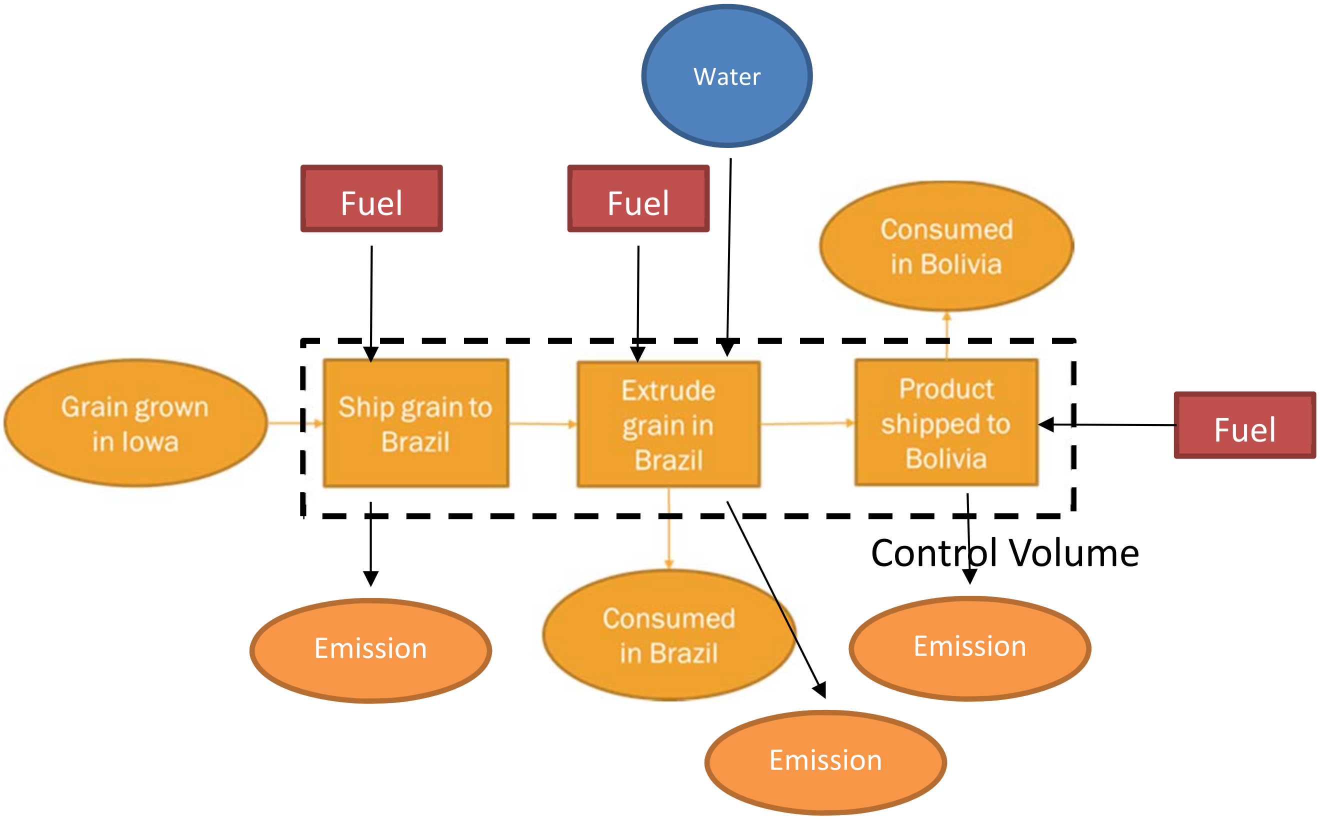

Figure 2b. Flowchart depicting the process if grain is grown in Iowa and extruded in Brazil, then shipped to South America for consumption.

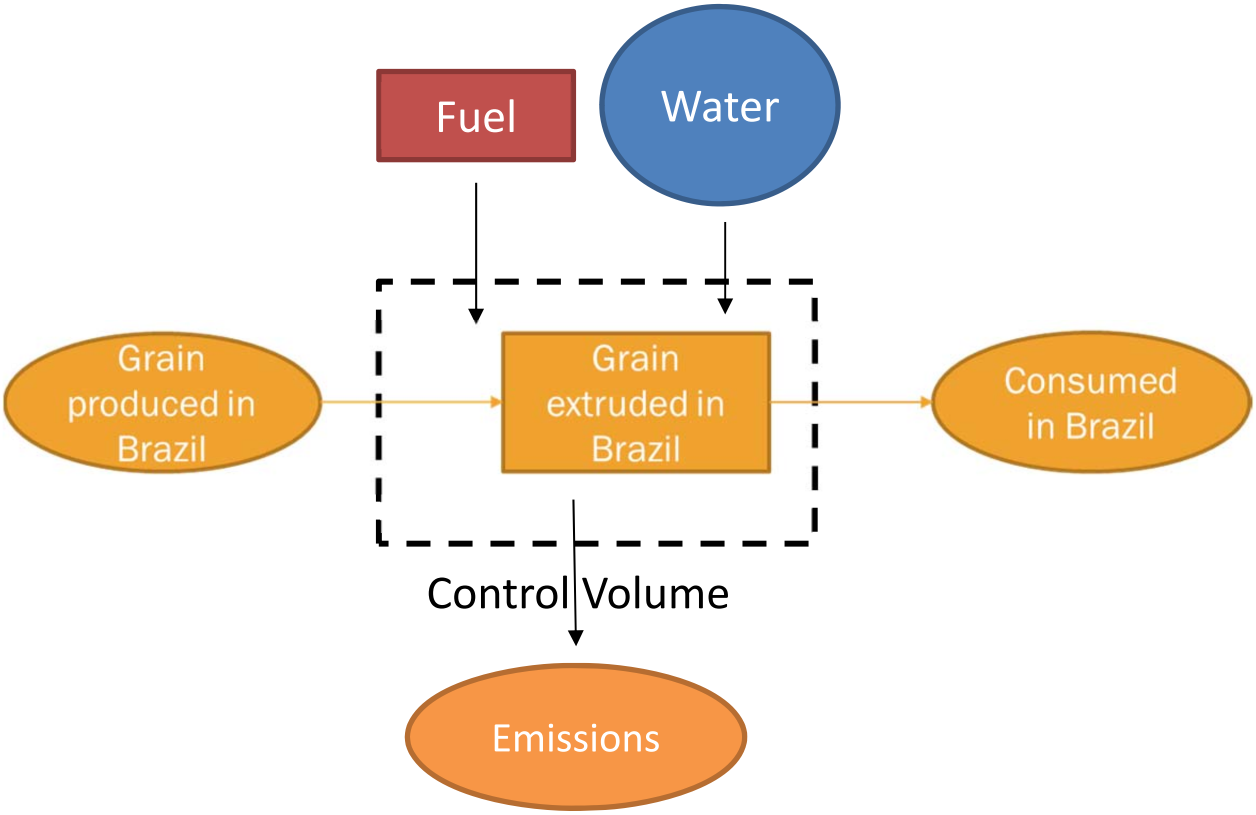

Figure 2c. Flowchart depicting the process if grain is grown, extruded, and consumed in Brazil.

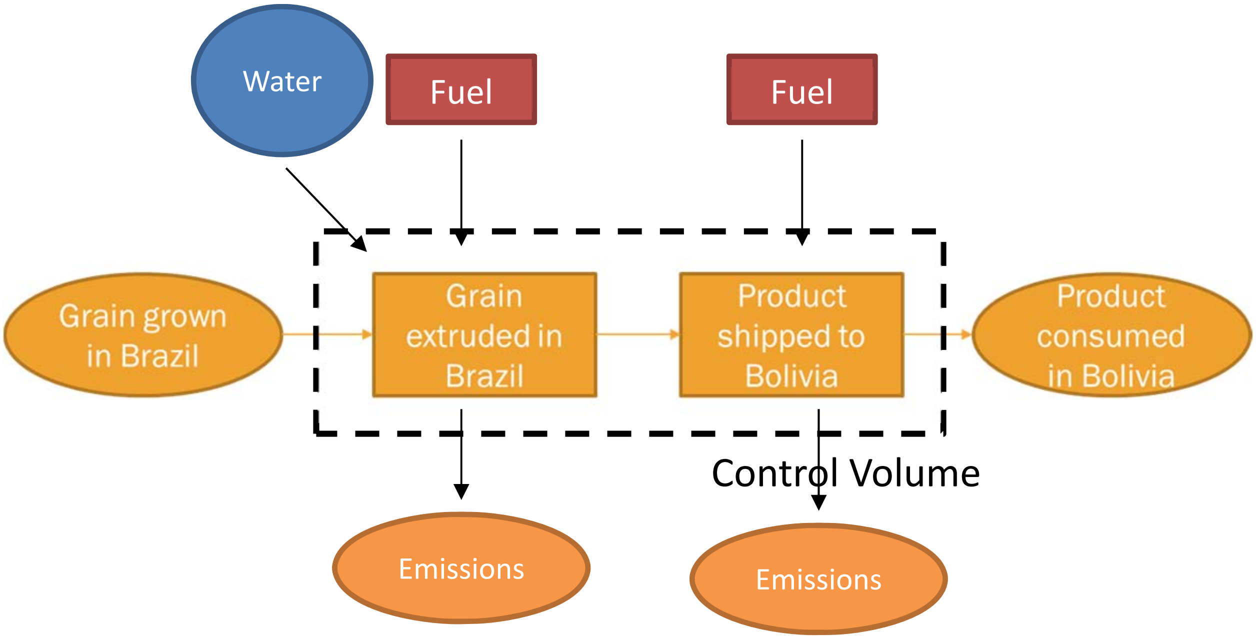

Figure 2d. Flowchart depicting the process if grain is grown and extruded in Brazil, then consumed in Bolivia.

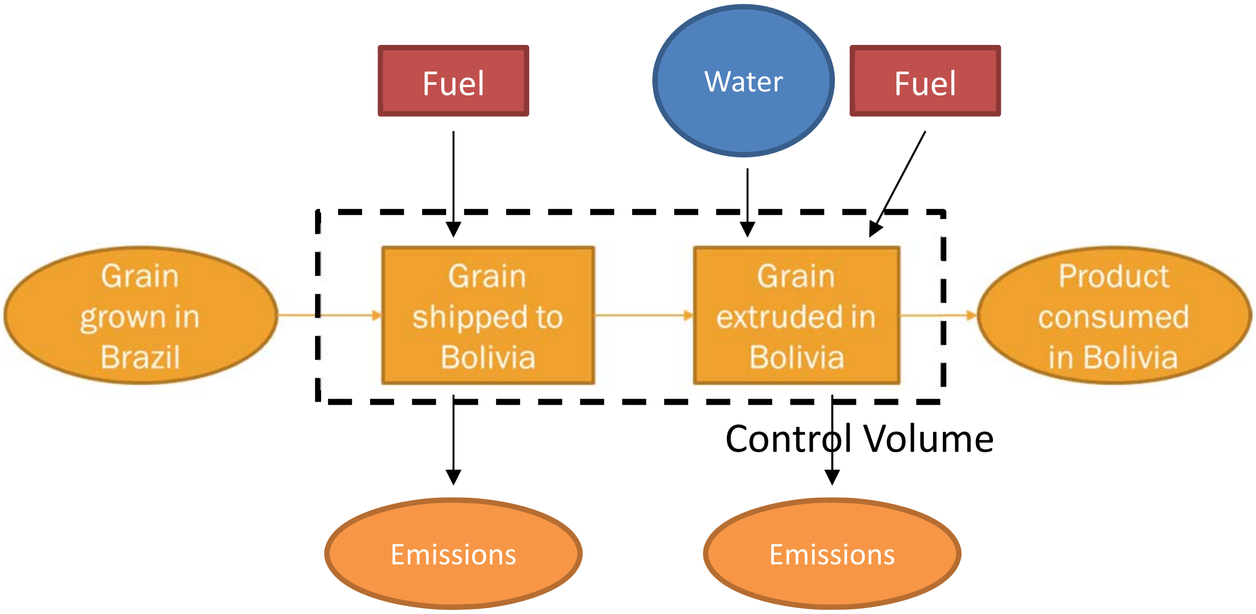

Figure 2e. Flowchart depicting the process if grain is grown in Brazil then extruded and consumed in Bolivia.

The five scenarios were selected based on likelihood of occurrence, availability of resources, and overall realistic approach. After the scenarios were selected, life cycle assessment and techno-economic analysis were conducted for each possible scenario.

Objectives

The objectives of the group are to analyze economic and environmental impact for several transportation scenarios and extruding grain products in three countries. We seek to identify the best transportation scenario and method based on economic cost, greenhouse gas emissions, and fuel required. We will identify the best country to exrude in based on cost to complete process, fuel needed, and greenhouse gas emissions. We will also recommend a grain or grain mixture that should be used for extrusion.

Constraints and Limitations

One constraint on our project is the transportation methods that can be considered. There are limited options for transporting large quantities of grain or extrued product over a long distance. We were only able to consider four viable transporation methods, and even with those, we had to make assumptions that could be limiting. An example of such an assumption is working on the assumption that train transportation is available wherever truck transportation is available.

A limitation placed on this project is identifying our target consumer. Our consumer is in need of an enriched diet that is lacking in protein or needs to make food last longer. TVP can be added to existing food, such as stew or rice, to add nutrition and get more servings from one dish. Our consumer likely lives in poverty, so this analysis is seeking the most economically sound process so it can be sold to them for the cheapest price.

Transportation Analysis

A life cycle assessment and techno-economic analysis were performed on the transportation methods that could be used for all five scenarios.

Before beginning the location analyses, assumptions (Table 2a) were made based on internationally recognized trade ports and routes, as well as large cities in the selected locations. Capacity of carrier data was compiled to maintain consistent results throughout all analyses. (Table 2b). Distances to be used for all analyses were found and stated (Table 2c).

Table 2a. Assumptions made for location analyses to maintain consistent results.

Location Assumptions	
#1	Grain produced and extruded in Iowa, shipped to Sao Paulo, consumed in Brazil
#2	Grain produced in Iowa, shipped to Sao Paulo, extruded and consumed in Brazil
#3	Grain produced in Brazil, extruded in Sao Paulo and consumed in Brazil
#4	Grain produced and extruded in Brazil, shipped to Santa Cruz, consumed in Bolivia
#5	Grain produced in Brazil, shipped to Santa Cruz, extruded and consumed in Bolivia

Table 2b. Capacity of different methods of transportation.

Capacity (tonne)	
Truck	20.454
Train	98.318
Barge (river)	1900
Panamax (ocean)	32500

Table 2c. Distances between shipping ports used to analyze transportation.

Distance (km)	
DSM-Davenport	350
Davenport-New Orleans	2312
New Orleans-Sao Paulo	9952
Campo Grande - Sao Paulo	1014
Sao Paulo - Santa Cruz	3509
Campo Grande- Santa Cruz	1712
DSM-Sao Paulo (land)	12500

Life Cycle Assessment Methods

Table 3a. Assumptions made before the life cycle assessment of transportation was performed.

Life Cycle Assessment Assumptions
Water is not consumed by transportation methods.
Railroads are available everywhere.
Adequate roads are available everywhere.
The grain produced in Iowa is local to Des Moines.
The grain produced in Brazil is local to Campo Grande in the state of Mato Grosso in Brazil.

Table 3b. Values used to conduct assessment (Sources: 4, 15).

Energy Consumption (MJ/tonne-km)		
Truck	2.5	
Train	1.2	
Barge	0.4	
Panamax	0.7	
CO_2 Produced (kg/tonne-km)		
Truck	0.2	
Train	0.069	
Barge	0.04	
Panamax	0.04	
VOC Produced (kg/tonne-km)		**CO_2 Equivalent (kg/tonne-km)**
Truck	0.00010	0.0025
Train	0.00007	0.00175
Barge	0.00004	0.001
Panamax	0.00004	0.001
NO_X Produced (kg/tonne-km)		**CO_2 Equivalent (kg/tonne-km)**
Truck	0.00226	0.67348
Train	0.00122	0.36356
Barge	0.00069	0.20562
Panamax	0.00069	0.20562
Total CO_2 Equivalent (kg/tonne-km)		
Truck	0.87598	
Train	0.43431	
Barge	0.24662	
Panamax	0.24662	

Energy consumed was calculated by multiplying the distance traveled in each scenario by the assumed energy required to travel per kilometer. This energy factor varied greatly depending on the type of transportation method: truck, train, vessel. This calculation allowed us to find both the total energy consumed per transportation scenario as well as how much energy was consumed per kilogram of product being transported.

The CO_2 equivalent emissions were calculated by multiplying an emission factor for each mode of transportation by the distance that vehicle would travel with product. The individual energy consumption of each mode was then totaled to find an overall total of the emissions of each transportation scenario. During these calculations, many different types of emissions were considered, including CO_2, NO_X, and VOC. Conversion factors were used based on the global warming potential of each emission to determine what these would represent in a unit of CO2 equivalents. The sum of all CO_2 equivalents was then used to find the total emissions produced. After the total emissions were found, the number could be divided by the quantity of the grain or extruded product being transported to find the kilograms of CO_2 equivalent produced per tonne of product transported.

An example of these calculations is given (Table 3c).

Table 3c. Example of table used to calculate values.

Scenario #1 (Des Moines to Sao Paulo)					
	Transportation Mode	**Capacity (tonne)**	**Distance (km)**	**Energy Consumed (MJ/tonne)**	**CO_2 Equivalents Produced (kg/tonne)**
Using Truck	Truck	20.454	350	875	306.593
	Barge	1900	2312	924.8	570.18544
	Panamax	32500	9952	6966.4	2454.36224
Total			**12614**	**8766.2**	**3331.14068**
Using Train	Train	98.318	350	420	152.0085
	Barge	1900	2312	924.8	570.18544
	Panamax	32500	9952	6966.4	1718.053568
Total			**12614**	**8311.2**	**2440.247508**

All scenarios were calculated for both train or truck transportation so that both methods of land transport could be accurately compared.

In addition to the five scenarios of transportation, a life cycle assessment was also conducted using the same methods assuming 100% transportation by land, both by truck and by train. The assumption was made that it was possible to transport from Des Moines, Iowa, to Sao Paulo, Brazil, over land.

Life Cycle Assessment Results

The gigajoules of energy consumed for each scenario and method of calculation vary greatly and impact the economic feasibility of offering a cheap product to consumers. The cheaper the transportation cost, the lower the price can be to sell the product to a low-income consumer who needs it. Table 4a shows the numerical value of energy consumed by each method of transportation.

Table 4. Depicts the amount of energy consumed by each scenario.

Scenario	Energy Consumed (GJ/tonne)
#1 (Truck)	8.7662
#1 (Train)	8.3112
#2 (Truck)	8.7662
#2 (Train)	8.3112
#3 (Truck)	2.535
#3 (Train)	1.2168
#4 (Truck)	8.7725
#4 (Train)	4.2108
#5 (Truck)	4.28
#5 (Train)	2.0544
100% Truck	31.25
100% Train	15

The scenarios that involve transporting grain or product from Iowa to South America use more energy than most scenarios analyzed in South America. The only exception is transporting extruded product from Brazil to Bolivia by truck. The least amount of energy consumed is for the scenario in which grain is grown and extruded in Brazil, then consumed in the same country. All possible scenarios can be visually compared in Figure 3a.

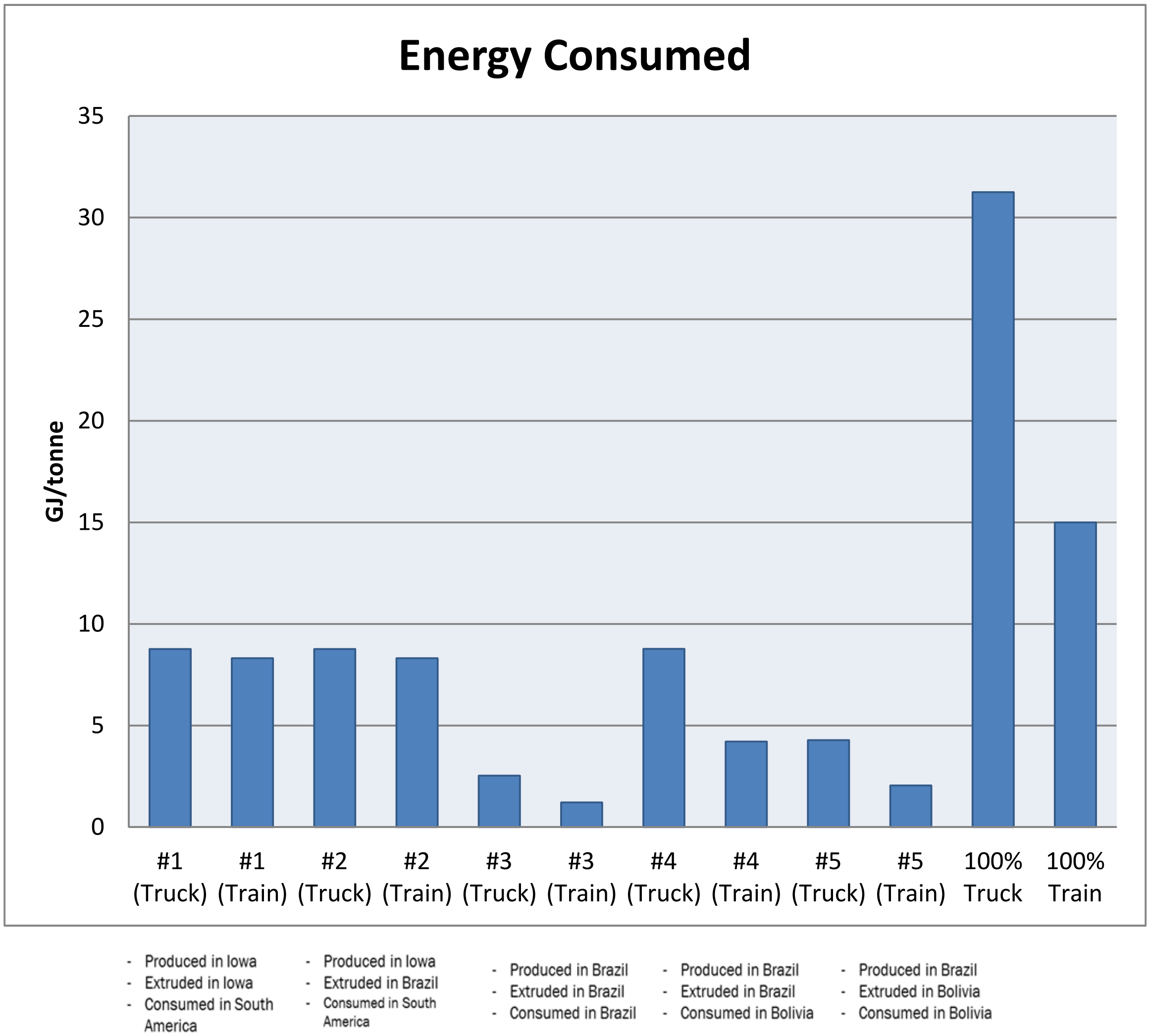

Figure 3a. Graph comparing the amount of energy consumed by each method of transportation for five scenarios.

Another graph was made to more closely examine all scenarios, without considering the outlier and unreasonable possibilities of 100% truck or 100% train transportation.

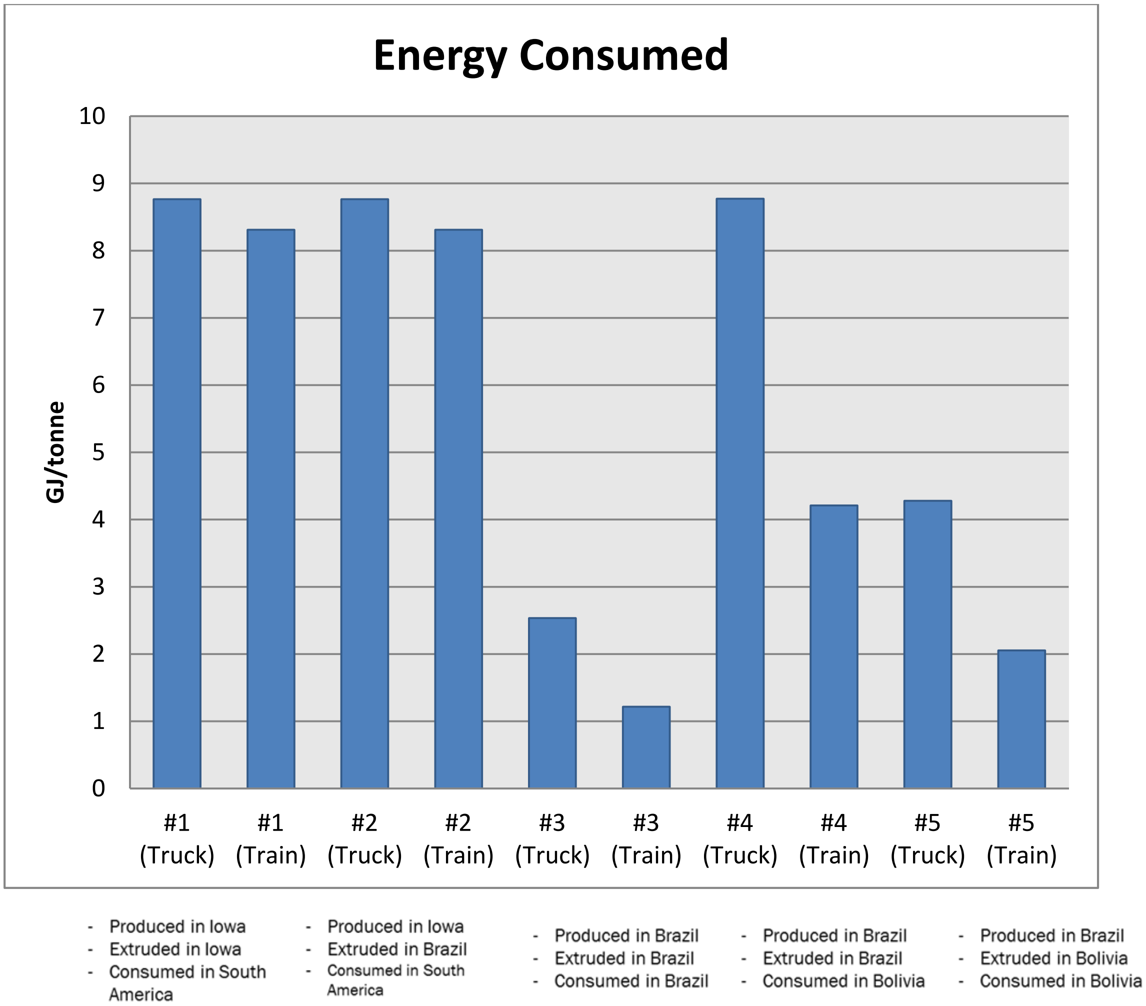

Figure 3b. Graph comparing the amount of energy consumed by each method of transportation for five scenarios.

The CO_2 equivalents produced for each scenario and method of calculation vary greatly and impact the sustainability of offering a helpful, needed product to consumers. The fewer emissions produced the more benefit the process can give to the people who need the extruded product while reducing environmental impacts. Table 4b shows the numerical value of CO_2 equivalents produced by each method of transportation.

Table 4b. Displays the amount of CO_2 equivalents produced by each scenario and method.

Scenario	CO_2 Equivalents Produced (kg/tonne)
#1 (Truck)	3331.14068
#1 (Train)	2440.247508
#2 (Truck)	3331.14068
#2 (Train)	2440.247508
#3 (Truck)	888.24372
#3 (Train)	440.39034
#4 (Truck)	3073.81382
#4 (Train)	1523.99379
#5 (Truck)	1499.67776
#5 (Train)	743.53872
100% Truck	10949.75
100% Train	5428.875

The scenarios that involve transporting grain or product from Iowa to South America produce more CO_2 equivalents than the scenarios analyzed in South America. The only exception is transporting extruded product from Brazil to Bolivia by truck, as that result is very comparable. The least amount of CO_2 equivalents produced is for the scenario in which grain is grown and extruded in Brazil, then consumed in the same country. All possible scenarios can be visually compared in Figure 3c.

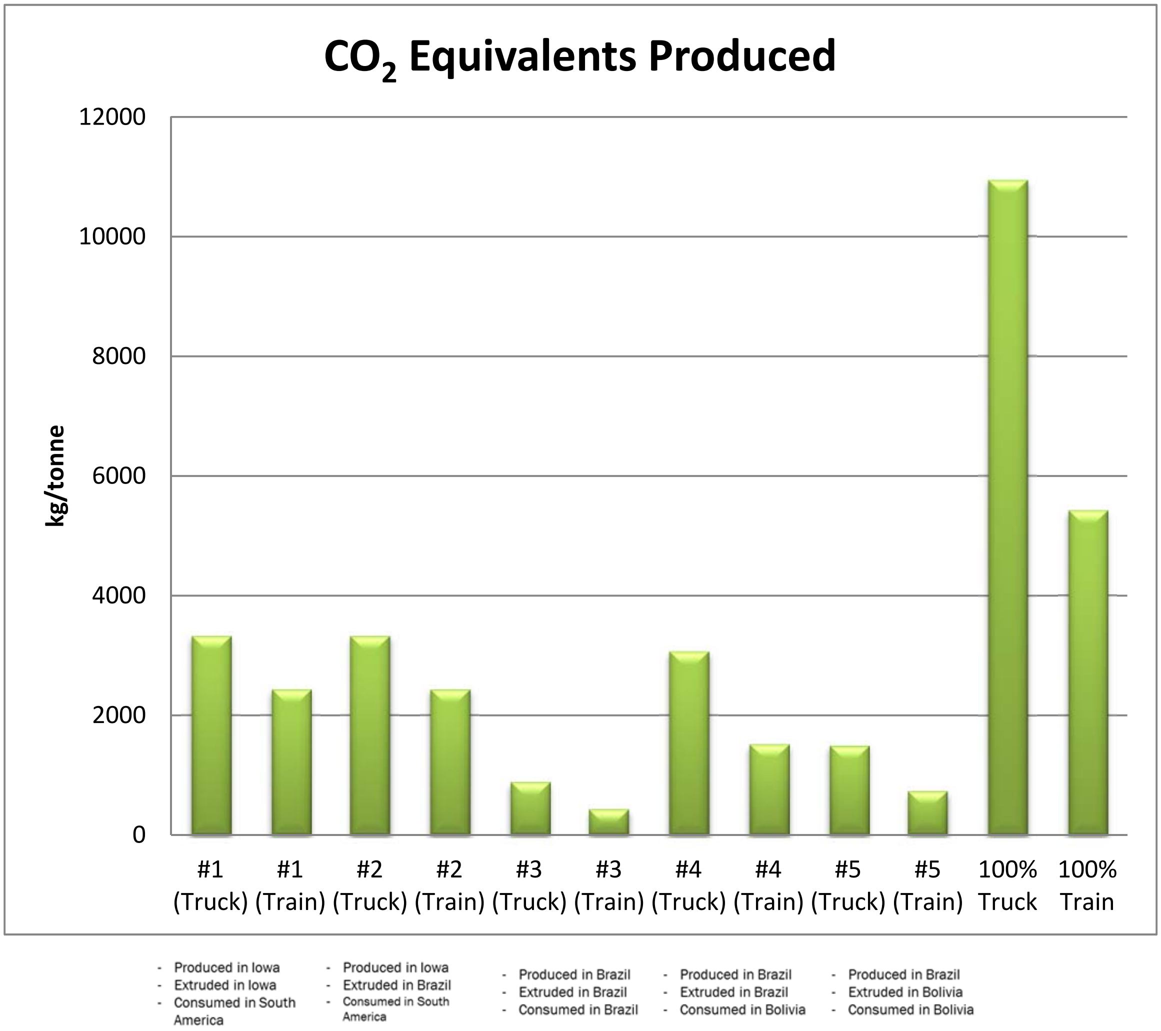

Figure 3c. Graph comparing the amount of CO_2 equivalents produced by each method of transportation for five scenarios.

Another graph was made to more closely examine all scenarios, without considering the outlier and unreasonable possibilities of 100% truck or 100% train transportation. This can be seen in Figure 3d.

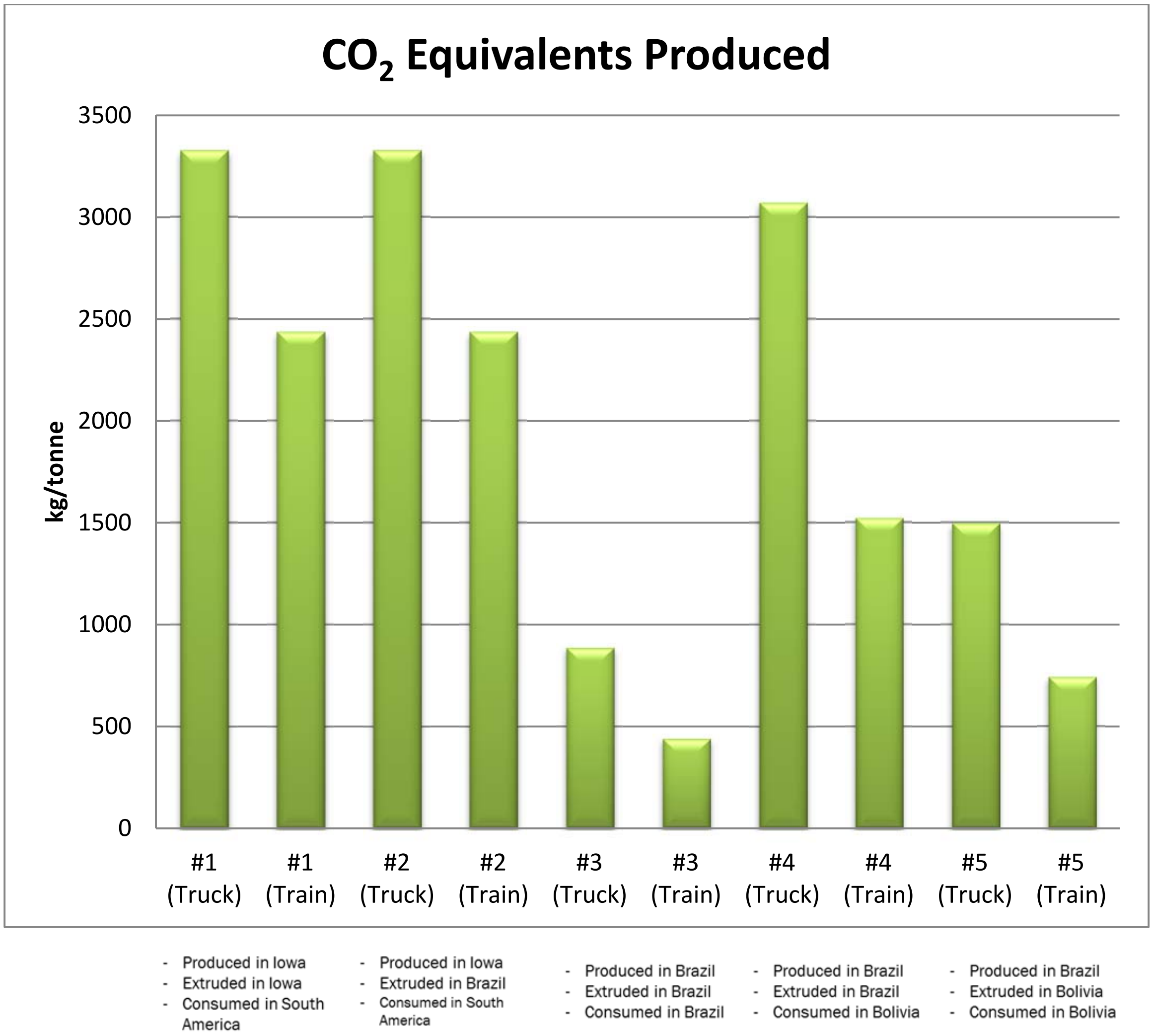

Figure 3d. Graph comparing the amount of CO_2 equivalents produced by each method of transportation for five scenarios.

Techno-Economic Analysis Methods

Table 5a. Assumptions made before the techno-economic analysis was performed.

Techno-Economic Analysis Assumptions
Diesel fuel price remains constant
Average speed of transportation is constant
Hourly wage remains constant
Railroad accessible in all countries
The tonnage that can be transported by certain methods was assumed as constant throughout all the countries.

Table 5b. Values used to conduct assessment (Sources: 8, 9, 11, 12, 14, 16, 20, 22, 23, 24, 25).

Freight Cost ($/tonne/km)	
Truck	0.1553
Train	0.0186
Barge	0.0062
Panamax	0.0062
Fuel Cost ($/gal)	
Diesel	3.82
Fuel Economy (tonne-km/gal)	
Truck	163
Train	754
Barge	1534
Panamax	926
Average Speed (km/hr)	
Truck	112
Train	100
Barge	35
Panamax	26
Number of Operators	
Truck	1
Train	2
Barge	5
Panamax	15
Labor Cost ($/hr)	
Truck	19
Train	22
Barge	20
Panamax	20

The purpose of the techno-economic analysis was to determine the overall cost of each transportation scenario as well as to determine what the cost in dollars per tonne of grain or extruded product transported would be for each of the five scenarios.

The techno-economic analysis was performed by determining the freight cost per tonne, the fuel cost per tonne, and the labor cost per tonne. The sum of these three costs resulted in the total cost for each transportation method in dollars per tonne of grain or extruded product transported.

The freight cost per tonne was calculated by multiplying the distance travelled using a method of transportation by the assumed fright cost per tonne per kilometer. The fuel cost was first calculated based the fuel economy of each mode of transportation. It was then calculated by multiplying the distance travelled using a method of transportation by the assumed fuel cost per tonne per kilometer. The labor cost was found based on multiplying the hourly wage of the operator by the duration of the transportation.

An example of these calculations is given (Table 5c).

All scenarios were calculated for both train or truck transportation so that both methods of land transport could be accurately compared. In addition to the five scenarios of transportation, a transportation techno-economic analysis was also conducted using the same methods assuming 100% transportation by land, both truck and train. The assumption was made that it was possible to transport from Des Moines, Iowa to Sao Paulo, Brazil over land.

Table 5c. Example of table used to calculate values.

Scenario #1 (Des Moines to Sao Paulo)								
	Transportation Mode	**Capacity (tonne)**	**Distance (km)**	**Freight Cost ($/tonne)**	**Fuel Cost ($/tonne)**	**Transport Duration (hr)**	**Labor Cost ($/tonne)**	**Total Cost ($/tonne)**
Using Truck	Truck	20.454	350	54.355	8.202	3.125	2.903	
	Barge	1900	2312	14.334	5.757	66.057	1.391	
	Panamax	32500	9952	61.702	41.055	382.769	3.533	
Total			**12614**	**130.392**	**55.015**	**451.951**	**7.827**	**193.233**
Using Train	Train	98.318	350	6.510	1.773	3.500	1.566	
	Barge	1900	2312	14.334	5.757	66.057	1.391	
	Panamax	32500	9952	61.702	41.055	382.769	3.533	
Total			**12614**	**82.547**	**48.585**	**452.326**	**6.490**	**137.622**

Techno-Economic Analysis Results

The total cost for each scenario and method of calculation vary greatly and impact the economic feasibility of offering a cheap product to consumers. The cheaper the transportation cost, the lower the price can be to sell the product to a low-income consumer who needs it. Table 6a shows the numerical value of total cost in U.S. dollars per tonne for each method of transportation.

Table 6a. Displays the total cost for each scenario and method.

Scenario	Total Cost ($/tonne)
#1 (Truck)	193.23
#1 (Train)	137.62
#2 (Truck)	193.23
#2 (Train)	137.62
#3 (Truck)	189.65
#3 (Train)	28.54
#4 (Truck)	656.29
#4 (Train)	98.75
#5 (Truck)	320.19
#5 (Train)	48.18
100% Truck	2337.87
100% Train	351.77

The scenarios that involve transporting grain or product from Iowa to South America use more energy than most scenarios analyzed in South America. The only exception is transporting extruded product from Brazil to Bolivia by truck. The amount of fuel consumed closely correlates to the cost of each transportation method and scenario.

However, using a truck to transport in South America is very costly compared to other scenarios due to the increased need for labor. Driving in Brazil and Bolivia simply takes longer due to lacking infrastructure that is meant for transportation of goods over long distances. The most cost effective mode of transportation is for the scenario in which grain is grown and extruded in Brazil, then consumed in the same country; this is the same scenario for which the least amount of energy consumed was also true. All possible scenarios can be visually compared in Figure 4a.

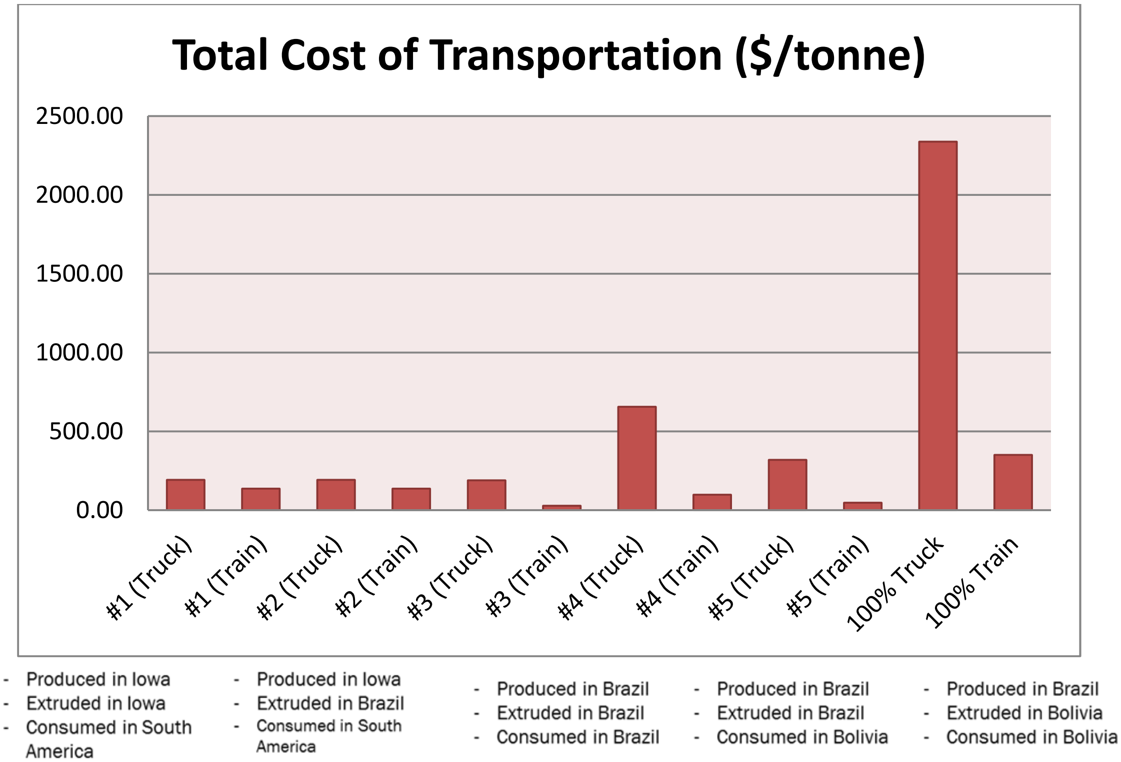

Figure 4a. Graph comparing the total cost in US dollars for each method of transportation for five scenarios.

Another graph was made to more closely examine all scenarios, without considering the outlier and unreasonable possibilities of 100% truck or 100% train transportation. This can be seen in Figure 4b.

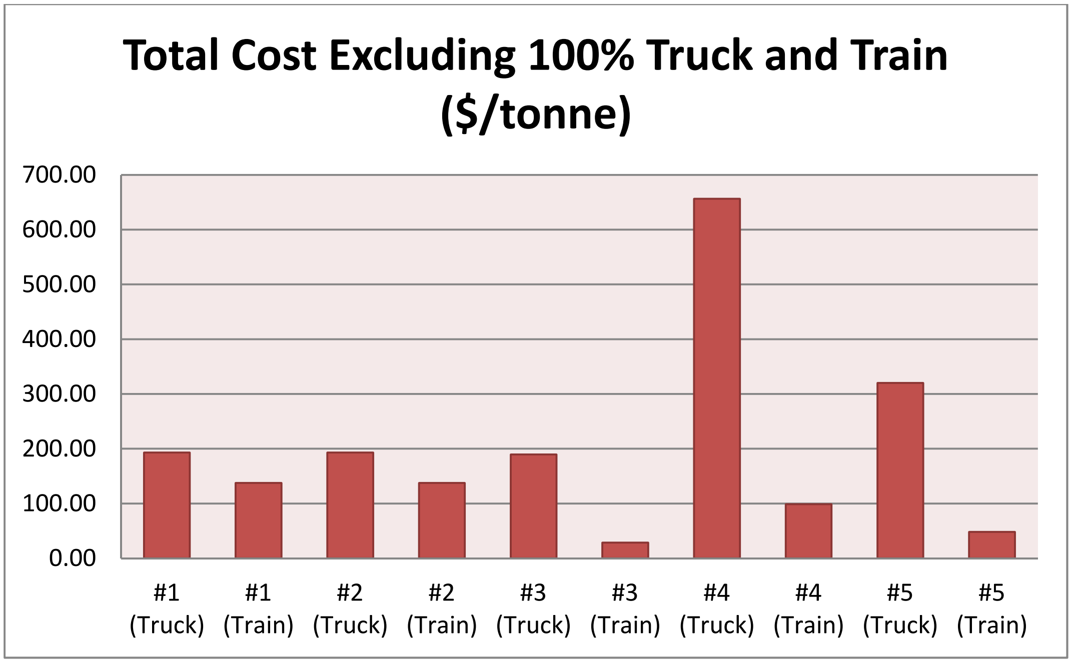

Figure 4b. Graph comparing the total cost in US dollars for each method of transportation for five scenarios.

Process Analysis

A life cycle assessment and techno-economic analysis were performed on the extrusion process for each possible location of extrusion or grain mixture. This analysis allowed for the comparison of resource depletion and cost to the company in each country.

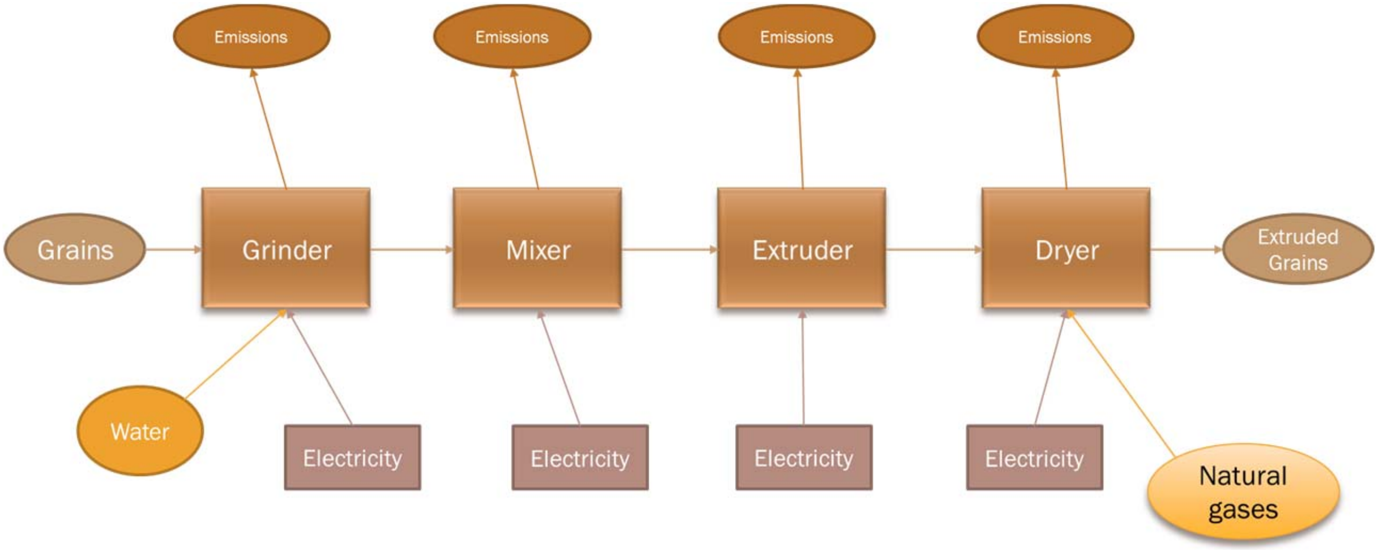

Figure 5. Flowchart depicting the extrusion process.

Before beginning the process analyses, assumptions (Table 7a) were made based on internationally agreeable work weeks.

Table 7a. Operation time assumed for analyses in all countries.

Operation Time	
8	hrs/day
5	days/week
50	weeks/year
2000	Total Hours/ Year
250	Total Days/Year

Life Cycle Assessment Methods

Table 8a. Assumptions made before the life cycle assessment of the extrusion process was performed.

Life Cycle Assessment Assumptions
Operate at 1000 kg/hr production rate
Use fraction of total capacity to estimate energy being used by each part of the extrusion process
Coal - fed power plant generates electricity for process in the United States
Natural gas fed power plant generates electricity for process in Brazil
4900 btu/kg of water is the amount of energy needed to dry the product

Table 8b. Values used to conduct assessment.

	CO_2 produced (kg/MWh)	NO_X produced (kg/MWh)	Methane produced (kg/MWh)
Iowa	875	2.727272727	0.081
Brazil	93	1.34	0.04
Bolivia	581	2.24	0.062

Table 8c. Values used to conduct assessment.

Equipment	Cost ($)	Capacity (kg/h)	HP
Grinder	2500	2000	20
Mixer	8610	1667	2
Extruder	270000	1667	150
Dryer	225000	1667	80
Total	506110		252

The life cycle assessment was performed by determining the energy used, water consumed, and CO_2 equivalents produced, including CO_2, Nitrous Oxides, and Methane. The energy used was determined by converting the horsepower needed for each component of the extrusion equipment to kilowatts to mega joules per kilogram of product by using the assumed production rate of 1000 kilograms per hour. This value was then multiplied by operating time to determine the mega joules per kilogram per day.

$$ {}^{MJ}\!\Big/\!{}_{kg}\Big/_{day} = KWh * \frac{3.6\ MJ}{kWh} * \frac{1000\ kg}{hour} * \frac{8\ hours}{day} $$

The same amount of energy was consumed no matter where the process took place. The same amount of water was also consumed everywhere based on the assumption of a one-to-one ratio that means for every 1000 kilograms of product 1000 kilograms of water were used.

The CO_2 equivalent emissions were calculated by multiplying an emission factor for each megawatt hour of energy consumed by the amount of energy consumed by each component of the process. The individual energy consumption of each machine component was then totaled to find an overall total of the emissions for extrusion in each country. During these calculations, many different types of emissions were considered, including CO_2, NO_X, and Methane. Conversion factors were used based on the global warming potential of each emission to determine what these would represent in a unit of CO_2 equivalents. The sum of all CO_2 equivalents was then used to find the total emissions produced. After the total emissions were found, the number could be divided by the quantity of the grain or extruded product being produced to find the kilograms of CO_2 equivalent produced per kilogram of product produced per day.

Life Cycle Assessment Results

The mega joules of energy consumed for each country is the same because the machine and process used is the same in theory no matter where it is done in the world. Table 9a shows the numerical value of energy consumed by the extrusion process in each country.

Table 9a. Calculated values of energy consumed by process in each country.

Country	Energy Consumed (MJ/kg product/day)
U.S.	25261.41121
Brazil	25261.41121
Bolivia	25261.41121

All possible scenarios for energy consumption can be visually compared in Figure 6a.

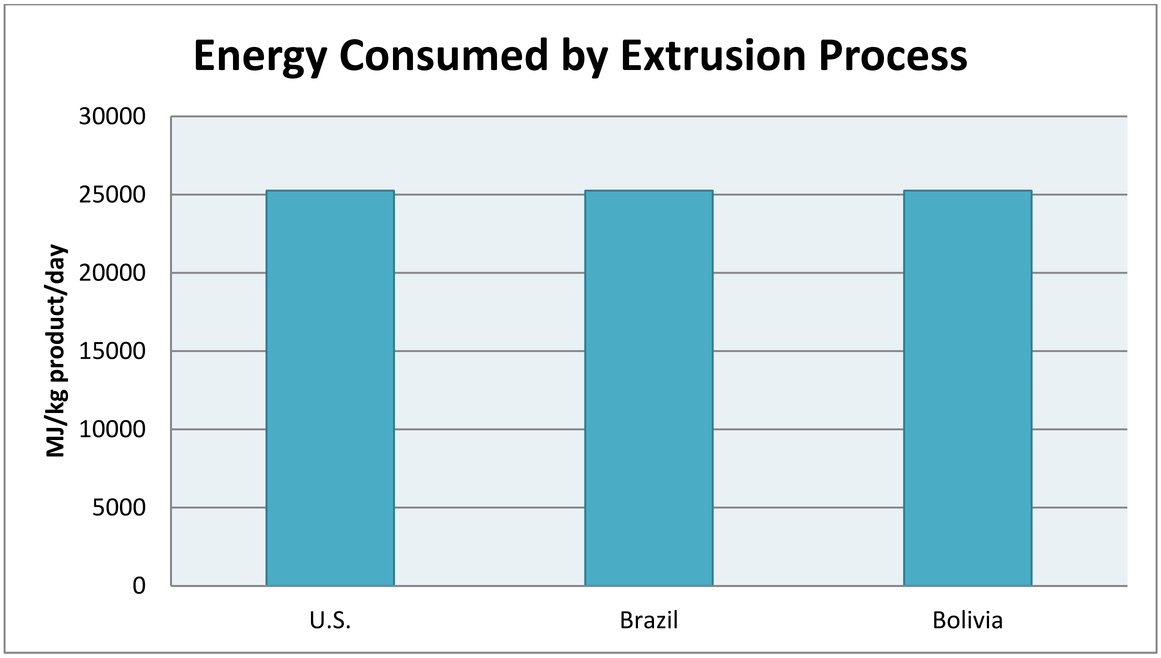

Figure 6a. Graph comparing the amount of energy consumed by the extrusion process in each country.

Table 9b. Calculated values of water consumed by process in each country.

Country	Water Consumed (gal/kg/day)
U.S.	2113.376
Brazil	2113.376
Bolivia	2113.376

All possible scenarios for water consumption can be visually compared in Figure 6b.

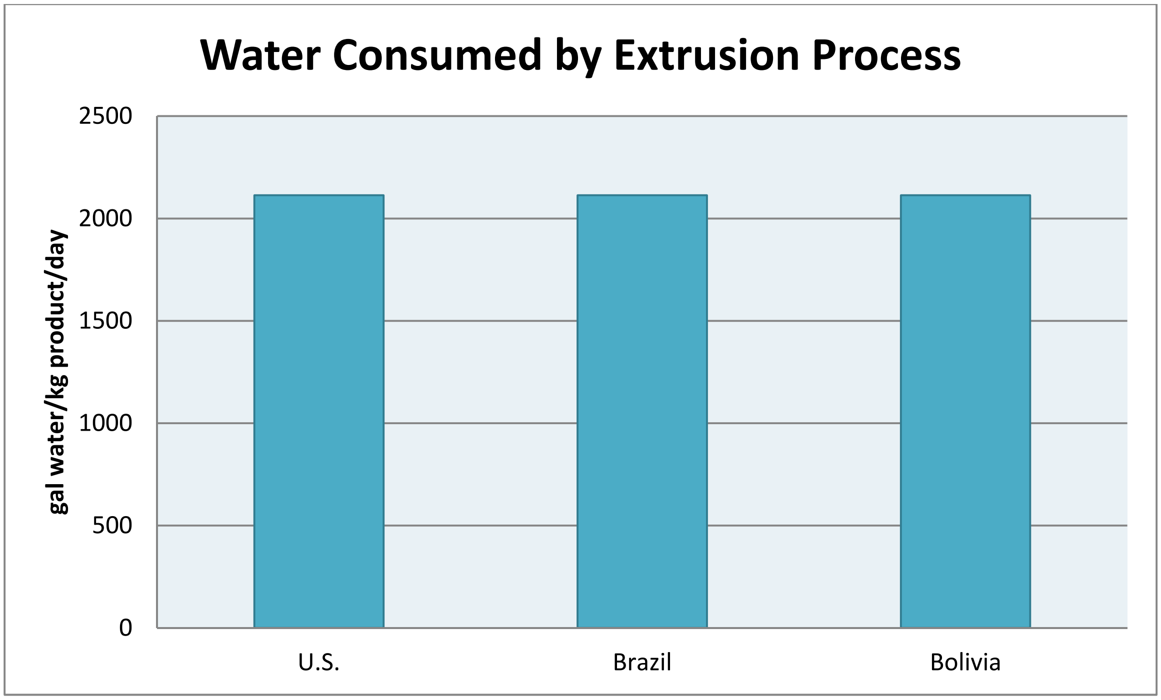

Figure 6b. Graph comparing the amount of water consumed by the extrusion process in each country.

The CO_2 equivalents released in each country depend directly on the fuel source used to power the electricity plant. It was assumed that coal is used to power the United States plant, natural gas in Brazil, and an oil-based fuel in Bolivia. The fuel source in Brazil greatly reduced the emissions generated from consuming the fuel source. Bolivia comes in second with emissions that could be improved, but are still not the worst. The United States has the highest emissions rate with coal-powered electricity plants.

Table 9c. Calculated values of CO_2 equivalents released by process in each country.

Country	CO_2 Equivalents (kg CO_2/kg product/day)
U.S.	31269.61705
Brazil	9129.105924
Bolivia	23133.10112

All possible scenarios for CO_2 equivalents released can be visually compared in Figure 6c.

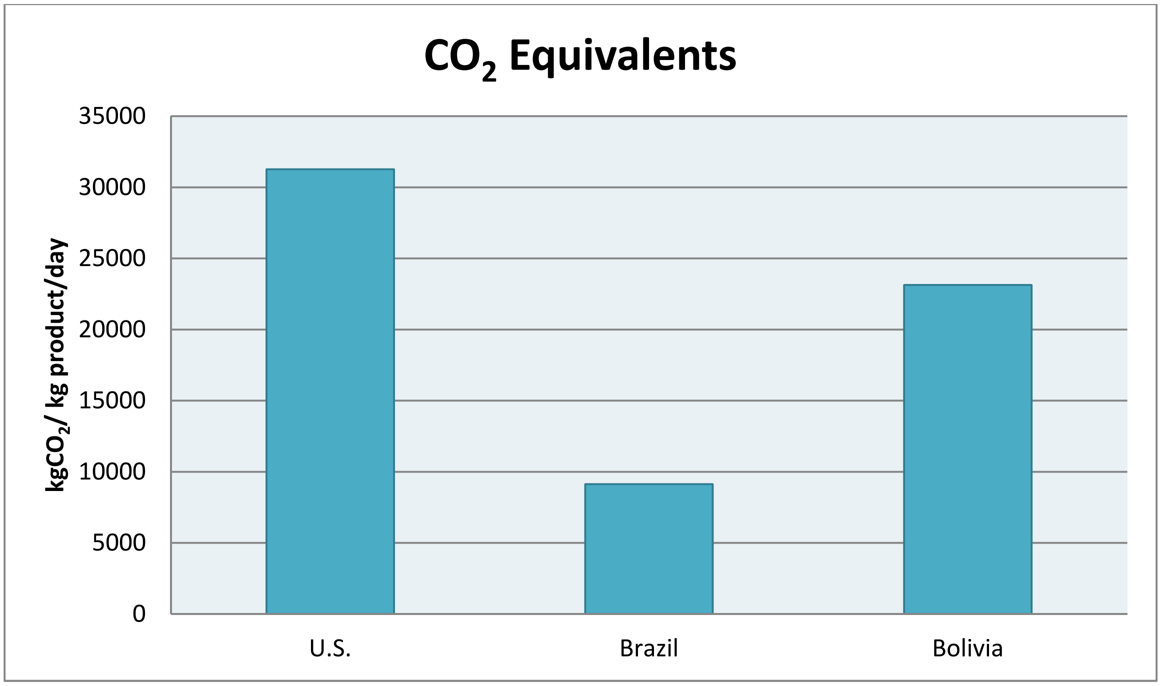

Figure 6c. Graph comparing the amount of CO_2 equivalents produced by the extrusion process in each country.

Techno-Economic Analysis Methods

Table 10a. Assumptions made before the techno-economic analysis for the extrusion process was performed.

Techno-Economic Analysis Assumptions
Hourly wage is 200% minimum hourly wage of country
Constant cost of water
10 year equipment life
5% interest
4900 Btu nat. gas to evaporate 1 kg water

The purpose of the extrusion process techno-economic analysis is to determine the total cost to produce an extruded product in each of the three countries. In addition to total cost, the techno-economic analysis will also determine a unit cost in dollars per kilogram of extruded product.

Table 10b. Values used to conduct the techno-economic analysis (Sources: 2, 6, 10, 19, 20).

Cost of Electricity ($/kWh)			
United States	0.043		
Brazil	0.19		
Bolivia	0.09		
Cost of Natural Gas	**($/ft^3)**	**($/Btu)**	**Required to Evap 1 kg water ($/kg-water)**
United States	0.0045	4.40744E-06	0.021596474
Brazil	0.00381	3.73164E-06	0.018285015
Bolivia	0.0015	1.46915E-06	0.007198825
Cost of Water	**($/gal)**	**($/kg)**	
United States	0.0015	0.000395778	
Brazil	0.0015	0.000395778	
Bolivia	0.0015	0.000395778	
Cost of Soybeans	**($/bu)**	**($/kg)**	
United States	12.79	0.4702	
Brazil	11.5	0.4228	
Cost of Corn	**($/bu)**	**($/kg)**	
United States	4.2325	0.1666	
Brazil	2.95	0.1161	
Labor ($/hr)			
United States	14.5		
Brazil	3.96		
Bolivia	3.64		

The total cost of the process is the sum of the capital and variable costs. The capital cost are the total cost of each piece of process equipment as well as shipment and installation of the equipment. It was assumed that the equipment would have a ten year lifespan, so it was annualized over a ten year period at an interest rate of 5%. The variable cost consists of the cost of labor, cost of grain, cost of water, cost of electricity, and cost of natural gas.

Three scenarios were modeled based on various nutritional requirements. The cost to extrude a product from 100% corn, 100% soybeans, and a 50-50 corn-soybean blend were all calculated. The cost of grain was calculated by multiplying the price per bushel by the determined quantity required. The total cost of water was found by multiplying the unit cost of water by the required amount. The cost of electricity was determined by multiplying the sum of all equipment power requirements in kW by the expected operation time in hours. This resulted in a quantity of total kilowatt-hours which could then be multiplied by the price per kilowatt-hour from a power company to determine the total electrical cost. The cost of natural gas was determined by assuming a ratio of 1:1 for water: grain in the extrusion process. A value of 4,900 Btu of natural gas energy is required to evaporate one kilogram of water completely. By using this value, an amount was found for the required volume of natural gas in cubic feet. This total could then be multiplied by the unit cost of natural gas in each respective country to determine a total natural gas cost. Labor was determined to be the hourly wage, at 200% of the minimum hourly wage in each respected country, multiplied by the process hours.

Each of the three extrusion compositions and locations were compared as both total cost per year as well as total cost per kilogram produced per year.

Additionally, for the cost of extrusion in the United States, scaling was performed to determine separate production costs at a rate of 100 kg/hr, 1,000 kg/hr, and 10,000 kg/hr. These resulted in a clear visual of what is commonly known as economies of scale.

Techno-Economic Analysis Results

The first result that had to be determined was the cost of the extrusion equipment and the amount of power that would be required by each component of the extruder when in production. This determination was important because the cost to purchase and install the equipment has to be considered by any person or company who may decide to do this.

The kilowatts used by each component of the extruder was crucial in determining the amount of energy consumed by each component and the corresponding energy cost. The energy costs provided the largest difference between countries because of the varying energy sources.

Table 11a. Values given for cost of extruder and then analyzed further to determine total cost of extruder and the kW required for the extrusion process.

Equipment	**Cost ($)**	**Capacity (kg/h)**	**HP**	**kW**
Grinder	2500	2000	20	14.7
Mixer	8610	1667	2	1.47
Extruder	270000	1667	150	110.25
Dryer	225000	1667	80	58.8
Total	506110		252	185.22
Equipment Installation (30%)	151833			
Equipment Freight (15%)	75916.5			
Equipment Wiring/Controls (5%)	25305.5			
Total Equipment Initial Cost ($)	**759165**			
Annualized Cost ($)	**98315.34065**			

Once capital costs were evaluated, variable costs were calculated and compared.

Table 11b. Cost of extruding different types of grain or grain blends in the United States.

Cost per day per unit - U.S. ($/day/kg)			
	Corn	**Soybean**	**Blend**
100 kg/hr	0.45	1.10	0.78
1,000 kg/hr	0.21	0.51	0.36
10,000 kg/hr	0.10	0.24	0.17

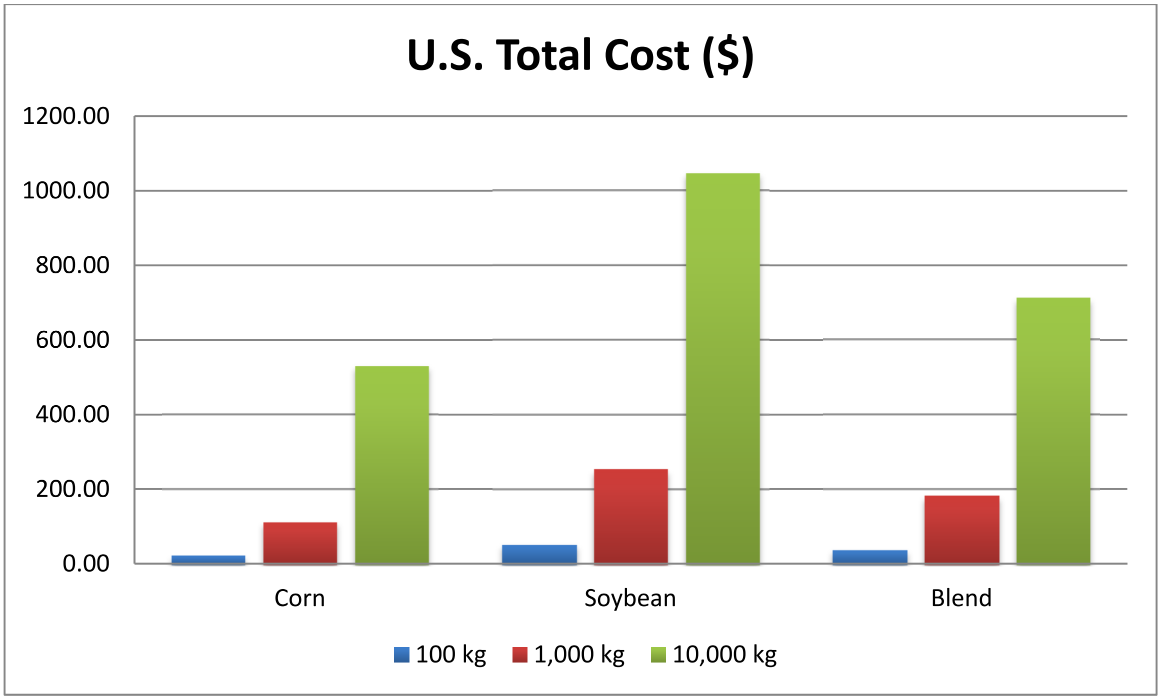

Figure 7a. Cost comparison of extruding corn, soybeans, and a blend at different scales of production in the United States.

Table 11c. Cost of extruding different types of grain or grain blends in Brazil.

Cost per day per unit - Brazil ($/day/kg)			
	Corn	**Soybean**	**Blend**
100 kg/hr	0.37	1.03	0.70
1,000 kg/hr	0.17	0.48	0.33
10,000 kg/hr	0.07	0.22	0.15

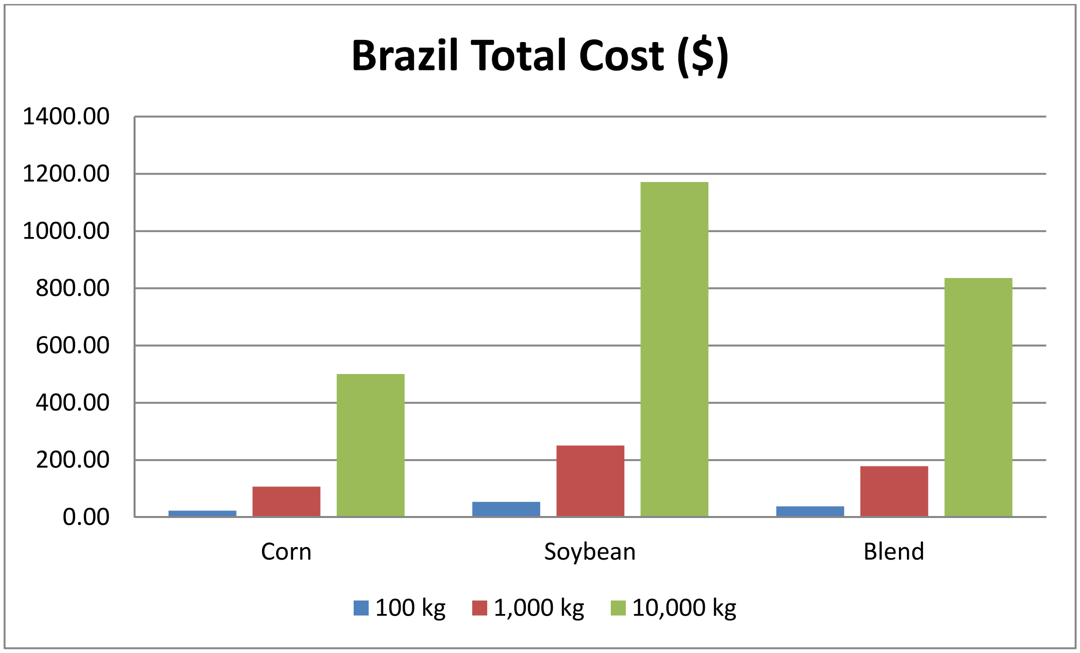

Figure 7b. Cost comparison of extruding corn, soybeans, and a blend at different scales of production in Brazil.

Table 11d. Cost of extruding different types of grain or grain blends in Bolivia.

Cost per day per unit - Bolivia ($/day/kg)			
	Corn	**Soybean**	**Blend**
100 kg/hr	0.31	0.96	0.64
1,000 kg/hr	0.14	0.45	0.30
10,000 kg/hr	0.07	0.21	0.14

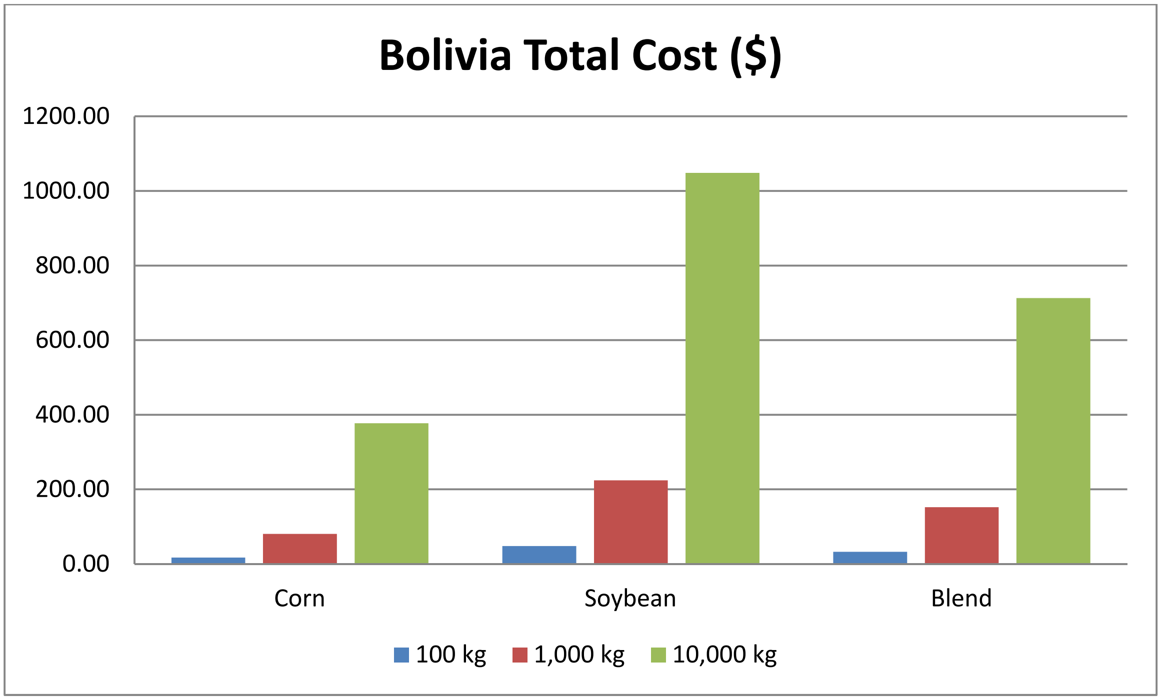

Figure 7c. Cost comparison of extruding corn, soybeans, and a blend at different scales of production in Bolivia.

Table11e. Cost comparison of extruding corn, soybeans, and a blend at 1000 kilograms per hour in our comparison countries.

	Corn	Soybeans	Blend
United States	0.26	0.56	0.41
Brazil	0.22	0.53	0.38
Bolivia	0.19	0.50	0.35

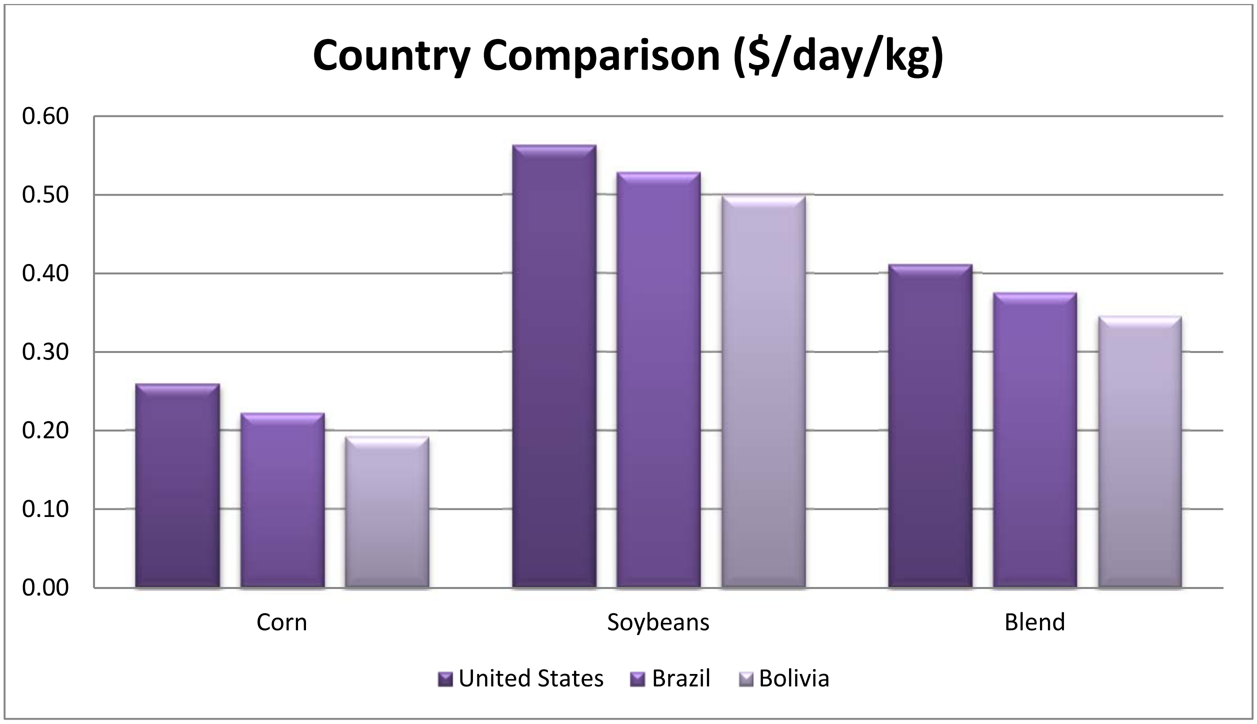

Figure 7d. Visual analysis of the cost comparisons of extruding corn, soybeans, and a blend of grain at 1000 kilograms per hour in our comparison countries.

Implications

The best transportation scenario is train transportation of grain produced local to Campo Grande in the state of Mato Grosso in Brazil, grain extruded in Sao Paulo, Brazil and the product being consumed in Brazil. This scenario has the lowest cost at $28.54 per tonne of transported grain or extruded product. This scenario also has the lowest emissions at 440 kilograms of CO_2 equivalents per tonne of grain or product transported. One of the main reasons for lower cost and emission is simply because of the shorter distance being travelled.

The suggested grain to be used for extrusion is a blend of corn and soybeans. This combination provides better nutritional content and makes the process run at its smoothest.

The best extrusion location is Brazil. Brazil has the lowest emissions rate at 9129 kilograms of CO_2 equivalents per kilogram of product per day. Brazil is also a comparable economic option to Bolivia, costing approximately $0.03 more per kilogram of product produced. Brazil and Bolivia are both much cheaper than the United States, mainly due to lower labor costs. Extruding in Brazil also makes the product accessible to the consumer, who may live in rural areas of Brazil or in Bolivia. Additionally, Brazil already has a manufacturing and industrial economy and the ability to begin a new machine based process. This project would require very little, if any, change to the existing infrastructure within Brazil.

Conclusions

In summary of this project, we spent the semester completing the following tasks. We began by completing a literature review to learn more about the extrusion process. We then reviewed four countries around the world where a TVP product could meet a need of local citizens. We selected Brazil and Bolivia as our countries to analyze and then looked at five scenarios based on the location of grain production, the extrusion process, and consumption by the consumer.

We conducted life cycle assessments and techno-economic analyses for all transportation scenarios and extrusion process locations. The life cycle assessments allowed us to quantify the energy consumed, emissions produced, and water consumed. The techno-economic analyses allowed us to compare the cost in U.S. dollars for each transportation scenario or extrusion in different countries.

Based on our results we recommend that grain grown in Brazil is used for the extrusion process which should take place in Brazil. The extrusion process should be completed with corn and soybeans that are grown in Brazil, specifically the Campo Grande area in the state of Mato Grosso. The extruded product can then be consumed in Brazil or Bolivia, although Bolivia would add additional cost and environmental impacts.

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