COMILLAS
UNIVERSIDAD PONTIFICIA
ICAI

BACHELOR'S DEGREE IN ENGINEERING FOR INDUSTRIAL TECHNOLOGY (GITI)

END-OF-DEGREE PROJECT

REDESIGN OF PLASTIC RECYCLING MACHINE WITH A SUSTAINABLE APPROACH AND STUDY OF ITS APPLICATION WITH LINEAR PROGRAMMING

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Madrid
July 2019

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Author: David Pérez Llorente
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Madrid
July 2019

REDISEÑO DE MAQUINA DE RECICLAJE DE PLASTICOS DESDE UN PUNTO DE VISTA SOSTENIBLE Y ESTUDIO DE SU APLICACIÓN CON PROGRAMACIÓN LINEAL.

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Director: Demange, Marc.

Entidad Colaboradora: RMIT University.

RESUMEN DEL PROYECTO

Este proyecto se formula a partir de la necesidad de los alumnos por desarrollar un enfoque mas realista y acercado a la industria de la cual formaran parte en un futuro, dejando de lado el mero estudio teórico de las asignaturas, donde clásicamente cesaba el aprendizaje académico para dar paso al mundo laboral. En este caso, de la mano de las asignaturas de Sustainable Engineering Practice and Design and Industrial Applications of Mathematics and Statistics 2, se ha conseguido realizar un enfoque mas práctico, orientado al mundo laboral, lo que aparece como un gran punto de partida para la realización del proyecto final de grado.

Con la ayuda de la primera asignatura se ha relizado un estudio de viabilidad sostenible para la idea de cambio y mejora en un sistema de reciclaje de plásticos, en el cual el principal objetivo es la aplicación de los conocimientos aprendidos, en cuanto a determinar cuan sostenible es un proyecto, y realizar una evaluación del ciclo de vida, junto con otros análisis de económicos y de diferentes tipos.

El aporte de la segunda asignatura en este aspecto corresponde a poner en practica los conocimientos adquiridos en Operation Research 1, a una aplicación a un proyecto de enfoque realista. Esta aplicación se realizará para debatir si la nueva idea de rediseño es mas eficiente en cuanto a los costes de transporte y procesamiento de los plásticos que la idea ya instaurada.

En dicho proyecto, para la parte de sostenibilidad no se necesitan mas herramientas que en cualquier trabajo de ofimática, por lo tanto, no se explicarán dichas herramientas. Por el contrario, en la parte de programación, cabe destacar que se realizó mediante el uso del lenguaje de programación Python, con el compilador de JetBrains para Python, PyCharm y utilizando el paquete de optimización de IBM, llamado Cplex.

Los objetivos particulares, que de forma colectiva suponen la consecución del proyecto son:

- Encontrar y explicar que aspectos de sostenibilidad pueden ser aplicados y son cumplidos por el rediseño propuesto.
- Realizar un análisis mas amplio del proyecto desde diferentes sectores y determinar que método de consultación es el adecuado, y el mayor impacto social que tendrá.
- Realizar una evaluación del ciclo de vida (LCA) del proyecto.
- Crear una cantidad suficientemente grande de instancias, que permita demostrar que los hallazgos realizados no son fruto de la casualidad y que tienen cierta constancia.
- Resolver el problema de enrutamiento de vehículos (VRP) asociado a la metodología actual de transporte y procesamiento de los plásticos.
- Resolver el problema del viajante (TSP) asociado a la metodología propuesta en el proyecto
- Discernir entre ambos métodos con los hallazgos realizados, cual es el mas efectivo.

La propuesta de rediseño que se realiza se basa en el diseño de una planta de reciclaje de plásticos artesanal, realizada por Precious Plastic, proyecto que empezó en 2013 de la mano de Dave Hakkens. Este proyecto lo que buscaba era la creación de una planta de reciclaje que de una manera mucho mas artesanal que las plantas de reciclaje comunes con maquinas de tamaño industrial e instaladas en grandes naves industriales, permitiera realizar el reciclaje de plásticos de una manera mucho mas sencilla y casera en cualquier parte del mundo, puesto que los materiales que se proponen para la construcción, esta comprobado que pueden encontrarse sencillamente en todas las regiones del mundo.

En este caso, la propuesta relizada en este proyecto para mejorar el ya propuesto por Dave Hakkens, o al menos hacerlo mas sostenible, es la de, aunar el uso de las cuatro maquinas que se proponen en su proyecto, trituradora, extrusora, maquina de inyección y de compresión, en tan solo la unión de la trituradora y la extrusora con un único motor que abastezca a ambas, ya que se cree que con estas dos maquinas es posible desarrollar todo el trabajo que se necesita realizar.

En primer lugar, se realiza una comprobación de los requerimientos mandatorios que la nueva maquina ha de cumplir para poder ser considerada sostenible, y se concluye que los requerimientos y los objetivos de estos son los siguientes:

Requerimientos de diseño	**Indicadores de redimiento**	**Objetivo**
Eficiencia enegética	Cantidad de energía	<5,774KWh por Ton
Uso de plástico	Porcentaje de plástico reciclado	>9%
Portabilidad	Espacio	<12.2x2.2x2.6m

Una vez aclarados los requerimientos mandatorios, se procede a discernir que otras características debería de cumplir la maquina para que su desarrollo y uso sea sostenible y así se decide que ha de constar con una innovación frugal, para la cual se desarrollan los siguientes objetivos:

Categorías	**Servicio convencional del producto**	**Innovación frugal**
Reducción subtancial de costes	Utiliza nueva materia prima para la creación de productos.	Reduce costes usando materiales desechados
Centrar el esfuerzo en las principales tareas	La trituradora y la extrusora tienen papeles separados en la creación de los nuevos productos.	Combinando trituradora y extrusora, permite la reducción de tiempo, esfuerzo y costes en la creación de nuevos productos a partir de desechos plásticos.
Optimizar niveles de redimiento	Trituradora y extrusora tienen sus propios motores y ocupan mas espacio.	Combinando ambas maquinas en una sola, permite prescindir de uno de los motores y reducir en gran parte el espacio ocupado por las mismas.

Otra de las características que se pretende adquirir con el diseño es la eco-eficiencia del proyecto, para ello se marcan ciertos aspectos que han de ser minimizados:

Recursos	**Minimización**
Materiales	Mantener el ecosistema inalterado
Espacio	Combinar trituradora y extrusora para minimizar el espacio usado
Impacto biologico	Reducir la emisiones toxicas

La siguiente de las características deseadas es la eco-efectividad, cuyos objetivos son:

Recursos	Eco-effectiveness
Materiales	Utilizar plásticos desechados para reducir la cantidad de plástico convertido en basura.
Energía	Añadir paneles solares a la maquina, para utilizar energía mas limpia.
Espacio	Reducir la ocupación de terrenos en comparación con la solución actual.
Impacto biologico	Usar plástico desechado, ayuda a generar una basura sin plásticos, lo cual ayuda enormemente al planeta.

Otra de las características del proyecto es el pensamiento global, pues es por el mismo, que el proyecto produce significativas mejoras con lo ya instaurado, si se desarrolla de manera individual, se desarrollan maquinas individuales como sucede hasta el momento, es solo cuando se utiliza el pensamiento global, que se puede ver la posibilidad de combinar ciertos procesos, haciendo el proceso general mas sostenible.

El ultimo de estos aspectos es el diseño de por vida, que tiene como objetivos hacer que las piezas sean fácilmente accesibles mediante una construcción modular que permite la fácil reparación y cambio de piezas. Mantener la maquina en funcionamiento el mayor tiempo posible, esto se consigue debido a la simplicidad de la maquina, y por su modalidad, la posibilidad de cambiar piezas sin efectos negativos para el resto de los componentes. Producir un desecho de la maquina que impacte medioambientalmente lo menos posible, esto se consigue usando la menor cantidad de materiales posible y prescindiendo de pinturas y barnices.

Un análisis de costes y beneficios es realizado para comprobar cual es la duración del proyecto que es mas conveniente. Tras el estudio de los costes y beneficios, se determina que el proyecto será mas beneficioso cuanto mas tiempo se mantenga en funcionamiento puesto que a partir del primer año los gastos y beneficios son constantes, por lo tanto, cada año a mayores que se mantenga en funcionamiento será mas beneficio obtenido. Con un ratio incremental de beneficios-costes de 2,608.

Un análisis con múltiples criterios es realizado igualmente para comprobar si la implementación de una caja de cambios en la maquina mejora la propuesta o no, tras el análisis mediante consumo energético, complejidad de la maquina, coste de construcción y ratio de producción, se deduce, que la implementación no mejoraría en el computo global la maquina, y por ende no se realiza la misma.

Para las consultas publicas, se considera que la mejor combinación, al ser un proyecto de carácter mas artesanal que industrial, será en primer lugar organizar una quedada popular en el cual los desarrolladores den a conocer la maquina a los posibles interesados, una vez esta fase se haya superado, se realizaran tallares para explicar el proceso y el funcionamiento mas en detalle para aquellos interesados en el mismo. Finamente con un propósito de mejora constante se dejará un buzón de sugerencias en cada uno de los establecimientos en los que se implemente la maquina para que la comunidad pueda aportar en la mejora del sistema.

Siendo concisos, el impacto global esperado es una mayor cantidad de reciclaje plástico y de una manera mas distribuida y artesana, sin una gran dependencia de las decisiones tomadas sobre el aspecto por las grandes industrias.

Se procede a la realización asimismo de un análisis de los costes del ciclo vital del proyecto, mediante el cual teniendo en cuanta ciertos aspectos clave del proyecto, se llega a concluir que, en un tiempo de 2 años, se puede lograr superar los costes generados a través de los beneficios generados por el proyecto en si.

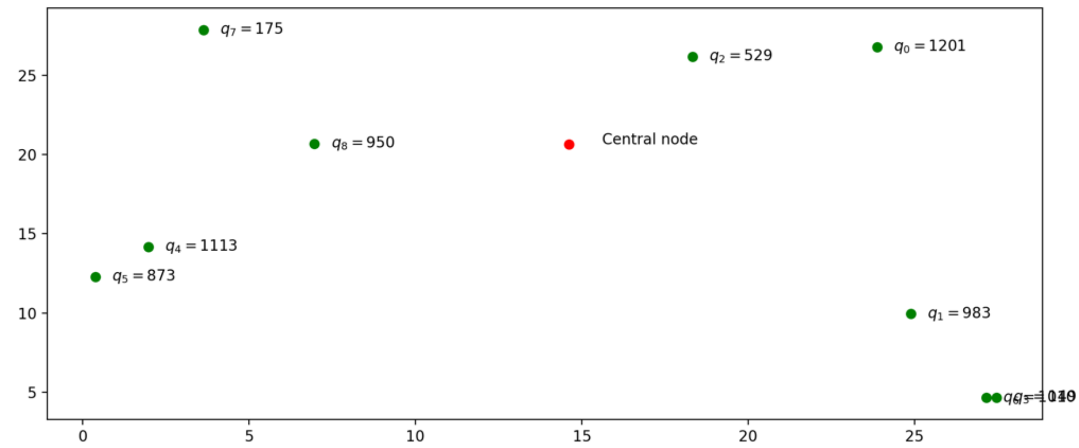
Finalmente, la evaluación del ciclo de vida es realizada, en la cual se tienen en cuenta todos los procesos particulares realizados dentro del proyecto global, lo que quiere decir, que se estudian todos los pasos desde la extracción de materiales del planeta, aunque en este caso son reciclados, hasta la deposición de lo desechos del proceso en el mismo planeta. De esta evaluación del ciclo de vida, se obtienen los siguientes datos en cuanto al impacto medioambiental:

Characterisation	**LCI**	**Quantity**	**units**	**Impact Category**	**Characterisation Factor**	**Midpoint Indicator**	**Unit Equivalent**
Electricity	Carbon Dioxide	5400	kg	GWP	1.000	**5400**	kg CO_2 eq
Gas	Fossil	2.016	m^3	FDP	0.836	**1.685**	kg oil eq
	Carbon Dioxide	0.068	kg	GWP	1.000	**0.068**	kg CO_2 eq
Raw materials	Steel	22.204	kg	MDP	42.700	**948.111**	kg Fe eq
Burned Plastic	Toluene	9.500E-07	kg	TP	0.820	**7.786E-07**	kg 1,4-DB eq
Water	Water, processing	50.400	m^3	WDP	0.001	**0.050**	m^3

De la misma se concluye que el impacto mas grande es el producido por el CO2 y que este impacto afecta en mayor medida a la salud humana que al medio ambiente y la perdida de recursos naturales. Aun así, no supone un gran riesgo en ningún aspecto, por lo tanto, el proyecto se puede llevar a cabo sin peligro alguno.

En cuanto a la parte de programación y optimización, se generaron una seria cantidad de instancias de manera aleatoria, con ciertas características, para que representaran de una manera realista una red de nodos y arcos, representando carreteras y municipios entre los cuales recoger y procesar los residuos plásticos.

Aquí se presenta un ejemplo de instancia:



A partir de esta instancia se desarrolla un problema de enrutamiento de vehículos (VRP), con la siguiente función objetivo:

$$Min \sum_{i \in V} \sum_{j \in V} c_{ij} x_{ij}$$

Sujeta a las siguientes restricciones:

$$\sum_{i \in V} x_{ij} = 1, \forall j \in V\{0\}$$

$$\sum_{i \in V} x_{ij} = 1, \forall j \in V\{0\}$$

$$\sum_{i \in V} x_{i0} = k$$

$$\sum_{j \in V} x_{0j} = k$$

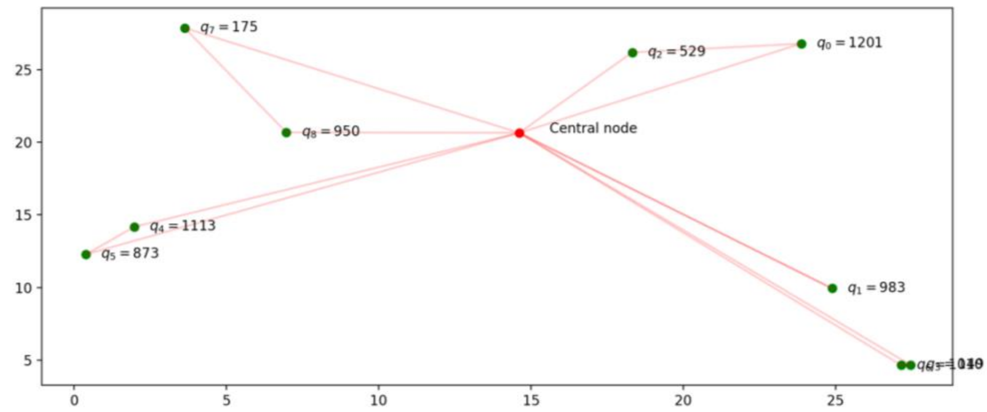
$$\sum_{i \notin S} \sum_{j \in S} x_{ij} \geq r(S), \forall S \subset V\{0\}, S \neq \phi$$

$$x_{ij} \in \{0,1\}, \forall i, j \ \in V$$

Con esta función objetivo y sus restricciones, lo que se consigue es generar una ruta que minimice la distancia, haciendo que a cada municipio solo pueda llegar y salir una vez el vehículo, a excepción del central, donde descargara los residuos plásticos una vez se llene la capacidad de este.

Con dicho programa obtenemos los siguientes resultados:

```
solution for: CVRP
objective: 94.297
x_0_2 = 1
x_1_9 = 1
x_2_9 = 1
x_3_9 = 1
x_4_5 = 1
x_5_9 = 1
x_6_3 = 1
x_7_8 = 1
x_8_9 = 1
x_9_0 = 1
x_9_1 = 1
x_9_4 = 1
x_9_6 = 1
x_9_7 = 1
u_0 = 1201.144
u_1 = 983.844
u_2 = 1730.913
u_3 = 1159.884
u_4 = 1113.359
u_5 = 1986.529
u_6 = 1010.675
u_7 = 175.452
u_8 = 1125.701
```



Este primer caso es el usado en la actualidad de recogida de residuos por municipios para ser depositados en una planta de reciclaje de plásticos donde son procesados todos juntos. Con este proyecto, se pretende demostrar, que con la idea de un diseño mas compacto de una maquina de reciclaje que sea portátil y se mueva por los distintos municipios procesando el plástico en cada uno de ellos, se pueden ahorrar gastos.

Para representar el caso propuesto se utiliza el siguiente programa, basado en el problema del viajante (TSP), con función objetivo:

$$Min \sum_{i \in V} \sum_{j \in V} c_{ij} x_{ij}$$

Sujeta a las siguientes restricciones:

$$\sum_{i \in V} x_{ij} = 1, \forall j \in V$$

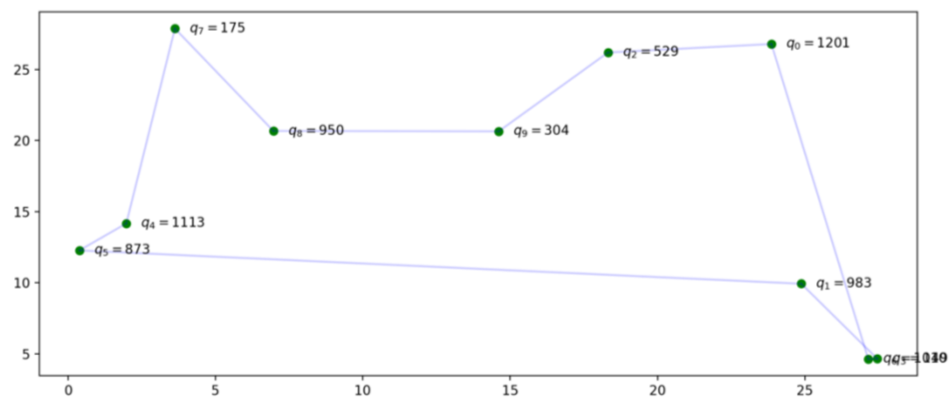
$$\sum_{i \in V} x_{ij} = 1, \forall j \in V$$

$$\sum_{i \in S} \sum_{j \notin S} x_{ij} \geq 1 \; for \; all \; S \subseteq V, S \neq \phi$$

En este caso de manera similar al anterior se pretende minimizar la distancia, haciendo que el vehículo pase por todos los municipios, por lo tanto, las restricciones limitan que a cada municipio solo pueda llegar una vez la ruta, y solo pueda salir una vez de este.

Con dicho programa obtenemos los siguientes resultados:

```
solution for: TSP
objective: 77.110
x1_0_2 = 1
x1_1_3 = 1
x1_2_9 = 1
x1_3_6 = 1
x1_4_5 = 1
x1_5_1 = 1
x1_6_0 = 1
x1_7_4 = 1
x1_8_7 = 1
x1_9_8 = 1
d_1 = 7.000
d_2 = 1.000
d_3 = 8.000
d_4 = 5.000
d_5 = 6.000
d_6 = 9.000
d_7 = 4.000
d_8 = 3.000
d_9 = 2.000
```



Como se puede comprobar al contrastar ambos programas, la función objetivo del segundo, ofrece un costo menor que la del primero, por lo tanto, la idea que se pretendía demostrar queda así demostrada a falta de una investigación mas detallada.

REDESIGN OF PLASTIC RECYCLING MACHINE WITH A SUSTAINABLE APPROACH AND STUDY OF ITS APPLICATION WITH LINEAR PROGRAMMING

Author: Pérez Llorente, David.

Director: Demange, Marc.

Colaborating Entity: RMIT University.

PROJECT SUMMARY

This project is developed based on the necessity of students of developing a more realistic industry related approach, as they will take part of that industry in the future, leaving aside the simple theoretical study of the subjects that traditionally was where academic studying would end and they would start their professional career. This time, with the help of Sustainable Engineering Practice and Design and Industrial Applications of Mathematics and Statistics 2, the consecution of this project was possible, with a more practical and real-world oriented approach, that presents itself as the perfect starting point for a final degree project.

With help from the first of these subjects, a sustainability study took place on the idea of changing and improving a plastic recycling system, in which the main goal was to apply the learned knowledge, so that it was possible to determined how sustainable the project was and perform a life cycle assessment, as well as an economic analysis and some other type of analysis.

The second mentioned subject was used to make a practical use of the acquired knowledge from the subject of Operations Research 1, to be applied in a project in a realistic manner. This application would take place to debate whether or not the new idea of redesigning the transportation and processing of plastic waste is more efficient that the existent one.

For this project, when performing the sustainability report, there is no need for any other tools that a normal office work should need, therefore the tools used in that part will not be explained. Meanwhile, the tools used for the programming part are a bit more complex and may need mentioning. The coding language used was Python, with an IDE developed by JetBrains for Python, PyCharm and using the optimization package from IBM, called Cplex.

The particular objectives, that all together allow the proper consecution of the project are:

- Find and explain the sustainable skills that can be applied and that take place in the proposed redesign.
- Analysis of the Project for different points of view and determine the consultations to be made and the wider society impact that it will have.
- Conduct a Life Cycle Assessment (LCA) of the project.
- Create a solid number of realistic instances of a network of nodes and arcs, so that the results can be proved not to be fortune, but to be constant.
- Solve the Vehicle Routing Problem (VRP) attached to the current system of collecting and processing the plastic waste.
- Solve the Travel Salesman Problem (TSP) attached to the system that is been proposed in this project.
- Work out, with the given results, which of the methods is more appropriate.

The proposition for the redesign is based on a artisanal plastic recycling plant, created by Precious Plastic, project that was started in 2013 by Dave Hakkens. This project was after the creation of a plastic recycling plant that worked in a much more artisanal manner than the common ones, with machines of industrial sizes and taking place in big industrial areas, would allow to perform a plastic recycle in a much simpler and home-made way, that could take place anywhere around the world, as the material proposed for the machines, has been proved that can be found easily all around the globe.

In this project, in order to improve the system made by Dave Hakkens, or at least make it more sustainable, the idea is to put together the different capabilities of the four machines being used in only one, that would be the combination of the shredder and the extruder, and will cover the activities of those two plus the injection and the compression machine, as it is believed that the combination of these two machine can perform all the actions needed. This new machine will only have a engine share by the two of them and it will be much more compact.

Firstly, there are some mandatory skills that a sustainable project needs to fulfill in order to be able to be consider sustainable. It is concluded that the requirements and objectives of this project are as follows:

Design Requirements	Performance Indicators	Targets
Energy efficiency	Energy quantity	<5,774KWh per Ton
Usage of plastic	Percentage of plastic reused	>9%
Portability	Space	<12.2x2.2x2.6m

Once the mandatory skills are clear, the time to decide what other skills should be complied so that its development and use are sustainable, and that is how the conclusion comes up that the machine needs to have the frugal innovation skill, which will include the following objectives:

Categories	Conventional product service	Frugal Innovation
Substantial cost reduction	Uses all new materials for producing the product.	Reduces cost by using scrap materials.
Concentration on core functionalities	Shredder and Extruder each has its own function for processing waste plastic into a new product.	Combining both shredder and extruder into one machine reduces time and effort for processing waste plastic into a new product.
Optimized performance levels	Shredder and Extruder has their own motors and occupy more space.	Combining both into one represents possibility of reducing one motor and space required for machine.

Another skill that is pretended to be include in the design is the eco-efficiency of the project, in order to achieve that, there are some aspects that need to be minimized:

Resource	Minimise
Materials	Eco system undisturbed
Space	Shredder and Extruder combined to minimise space
Biological Impact	Toxic emission

The next desired skill is eco-effectiveness, which objectives are:

Resource	Eco-effectiveness
Materials	Reusing scrap metals for material to reduce waste
Energy	Attached solar panel to our product for cleaner energy
Space	Reduces land occupation
Biological Impact	Increased usage of waste plastic helps developing a plastic free garbage that effects environment.

Another one of the skill for the project is the whole system thinking, as it is because of that, that the project produces significative improvements when compared to the already used system, as if it is individually developed, the machine will be developed individually as well as it was used to be done up to the present time, it is only when whole system thinking is used, that the possibility of combining certain processes comes up, making the global process more sustainable.

The last of these skills is design for a lifetime, it has as objectives make sure that the different parts are easily accessible, by a modular construction that allows an easy fix or change of the parts. Keep the machine runing for as long as possible, this is achieved by the simplicity of the machine and because of its modularity, that it offers the opportunity of changing different parts without having a negative impact in the other parts of the machine. Enable a responsible end of life, so that the machine has the lest environmental impact as it can be achieved, in order to do this the machine is built with as few materials as possible and avoiding the use of paints or additives.

A benefit-cost analysis is made to find which is the optimal duration of the project. And after studying the situation, it is determined that the project will be more profitable when it is run through the most years. This is because, excepting the first year, benefits and costs are equal, therefore, every year that the project keeps going, the profit will keep augmenting, with a an incremental benefit cost ratio of 2.608.

A multi-criteria analysis is equally done to prove is the implementation of a gearbox to the machine would be beneficial in the long run or not, after the analysis taking into account energy consumption, machine complexity, manufacturing costs and production ratio, the idea of implementing the gearbox is discard, as it would not improve the machine as a whole.

For the public consultations, it is considered that the best way of doing it, as it is an more artisanal than industrial project, firstly the will take place a public meeting, where the developers would introduce the machine to the potential user of it, once this phase is done, the will be some workshops conducted to explain the process and how to use the machine to those ones that are actually going to implemented it. Finally, with the purpose of keep improving, the will be a mailbox installed in every store or workshop where the machine is implemented, so that the community can take part on the process of improving, and leave some recommendations there, that they think should be implanted.

Trying to summarize, the wider society impact expected is greater plastic recycling quantity and in a less focused way, and more artisanal, without a big influence of the decisions made by the big industries.

Equally the realization of a life cycle cost analysis of the project takes place, with which taking into account certain key aspects of the project, a conclusion is made that, in a period of 2 year, the profits made by the machine can outrun the costs.

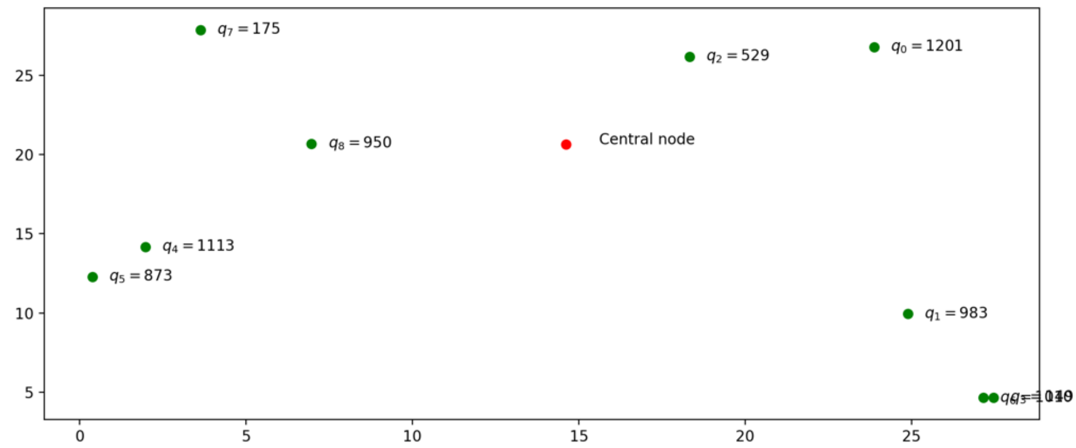
Finally, the life cycle assessment takes place, in which all the particular processes done inside the global process are taken into account, it is to say that all the processes from the extraction of the raw material from the ground, although in this case, the raw material is plastic waste, until the moment when the process is finished and the residual products are left in the ground again. In this life cycle assessment, some important data on the environmental data is obtained:

Characterisation	LCI	Quantity	units	Impact Category	Characterisation Factor	Midpoint Indicator	Unit Equivalent
Electricity	Carbon Dioxide	5400	kg	GWP	1.000	**5400**	kg CO_2 eq
Gas	Fossil	2.016	m^3	FDP	0.836	**1.685**	kg oil eq
	Carbon Dioxide	0.068	kg	GWP	1.000	**0.068**	kg CO_2 eq
Raw materials	Steel	22.204	kg	MDP	42.700	**948.111**	kg Fe eq
Burned Plastic	Toluene	9.500E-07	kg	TP	0.820	**7.786E-07**	kg 1,4-DB eq
Water	Water, processing	50.400	m^3	WDP	0.001	**0.050**	m^3

From this very table it can be conclude that the biggest impact produced by the process is the production of CO2 and that this impact affects majorly to human health mora than to the environment or the resource. Even though it is like that, it does not present a great risk in any aspect, hence, the project can be carried out without any major risks.

When entering the part of programming and optimization, a solid quantity of random instances was created, with some characteristics, so that it would represent more accurately a network of nodes and arcs, representing roads and municipalities within which the vehicles have to pick and process the plastic waste.

Here there is presented an example of an instance:



Based on this instance, a vehicle routing problem(VRP) is developed, with the following objective function:

$$Min \sum_{i \in V} \sum_{j \in V} c_{ij} x_{ij}$$

Subject to the following constraints:

$$\sum_{i \in V} x_{ij} = 1, \forall j \in V\{0\}$$

$$\sum_{i \in V} x_{ij} = 1, \forall j \in V\{0\}$$

$$\sum_{i \in V} x_{i0} = k$$

$$\sum_{j \in V} x_{0j} = k$$

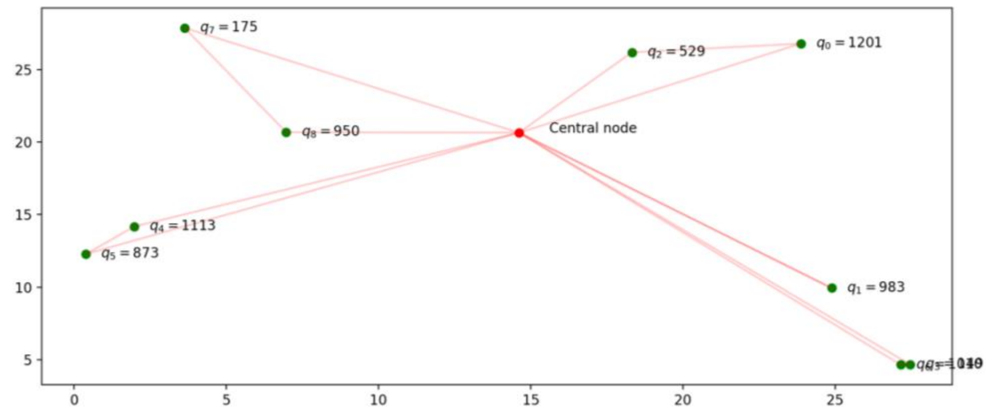
$$\sum_{i \notin S} \sum_{j \in S} x_{ij} \geq r(S), \forall S \subset V\{0\}, S \neq \phi$$

$$x_{ij} \in \{0,1\}, \forall i, j \in V$$

With this objective function and its constraints, what is achieved is a route that minimizes the distance, making sure that each municipality can only be arrived to once and depart from once, excepting the central node, where all the plastic waste would be dumped when the maximum capacity is reached.

With the above program the following results were obtained:

```
solution for: CVRP
objective: 94.297
x_0_2 = 1
x_1_9 = 1
x_2_9 = 1
x_3_9 = 1
x_4_5 = 1
x_5_9 = 1
x_6_3 = 1
x_7_8 = 1
x_8_9 = 1
x_9_0 = 1
x_9_1 = 1
x_9_4 = 1
x_9_6 = 1
x_9_7 = 1
u_0 = 1201.144
u_1 = 983.844
u_2 = 1730.913
u_3 = 1159.884
u_4 = 1113.359
u_5 = 1986.529
u_6 = 1010.675
u_7 = 175.452
u_8 = 1125.701
```



This first case is the one that is being used presently when picking plastic waste from municipalities and being dumped at the central node to be process there. With this project, there is an intention of demonstrate that, with the idea of a new and more compact design of the plastic recycling machine so that it is portable and it can be moved around through the different municipalities processing the plastic waste in situ, some improvement can be done over the costs.

In order to represent the purposed case, the following program is used, based on the Travel Salesman Problem (TSP), with the objective function:

$$Min \sum_{i \in V} \sum_{j \in V} c_{ij} x_{ij}$$

Subject to the following constraints:

$$\sum_{i \in V} x_{ij} = 1, \forall j \in V$$

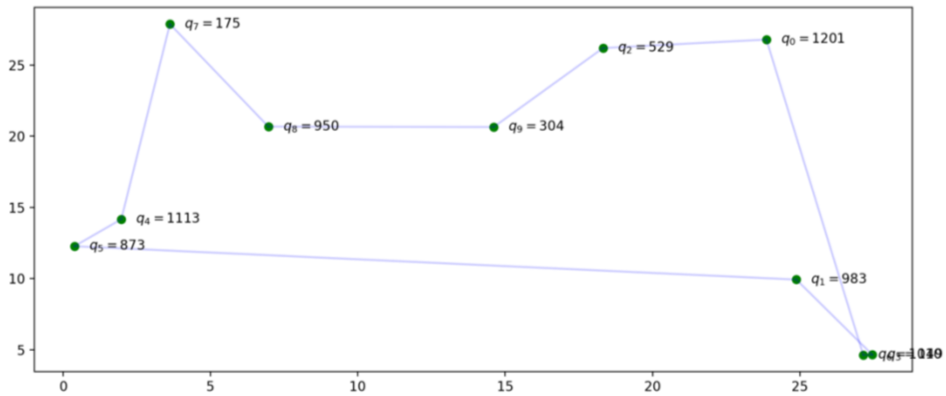
$$\sum_{i \in V} x_{ij} = 1, \forall j \in V$$

$$\sum_{i \in S} \sum_{j \notin S} x_{ij} \geq 1 \; for \; all \; S \subseteq V, S \neq \phi$$

In this casr, simillarly to the previous one, the goal is to minimize the distance, making the vehicle go thorugh all the municipalities, thus, the constraints limit that each municipality only is arrieved to once and depart from once.

With the mentioned program the following results are obtained:

```
solution for: TSP
objective: 77.110
x1_0_2 = 1
x1_1_3 = 1
x1_2_9 = 1
x1_3_6 = 1
x1_4_5 = 1
x1_5_1 = 1
x1_6_0 = 1
x1_7_4 = 1
x1_8_7 = 1
x1_9_8 = 1
d_1 = 7.000
d_2 = 1.000
d_3 = 8.000
d_4 = 5.000
d_5 = 6.000
d_6 = 9.000
d_7 = 4.000
d_8 = 3.000
d_9 = 2.000
```



As it can be observed when looking at the results from both programs, the objective function of the second one, shows a smaller cost than the first one does, thus, the idea that tried to be proved is proved up to now, waiting on a more detailed research.

Index

Index of Figures

Index of Tables

1. Introduction and approach of the project

The project further referenced, is being supervised by the Associate Professor in Mathematical Sciences Marc Demange from RMIT University. This project takes place as useful material for a mixture of subjects from the institution mentioned. The subjects that this project is going to embrace are Sustainable Engineering Practice and Design (OENG1118) and Industrial Application of Math and Statistics (MATH2197), both of them, being project-based subjects, that bring the perfect opportunity to join two different fields of engineering for one project.

The proposition of each subject is the following: Sustainable Engineering Practice and Design, proposes a project, to make a redesign of a system using skills learned in the subject throughout the semester, while Industrial Application of Math and Statistics, as per the title, focuses on the use of linear programming for the study of optimal applications.

This is why, the project is based on the redesign of a plastic recycling system into a more compact one, and the proof of its efficient application through linear programming. For this process, the material used will be the course skills learned about sustainability and ecology, combined with the posterior use linear programming and coding with the use of an IDE that provides the opportunity to compile the code created and revise it in the search of errors, providing finally the option of building graphics and charts to show more visually the results of the conducted studies.

Finally, as a brief introduction for a plastic recycling system, it is usually composed by different stages with different machines. Firstly, the old plastic is shredded to smaller pieces, which usually are heated afterwards with the aiming of putting it into molds or shaping it in different ways and forms, so that new items can be created by crafting this waste material.

1.1. Sustainable introduction

According to Nace of Forbes (2017) [1], a million plastic bottles are purchased every minute globally and 91% of that plastics are not recycled. Polyethylene terephthalate (PET) is the common ingredient to manufacture plastic bottles or hard plastics. This material can take up to 400 years to naturally decompose. It is estimated that plastic bottles will be sold more than half a trillion by 2020 and the ocean will contain more plastic by weight than fish in 2050.

The production of plastics has increased exponentially and there are no signs of decreasing in plastic production. Therefore, this project aims to redesign a more practical and sustainable recycling machine that can repurpose these single-use hard plastics into another product. The design of this recycling machine must be modular, compact, portable and self-sustainable.

Figure 1 shows the typical industrial plastic shedder to produce plastic flakes which is then used in the plastic extrusion to manufacture recycled plastic pipes [2]. Figure 2 displays the project’s inspirational design for a more compact plastic shredder and extrusion.

Figure 1. Industrial Plastic Shredder and Extrusion (MG Machinery 2018)

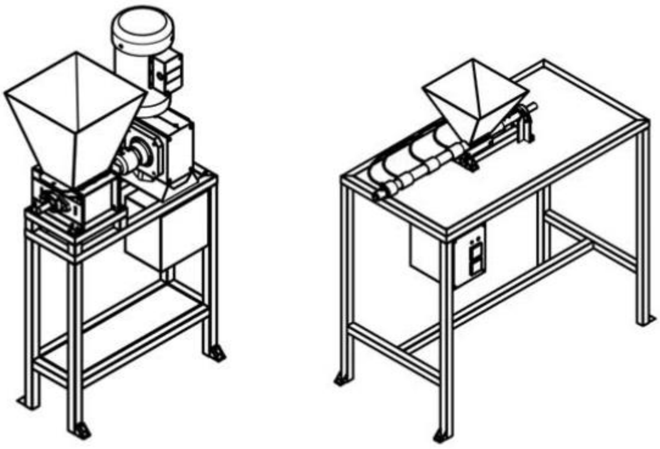


Figure 2. Compact design for plastic Shredder and Extrusion (Precious Plastic 2018)

This project's intention is to combine the two plastic shedder and extrusion into one machine to produce a line of recycled plastic; well suited for 3D printer filament. Blueprints with labels for plastic shredder and extrusion are shown from Appendix A to C. In this report, the three mandatory requirements for sustainable design is discussed along with five fundamental engineering skills.

In addition, project evaluation for benefit-cost analysis and net present value will be examined alongside public consultation and wider society impacts of our product. Life cycle costing and assessment of our product will be studied in detail to understand the environmental impacts, inventory analysis and finally to interpret our findings.

1.2. Optimization introduction

This project takes place as part of the subject of Industrial Applications of Mathematics and Statistics 2 (MATH 2197), but the project itself is carried out based on the knowledge acquired in the subject of Operations Research 1, Linear Programming and Applications (MATH 1288). As part of the mention subjects, the project aims to bring together the students with the real, industrial world, by using the tools of linear programming and coding learned throughout the year.

This is why the project is based on a proof of concept using the different tools learned in the subject. What in this project is tried to prove, is the potential improvement in costs of the model of collection of plastic waste through different nodes, for later on, being bring all together in a recycling plant where it will be processed and transformed into new products or raw materials that can be commercialized again to prolong the life of a single piece of plastic. This potential improvement will be achieved by the transportation of a smaller and portable machine, that although slower, as it can be brought to all the different nodes instead of needing to collect all the waste from the nodes and being brought to a central one, is expected to reduce significantly the costs of this process. Although it is also true, that with the machine planning to be used, new products are obtain straight away after the recycling, thus, there is no need for a later distribution of the new products and the costs will be decreased even more as the new products need to be later on distributed through the nodes. But in this project the point of proof will be only the collection of the waste.

For this process, the material used will be the course skills learned, using linear programming and coding with the use of an IDE that provides the opportunity to compile the code created and revise it in the search of errors, providing finally the option of building graphics and charts to show more visually the results of the conducted studies.

1.3. Motivation

The proposal that is made in this project is in order to make this artisanal system even more simple and maneuverable for the easier use of their operators.
The change that is purposed is the combination of both, the shredder and the extruder together, as it is believed that with these two machines, all the options of final products can be covered.

The combination of both machines will be done, by the common use of a single engine, attached to both shafts, adding up to have one engine and one shaft instead of having one per machine. This will certainly help with the efficiency and sustainability of the system, as it requires less parts, hence, less costs of manufacture, and less energy, as there will only be one machine. This will comply with the different skills learned throughout the course of Sustainable Engineering Practice and Design (OENG1118).

There will be also conducted a proof of concept through programming, to try and proof, that a system build with these compact machines moving around the different points of collection of plastic waste, can be more cost effective than having to transport all this waste from the different collection points to the main recycling plant. This proof will be conducted through code programming, taking advantage of the knowledge gain from the course of Industrial Application of Math and Statistics (MATH2197).

2. Description of Technologies

In this section there will be conducted a literature review on the different methods and technologies used for the consecution of this project.

2.1. Product Design and Systems

2.1.1. Product General Description

The concept of the product being designed is to process plastic by two machines performing two basic functions:

- Shredding; in which raw plastic material –in this case waste plastic- is destroyed, crushed and shredded into flakes, by passing through a motor driven blades shaft.
- Extruding: Melting the plastic flakes into liquid like state and ejecting it out of a nozzle by a compressing screw shaft. The ejected plastic is repurposed to make filament or injected it directly into a mold.

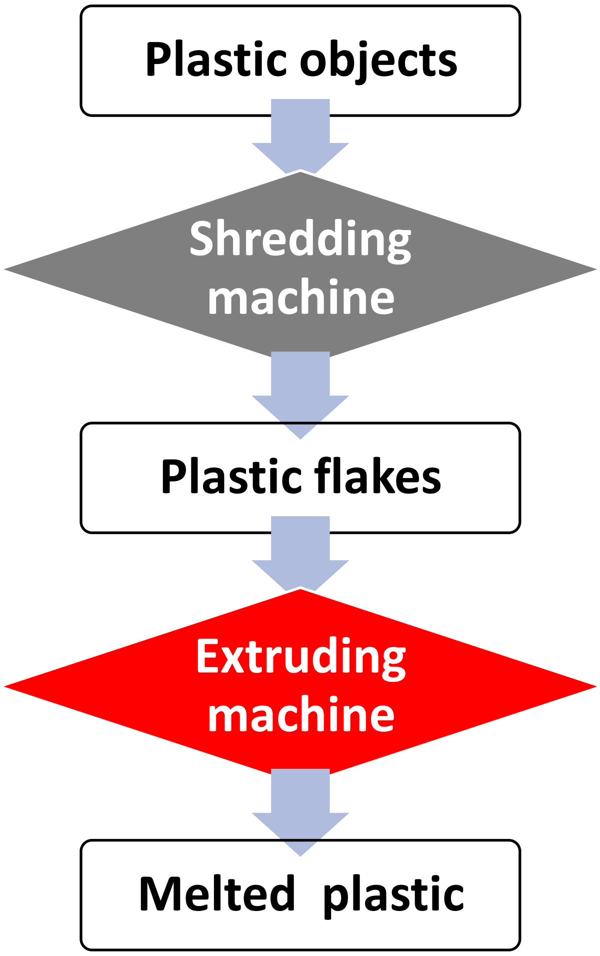


Figure 3. The various stages of the process

Figure 4. Plastic flakes produced by the machine (Precious Plastic 2018)

Figure 5. The shredding machine in an assembled form (Precious Plastic 2018)

Figure 6. Extruding machine with some winded plastic line (Precious Plastic 2018)

2.1.2. The Subsystems

- The Electrical system: which includes the control board and monitoring panel in both machines. Also, the heating element in the extrusion machine, which generates heat up to 230°C in the nozzle.
- Electro-mechanical system: which includes the drive motors and their associated transfer cases, to give different speeds and torques to control the flow of process.
- Materials selection and rigid components: which deals with the frame, stand, hoper etc and the material of which they are made of.

2.2. Vehicle Routing Problem

In the last decades there has been an improvement in optimization packages based on operations research or mathematics programming, in distribution systems for a proper control of stock and services.
It has been proved that an optimal planification of the distribution processes can produce savings of between 5% and 20% of the global transportation costs.
The transportation process represents between 10% and 20% of the global costs of goods.

The Vehicle Routing Problem, VRP, is one of the classics of combinatory optimization with multiple applications. The main features of this type of problem are:

- A central depot
- Clients that need a certain quantity of products
- A fleet of vehicles with a fixed capacity
- The objective is to plan the route of delivery that minimizes the costs of transportation, with everything that it involves.
- It is required to design a route for the fleet of vehicles departing from the depot and coming back to it, satisfying the demand of the customers with some other constraints

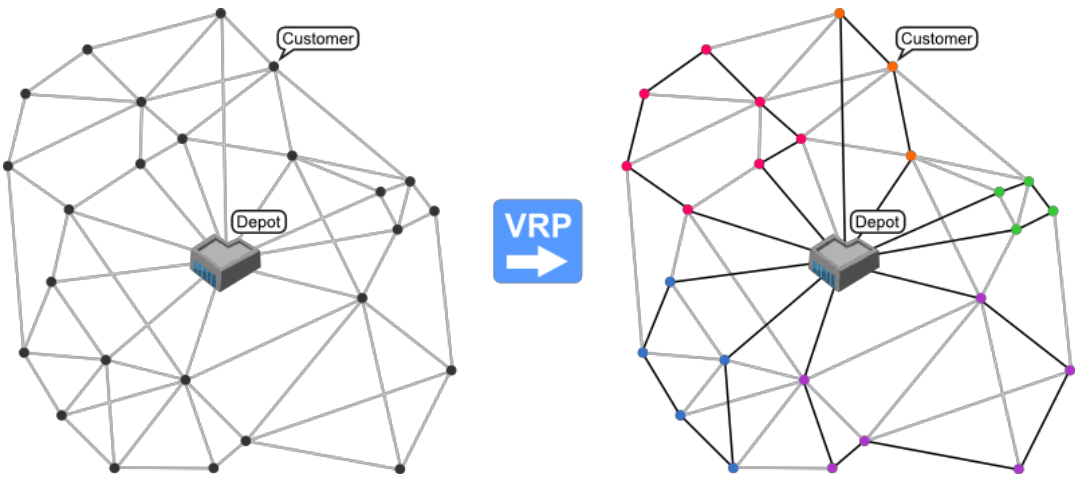


Figure 7. Vehicle Routing Problem

The roads network is described usually with a graph, the arcs represent sections of the road and the vertices represent the customers. Each arc has a weight attached that represent the distance or the traveling time.
When instead of having multiple vehicles with a certain capacity, there is only one, with limitless capacity, this is considered as a Travel Salesman Problem, TSP.
The Vehicle Routing Problem is usually harder to solve than the Travel Salesman Problem.

There are different mathematical formulations that need to be considered in a Vehicle Routing Problem:

- Vehicles flow formulations: integer variables attached with each arc of the graph; they count the number of times that a vehicle makes use of a certain arc.
- Products flow formulations: additional integer variables attached to the arcs and showing the quantity of products that travel through the vehicle's routes.
- Sets partitions formulations: exponential number of binary variables, each of them attached to a feasible route.

There classic types of VRP are:

- VRP with capacities, CVRP
- VRP with time windows, VRPTW
- VRP with pick and delivery, VRPPD
- VRP with periodic cycles, PVRP

This time there will only be conducted a review of the VRP with capacities, as is the most suitable one for the conducted project.

2.2.1. CVRP

Base model: Fleet of k vehicles, each with the same capacity Q.

The CVRP consists on achieving a set of exactly k cycles, each one of them represent the route of each vehicle on the fleet, with a minimum cost. The total cost is define as the sum of the cost of each arc that takes part of the cycle so that every cycle goes through the depot, each customer is reached only once and that the sum of the demands of the vertices of one cycle is not superior to the capacity of the vehicle Q.

The mathematical formulation is as follows:

- $G = (V, A)$ complete undirected graph
- $V = \{v_0, v_1, v_2, \dots, v_n\}$ Set of nodes, v_0 is the depot
- $A = \{(i, j) : i, j \in V, i \neq j\}$ Set of arcs
- $C = (c_{ij})$ Matrix of cost for going from node i to node j
- $d_i =$ Demand of node i
- $k =$ Number of available vehicles
- $Q =$ Capacity of the vehicles

The model to be used has as the decision variables:

$$x_{ij} = \begin{cases} 1, if\ the\ solution\ uses\ the\ shown\ arc\ (i,j) \\ 0, otherwise \end{cases}$$

$$Min \sum_{i \in V} \sum_{j \in V} c_{ij} x_{ij}$$

Subject to

$$\sum_{i \in V} x_{ij} = 1, \forall j \in V\{0\}$$

$$\sum_{j \in V} x_{ij} = 1,\ \forall i \in V\{0\}$$

$$\sum_{i \in V} x_{i0} = k$$

$$\sum_{j \in V} x_{0j} = k$$

$$\sum_{i\notin S}\sum_{j\in S} x_{ij} \geq r(S), \forall S \subset V\{0\}, S \neq \phi$$

$$x_{ij} \in \{0,1\}, \forall i,j \in V$$

The fifth constraint avoids the creation of subtours: constraints of branch and cut.
r(S) is the minimum number of vehicles needed to satisfy the demand in the subset S.
These constraints have a cardinality that grows exponentially with n, it is advised to substitute it by a family of constraints with a polynomial cardinality, given by:

$$u_i - u_j + Qx_{ij} \leq Q - d_j,$$
$$\forall i,j \in V\{0\}, i \neq j, so\ that\ d_i + d_j \leq Q$$

$$d_i \leq u_i \leq Q, \qquad \forall i \in V\{0\}$$

Where $u_i, i \in V\{0\}$, are additional continuous variables that represent the load of the vehicle after passing through the customer I [3].

The objectives of a VRP can be summarize as:

- Minimize costs
- Minimize routes length
- Minimize length of longest route
- Balance either the load, the number of clients or the time of the route
- Maximize the satisfaction of clients
- Minimize the number of vehicles
- Maximize the compactivity of the routes

There are two methods of solving VRPs, these methods can either be exact or approximations [4].
Exact methods are:

- Branch & Bound
- Branch & Cut

When doing approximations, the methods can be:

- Heuristics: The classic heuristic algorithms for VRP can be divided in three main categories:

    - Constructive algorithms: A feasible solution for the program is built gradually, aiming to optimize the objective function, but there is no improvement phase for the achieved solution.
    - Double phased algorithms: The problem is naturally decomposed in two stages, one building sets of vertices and another one building routes.
    - Improvement algorithm: It is started with an initial feasible solution and try to improve it changing arc or vertices within one or multiple routes.

- Metaheuristics:

    - Tabu Search (Cordeau)
    - Genetic algorithms (Prins)
    - GRASP

2.3. Travel Salesman Problem

In the Travel Salesman Problem, TSP, the objective is to find a route that connects all the nodes of a network, each node has to be passed only once and the route has to finish at the starting point, on top of this, either the total time or the total distance of the route needs to be minimized.
This type of problems has a major application in logistics and distribution fields, as well as in production curves programming.

The TSP can vary a lot depending on the symmetry of the distances. It is to say, that if the distance from point A to B is the same as from point B to A, the distance between these two places is symmetric, but this is rarely achieved in real life.
The number of feasible routes is given by the equation:

$$(n-1)!$$

It is to say that in a network of 5 nodes, the number of feasible routes is (5-1)! = 24, and as the number of nodes increases, the number of feasible routes increases factorially. In the case of a symmetric problem, the number of feasible routes is reduced to half of the ones before, it is to say:

$$((n-1)!)/2$$

Which means a significant reduction on the processing time for big routes.

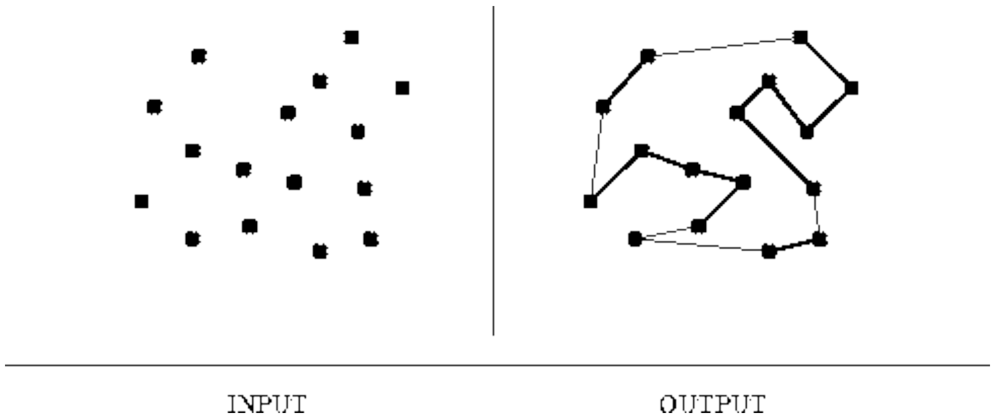


Figure 8. Travel Salesman Problem

The objective function for a TSP is as follows:

$$Min \sum_{i \in V} \sum_{j \in V} c_{ij} x_{ij}$$

Subject to:

$$\sum_{i \in V} x_{ij} = 1, \forall j \in V$$

$$\sum_{i \in V} x_{ij} = 1, \forall j \in V$$

$$\sum_{i \in S} \sum_{j \notin S} x_{ij} \geq 1 \; for \; all \; S \subseteq V, S \neq \phi$$

2.3.1. Solving Methods

The complexity on the calculus of the TSP has awaken multiple initiatives to improve the efficiency in routes solving. The most basic model is one known as the brute-force approach, it consists on the calculus of every possible route, which comes back to be extremely inefficient and makes almost impossible to solve big networks. There are also some heuristic methods that have been developed because of the complexity of the calculus of optimal solutions in big networks, that is why there exist some methods as the nearest neighbor. Lastly, there are some algorithms that come up with optimal solutions such as, the branch and bound method, that approaches the problem as an assignation algorithm, and it solves it with the simplex method [5]. Some of the solving methods are:

- Brute-force approach: The brute-force approach does not imply the application of any other systematic algorithm; it simply consists of exploring every feasible route. As explained before, if the network is symmetric, the number of feasible routes is half of a non-symmetric one.

- Nearest neighbor method: The nearest neighbor algorithm is a heuristic algorithm designed to solve the TSP, it does not assure an optimal solution, but it uses to generate pretty good solution, and it has an efficient solving time. The development of the method is pretty similar to the one used to solve the minimum expansion tree problems.
  The method is carried out following the next steps. Once the initial node is chosen, the nearest node is chosen as the next stop of the route. Once there, the next stop would be the nearest neighbor, that has not been part of the route already.

- Branch & Bound method: The branch and bound method, gives back an optimal solution for the TSP, solving with the simplex algorithm the model. While the network size increases, so does the solving time, that can reach extremely long times, but for average network sizes it can be an excellent alterative.

2.4. Programming Language, IDE and Package

In this section the different tools used for the consecution of the project will be discuss. In this case, when talking of tools, it is referred to computational tools, not to intellectual ones. In this case the language, the chosen one was Python, the IDE was PyCharm and the package Cplex.

2.4.1. Python

Python is a high-level programming language which philosophy insists in a clean and easily readable syntaxis. It is the case of a multiparadigm programming language as it can handle object-orientated approach, imperative programming and, less commonly, functional programming. It is an interpreted language, uses dynamic typing, it is strongly typed and multiplatform [6].

Python presents a list of advantages that make it really appealing, for a professional use as well as for a programming learning use. Within the most interesting ones we have:

- Python is a really expressive language: Python programs are really compact; a Python program tends to be much shorter than its equivalent in some other languages as it can be C.
- Python is really readable: Python's syntaxis is really elegant and it allows the use to write programs with afterwards reading becomes really easy.
- Python offers an interactive environment that facilitates checking the code in the search for errors.
- The execution environment of Python detects a lot of programming errors that an IDE may not be able to detect, and it provides really useful information on how to detect them and eradicate them.
- Python can be used as an imperative procedural language or as an object-oriented language.
- It has a great variety of data structures that can be manipulated easily.

Python has been designed by Guido van Rossum and is been continuously developed by a community of programmers.
Approximately every six months a new, usually improved version goes public. But this doesn't mean that every half year the programming language suffers a dramatic change, the goal of this updates is to somehow improve the language keeping it as similar as possible to the older versions so that there are as little as possible compatibility problems with older codes [7].

A basic advantage of Python over some other languages is the fact that its interpreter comes freely. The interpreter can be download straight from the Python's webpage. The interpreter has version for almost any type of platform: Linux, Windows, Apple, etc.

2.4.2. PyCharm

PyCharm is an IDE or integrated development environment multiplatform used to program in the coding language of Python. It provides code analysis, graphic depuration, integration with VCS/DVCS and support for the web developer Django, within other aspects. PyCharm is developed by JetBrains and due to its licenses program nature, it has two versions, one called Community that is free and oriented to education and pure development of Python and the Professional, that includes wider functionalities like the support for web designs, and it has a different range of prices.

The main features of PyCharm are as follows [8]:

- Assistance and code analysis, with code execution, syntaxis and errors check
- Surfing through projects and codes
- Python Refactoring: Includes rename, export method, add variables, add constants and others.
- Web frameworks support: Django, web2py and Flask
- Python debugger included
- Section check integrated, with line-by-line function
- Python development with Google App Engine
- Integration of version control: User interface unify for Mercurial, Git, Subversion, Perforce and CVS with change and combination lists.

It competes with some other Python oriented IDEs, including PyDev from Eclipse, that is a Komodo IDE but it is not as focus on only Python [9].

3. Description of the Developed Model

3.1. Project Objectives

The project final objective may be the sum of the following:

- Find and explain the sustainable skills that can be applied and that take place in the proposed redesign.
- Analysis of the Project for different points of view and determine the consultations to be made and the wider society impact that it will have.
- Conduct a Life Cycle Assessment (LCA) of the project.
- Create a solid number of realistic instances of a network of nodes and arcs, so that the results can be proved not to be fortune, but to be constant.
- Solve the Vehicle Routing Problem (VRP) attached to the current system of collecting and processing the plastic waste.
- Solve the Travel Salesman Problem (TSP) attached to the system that is been proposed in this project.
- Work out, with the given results, which of the methods is more appropriate.

3.1.1. Methodology of Work

For the realization of the project, the following steps were followed through:

- Theoretical study I: Study of the different skills needed in a project in order to be sustainable and which ones are beneficial but not mandatory.
- Application of skills: Show how the chosen project complies with the mandatory sustainable skills and to some of the additional ones.
- Theoretical study II: Study of optimization through linear and integer programming.
- Theoretical study III: Study of the different ways of analysis of projects and its impacts and how to conduct a life cycle assessment.
- Introduction to the software: introduction to the program used for the coding and to the algorithms in which the project will be based, such as vehicle routing problem, travel salesman problem, Dijkstra method and Bellman-Ford method.
- Analysis of the project: conduct the different analyses and the LCA
- Create instances: Create instances and their preferred route with the system as it is currently.
- Proof of concept: Optimize the route for the new system and compare it to the current one.
- Redact the memories.

Planning	March				April				May				June				July			
	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4
Theoretical Study I																				
Application of skills																				
Theoretical Study II																				
Theoretical Study III																				
Introduction to the software																				
Analysis of the project																				
Create instances																				
Proof of concept																				
Redact memories																				

Table 1. Project Planning

3.1.2. Resources to Use

For the realization of the project, the resources to be used are the following:

- Mathematical computer program Matlab
- Coding language Python
- Compiler PyCharm
- Different packages for the consecution of the goal

3.2. Redesign for Sustainability

The machines detailed in the previous sections are improvised to build a more compact machine, ensuring practicality and sustainability. This new design is expected to replicate the functions of the above machines in Figure 1 more effectively and compactly.

In the modified design, it is sought to combine the shredder and the extruder. This would mean that, once the shredder cuts through raw plastic waste and produces plastic pieces of desired sizes, these pieces are collected in the collection unit.
From here, these pieces are fed to a rotating extrusion screw which then compresses the plastic flakes while it is being exposed to the high temperatures created by the heating element. The benefit of such a system would be the reduction of material that goes into making the machine.
Also, since the motor used in the shredder is expected to be of high power, there is no necessity to include another motor to act on the extrusion screw. Thus, this system is compact, occupies less space; thereby reduces the electrical and mechanical components involved in the actual design.

3.3. Engineering Skills for Sustainability

3.3.1. Mandatory Requirements

In order to comply with the mandatory requirements of a sustainable design, the new design features some elements and characteristics meant to satisfy these requirements. To assure the compliance of having a sustainable and regenerative development, the product will use in a sustainable energy supply, as it will only have one engine for multiple functions instead of having one for each.

The regenerative aspect of this development is visible in the use of plastic waste as the raw material for new products. Although this is the most important and visible regenerative aspect, there are some others. One of which being the community autonomy to build their own products to the extent possible, and the portability, which prevents from building multiple recycling stations, and opens the possibility of sharing the same station for multiple locations.

Secondly, there are some design requirements and performance indicators. The first sustainable requirement is the energy efficiency, the goal, obviously is to minimize the energy used in the process and the performance indicator would be the quantity of energy used for that.

Additionally, the goal is to reuse as much plastic as possible and the performance indicator would be the percentage of the plastic waste that is used for new products. For the customer requirement we have the portability, which performance indicator would be the space it uses.

For the theoretical targets of our requirements the main goal is to improve the technology that is already being used. While recycling a ton of plastic, 5,774KWh of energy can be saved which is the energy required when manufacturing a ton of new plastic products from oil [10]. Therefore, the goal is to have a lower consumption of energy while recycling a ton of plastic, that the one used in producing a ton of new plastic.
For the usage of plastic, the target would be to beat the actual percentage of plastic being recycled - around 9% in the US [11]. In terms of compactness, the goal is to reduce the size of the actual station, which is installed inside a container, therefore the size should be smaller than a standard container of 12.2mX2.2mX2.6m [12]. Table 2 shows the summary of the three mandatory requirements for designing the recycling system.

Design Requirements	Performance Indicators	Targets
Energy efficiency	Energy quantity	<5,774KWh per Ton
Usage of plastic	Percentage of plastic reused	>9%
Portability	Space	<12.2x2.2x2.6m

Table 2. Three mandatory requirements

3.3.2. Frugal Innovation

Frugal Innovation according to Weyrauch and Herstatt (2016) [13] is reducing the cost of product and making it more user friendly. Our products are developed by producing the body from scrap, while using the best quality materials for core mechanism like blades and motor. This significantly reduces the cost of product while maintaining quality. Furthermore, mentioned in Table 2 are core concepts are related to frugal innovation in our product.

The new design means that required space is reduced making it user friendly. We speculate that around 30% of area occupied can be reduced and thus reducing transportation and storage costs.

Categories	Conventional product service	Frugal Innovation
Substantial cost reduction	Uses all new materials for producing the product.	Reduces cost by using scrap materials.
Concentration on core functionalities	Shredder and Extruder each has its own function for processing waste plastic into a new product.	Combining both shredder and extruder into one machine reduces time and effort for processing waste plastic into a new product.
Optimized performance levels	Shredder and Extruder has their own motors and occupy more space.	Combining both into one represents possibility of reducing one motor and space required for machine.

Table 3. Core concepts of frugal innovation

3.3.3. Eco-Efficiency

The shredding and extruding machines brings ecological damage to a minimum while at the same time maximizes efficiency of production process. Stated below are eco efficiency aspects of this product resources for design.

- Maximum use of renewable resources and improved Recyclability:
  This system is designed from reusable metals (aluminium, carbon steel, copper steel, etc) and does not utilise any natural resource for functioning, apart from Electricity. The system thus utilises only recyclable waste and electricity to generate goods that are recyclable after usage.
- Toxic Emission:
  Toxic emission during heating process is controlled by measuring good ventilation and providing gas masks, melting plastic can caused toxic white fume/aerosol toxic.
- Space Requirement:
  By combining units, area occupied by the system is reduced.

The following Table 4 identifies resources that increase eco efficiency of the product design.

Resource	Minimise
Materials	Eco system undisturbed
Space	Shredder and Extruder combined to minimise space
Biological Impact	Toxic emission

Table 4. Eco-Efficiency of the product design

3.3.4. Eco-Effectiveness

Our product focuses on increasing economic value while simultaneously decreasing the impact upon ecological systems by emitting zero waste. The following Table 4 illustrates the concept of eco-effectiveness implemented in our product.

Resource	Eco-effectiveness
Materials	Reusing scrap metals for material to reduce waste
Energy	Attached solar panel to our product for cleaner energy
Space	Reduces land occupation
Biological Impact	Increased usage of waste plastic helps developing a plastic free garbage that effects environment.

Table 5. Concept of Eco-Effectiveness

As for now, our product does not include solar panel; however, adding solar panel can contribute in reducing carbon emissions. Compared to actual shredder and extrusion machinery size, our product will significantly reduce land occupation; small enough to fit in a garage.

3.3.5. Whole System Thinking

The technique of Whole System Thinking allows one to see a bigger picture of the social, environmental and technical system that a product is a part of. This helps in identifying areas that are worth developing, opening possibilities for innovation.
Our proposed product is part of the recycle process wherein recyclable plastic waste is converted into consumer product. Figure 9 explains the role of our product in the Recycling industry at large.

Using whole system thinking skill, we identified the leverage points for our product as to combine the shredder and extruder as one system. This enables us to improve the below aspects:

- Electrical energy consumption is reduced as one motor is used for running both the shredder and extruder. Figure 10 is a pictorial representation of effect of applying the leverage point.
- Material usage for designing this system is reduced.
- Product manufacturing cost is reduced by using reusable waste metals for designing the product.

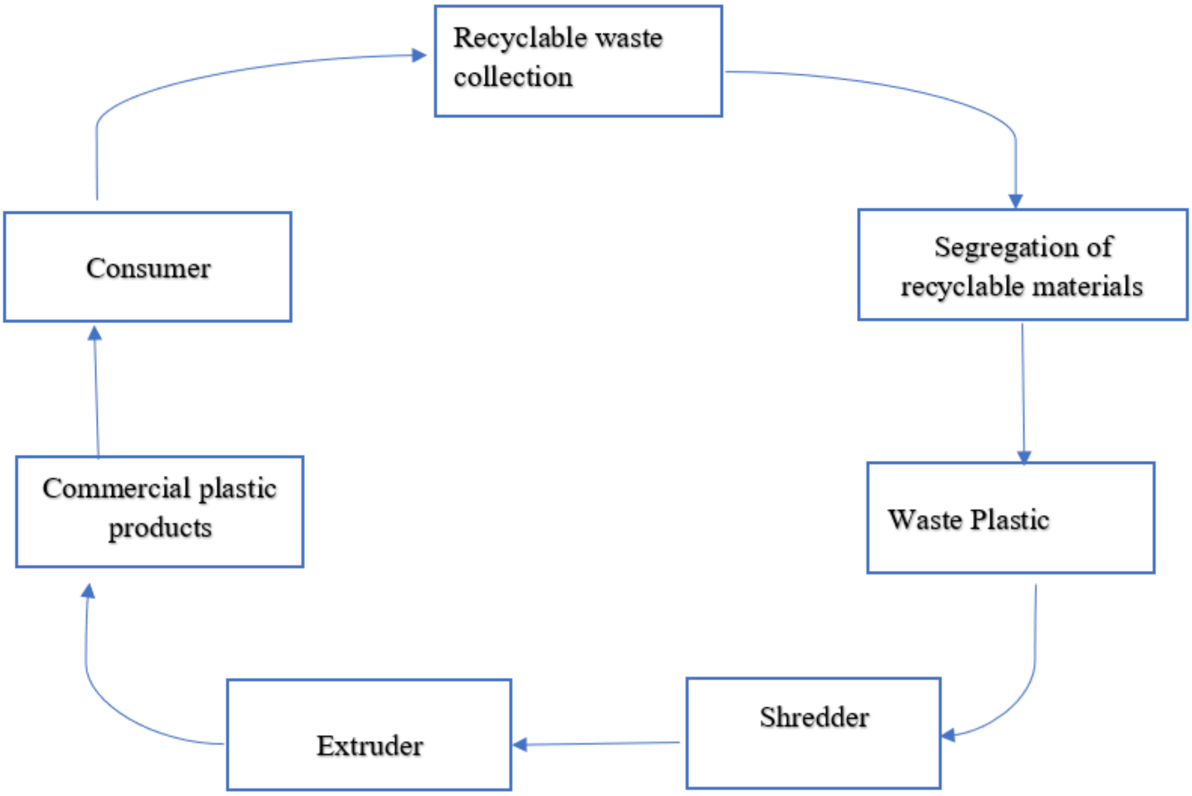


Figure 9. Plastic recycle process

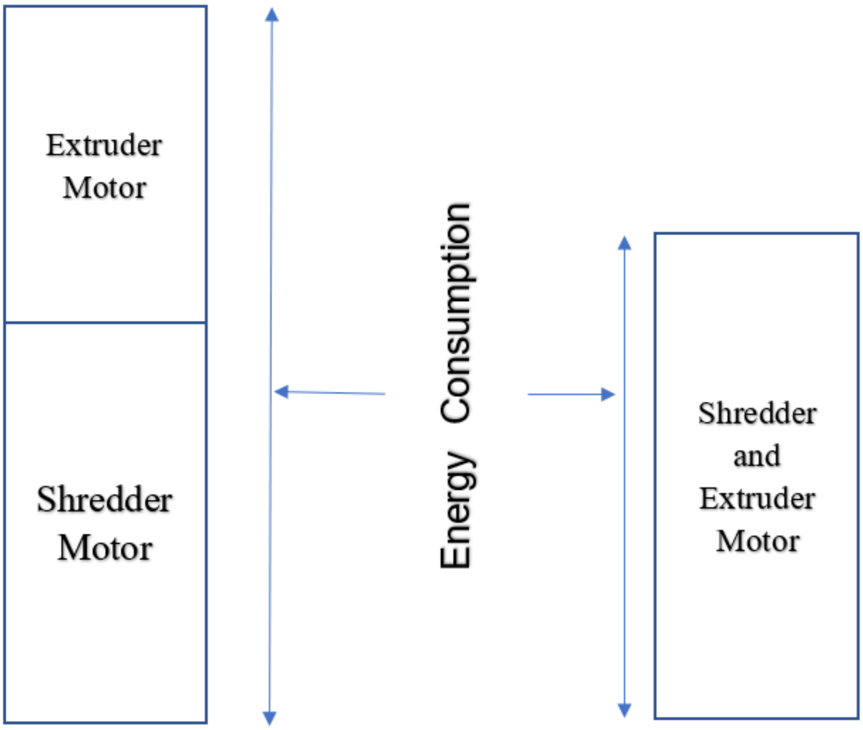


Figure 10. Energy consumption before and after leverage

3.3.6. Design for a Lifetime

Design for Lifetime ensures that the product is designed in such a way that the below sub skills are applied.

- Access a product's components (design for disassembly):
  In this design ensured that all the components are easy to take apart quickly, the details are given below.

  - ❖ Parts:

    - ➢ In our product minimise the number of parts by simplified the design.
    - ➢ Simplify structure of assembly and form in to convenient manner.

  - ❖ Tools Fasteners:

    - ➢ Required only a few standard tools.
    - ➢ Avoided requiring tools for the most common actions.
    - ➢ Minimize the number and verity of fasteners.
    - ➢ Use sliding connections.
    - ➢ Design connections that are visually and physically accessible.
    - ➢ Access fasteners from the same axis.
    - ➢ Hold multiple parts with one fastener.
    - ➢ Coarse threaded screws for speed and plots and nuts for strength.
    - ➢ Hand strength press fit instead of tight fit.
    - ➢ Fasteners for over repeated use.

- Keep it alive longer (design for repair and upgrade):
  This product repairs are simple to do and not required any special skills. Also, any part can be replaced with a new part without having a negative impact on the other parts.

  - ❖ Product architecture:

    - ➢ Used modular assemblies that enable the replacement of discrete components.
    - ➢ Easy access to parts likely to need maintenance.
    - ➢ Used self-locating parts.
    - ➢ Standard size modular parts are used to enable the interchangeability and customization.
    - ➢ Design easy access parts likely to become obsolete.
    - ➢ Used standard cross platform to replace with minimal effort.

- Enable responsible end of life (design for recycling and remanufacturing):
  This design helps easy to properly dispose for the recycling process with less bad effect to environment and reuse of old components in new products with the following components.

  - Materials:

    - Material used to recycle everywhere.
    - Minimize the number of materials used. When possible, use only one.
    - Avoided paints, additive and surface treatments.
    - Avoided combination of materials that are difficult to separate.

3.4. Project Evaluation

3.4.1. Benefit-Cost Analysis

In order to perform a proper project evaluation, there was a research conducted on the different parts, tools and materials needed to start the project, and to keep its activity going. This research was based on the website of "Precious Plastics", because, although it is not a scientific webpage of any short, the project is based on them, therefore there is no better place to acknowledge the different needs for it. In this case the main difference between the original project and this one is that there will be one less engine and the power consumption will be reduced. The costs for all these items and an approximation in sells is shown in Appendix D. After this research, a table with different options on the duration of the project is shown. This table there can be seen the Net Present Values of Cost and Benefits, as well as the Profit and the Benefit-Cost Ratio, the regular one, and the incremental one.

Alternative	NPV Costs	NPV Benefits	NPW	BCR	Incremental BCR
Start up	$9,591.20	$0.00	$-9.591.20	0	0
1 Year	$20,854.76	$29,370.61	$8,515.85	1.408	2.608
2 Years	$31,381.45	$56,819.79	$25,438.33	1.811	2.608
4 Years	$50,413.90	$106,448.39	$56,034.49	2.111	2.608

Table 6. Economical study of the alternatives

As can be observed in the table, the profits increment gradually per year, as well as the regular Benefit-Cost Ratio, while the Incremental Benefit-Cost Ratio, stays constant. These is the case due to the constant benefits and cost per year, as these two variables change equally every year, the Incremental Benefit-Cost Ratio stays constant, thus the best alternative for these project would be to keep it working as long as possible, because, as shown above, the profits will increment gradually every year. So, in this case, the chosen option would be 4 years.

In the above table, the discount rate has been taken as 7%, as required by the Australian Government. But a sensitivity analysis has been conducted to the change of this variable, performing it with 5% and 10% as well. The results are shown in the table below for the alternative previously chosen.

Sensitivity Analysis	5%	7%	10%
NPW	$59,110	$56,034.49	$51,823.5
BCR	2.13	2.111	2.084

Table 7. Sensitivity analysis for 4 years

As seen in the table above, the lower the discount rate, the higher the profits and the Benefit-Cost Ratio.

3.4.2. Multi-Criteria Analysis

Now there will be conducted a Multi-Criteria Analysis, on whether or not it is a good idea to implement a gearbox to the machine, to allow the shaft to rotate with different speeds.
In this case the goal is to determine if the implementation is worth it or not.
The criteria used in the analysis is the energy consumption, the complexity of the machine, the cost of its manufacture and the production rate.
After this, the next steps would be to rate the alternatives and assign weights to each one, get the scores for each one, by multiplying the rate by the weights.

Criteria	Weight	Rate Original	Rate Alternative	Score Original	Score Alternative
Energy consumption	30	3	2	90	60
Machine complexity	20	1	4	20	80
Cost of manufacture	20	1	3	20	60
Reduction of production rate*	30	3	2	90	60
Sum	100			220	260

Table 8. MCA for gearbox implementation

As we can see in the table, the score sum for the alternative with the gearbox is greater, but in this case, that does not mean that is the best option, actually in means the opposite. This is because in this analysis, the criteria use for it was formed with negative skills instead of the usual one, in which the one with the greater score is the best alternative is the best one, in this case it is the other way around. Hence, for this project, the best alternative is to keep it simple and do not implement a gearbox.

*Although these criteria do not make the best sense here, it was necessary to put it this way, so that the sum of score would make sense, as explained the less the better.

3.5. Public Consultation

For this section of the Project, as it is more of a local project, there is no need for big and complex systems of public consultation. Hence the next system is proposed:

As it is a project planned for local and non-industrial aiming, the first step in the consecution of its acceptance by the community would be to hold a public meeting, in a local area with workshops and business if the kind, that way, the idea can be explained and discuss with those that may have interest in it and may put it in practice.

Once the idea has been explained and review for the locals, there will be some workshops conducted, so that those interested can learn and realized by themselves the simplicity of the process and the opportunities that it may offer to their business or to their local environment.

Lastly, and as a way of maintaining the interest on the public opinion, not only during the set up and the start of the project, but all through its existence, hoping to improve, and meet with the requirements and hopes of the public, so that they will be the ones also aiming on the development of the project feeling like their own somehow, as it affects the community. This last option of consultation will be a mailbox installed in every workshop that implements the machine, so that the public that attend to them and is influence by it can leave their thoughts and ideas in regards to the project, so that they can be periodically collected and discuss in the meeting of a study group, formed by the owners of the participant workshops and some local representative, to decide whether to act or not on the purposes, taking into account the public opinion, and the business plan of the project.

3.6. Wider Society Impacts

As said before, this project is planned for an individual or local implementation, mora than a national/global one, although it can get to that point if there is a big implementation locally.

The expected impact locally is to give back to the people value for their plastic waste, in a way they are their own helpers and business. It is expected a higher recycling rate, as now, all the process will be much more personal, hence it will feel like a group job with the whole community. It is not only the person that owns the workshop and the machines, but all the neighbours and people around, that support it with their own plastic waste as raw material, and also sporadically buying some of the products made afterwards. The best and most obvious consequence is the improvement in plastic recycle, but also it is a new business opportunity for the community and a way of bringing them together for the benefit of them all.

More specifically, the alternative proposed by this project, will bring to the community the opportunity of sharing one machine and moving it to different places, instead of having to build different workspaces all around. This will reduce a lot of costs, first of all, the cost of building all the individual machines per workspace can be reduce, by sharing the cost of building one common one, plus, as it will be moving around, it will have more plastic collected and it can work constantly, without having to turn it on and off, with all the energy consumption that it produces (like having to warm up the extruder each time). Hence the energy consumption will not only be reduced because of the change of multiple machines for only one, but for the more efficient way in which this machine will be used.

If this local project is implemented more widely, it would lead the whole country to have better rates of recycling and generate some new jobs. Although these way of processing the plastic is less efficient than the industrial way, if it can make a big enough impact in society and it grows big, the positive impact of more plastic recycle, will easily surpass the economic losses. Also, another positive point of this project, is that, as it is composed by really simple materials, it can be adapted and used all around the world as the materials can be found everywhere.
In any case, if the project was to be adopted in a bigger, national or global way, changes should be done to it, in order to make more efficient for the vast quantities of plastic that it would encounter.

3.7. Life Cycle Costing

One of the most important decision an owner or manager has to make is about the assets. This decision effects the acquisition of new assets, usage of already acquired assets and inventory facilities to store these assets. The initial costs of acquisition play a major role, but, is accompanied by several other future costs that may significantly influence the decision.

For this, a key indicator is the Life Cycle Costing (LCC). It is defined as the process which involves the documentation of all identified costs that occur in throughout the lifecycle of the asset under consideration [14]. In this section of the report, we present the life cycle costing for the proposed sustainable redesign of the plastic shredder and extrusion machines for enhanced efficiency.

3.7.1. LCC for Redesigned Machine

In order to determine the LCC, we look through all the aspects that influence costs from the stage of acquisition to the stage of disposal. These costs and derived gains can be categorised as:

1. Initial Capital Costs
2. Operational Costs
3. Maintenance Costs
4. End of life Costs
5. Key Benefits
6. Residual Value

Expenses (over a period of 5 years)		Conventional Shredder and Extruder Machines	Redesigned Shredder+Extruder Machine
Initial Capital Costs	Electric Motor	$931	$700
	Frame	$80	$50
	Shredding Axle and Blades	$50	$50
	Extrusion Screw	$40	$40
	Electrical wiring and other components	$135	$100
Operational Costs	Certification	$50	$50
	Insurance	$90	$90
	Energy Costs	$7200	$4000
Maintenance Costs	Regular Checks	$1000	$800
	Repairs	$1200	$1500
End of life Costs	Repurposing	$200	$200
Residual Value Costs	Resale	$-100	$-60
	Total	**10876**	**7340**

Table 9. Product's Life Cycle Costing

3.7.2. Net Present Value (NPV)

The NPV is a crucial method that is used to determine the current value of all future costs and benefits. It is calculated using the following formula:
Ie. The Net Present Value = FV/(1+r) ^n

Here,
'FV' - Amount of money to be spent in future
'n' - Number of time intervals
'r' - the discount rate = 7%
Initial investment = 9591.2

Year	Cashflow	Present Value	Balance
0	-9591.2	$9591.2/(1+0.07)^0 = -9591.2$	-9591.20
1	8515.85	$8515.85/(1+0.07)^1 = 7958.73$	-1632.47
2	8515.85	$8515.85/(1+0.07)^2 = 7437.42$	**5804.95**

Table 10. Net Present Value for proposed machine

3.7.3. Discounted Payback Period

The discounted payback period is defined as the time taken for the present benefit to exceed present cost.

I.e.
Discounted Payback period = Initial investment / Net annual savings

Here we have calculated the 'Discounted payback period' of the proposed machine considering 7% discount rate of interest.

Based on the NPV table, we get the Discounted Payback Period as 2 years.

3.8. Life Cycle Assessment

3.8.1. Machine Manufacturing and Life Cycle

Assessment of the life cycle is a cradle to the grave approach to industrial systems assessment. Cradle to the grave begins with the collection of earth's raw materials to create the product and ends at the point of returning all materials to earth. LCA assesses all stages of a product's life from an interdependent perspective, which means one operation leads to the next.

The internationally recognized standard for Life Cycle Assessment is the International Organization for Standardization (ISO) standard 14040. ISO defines life cycle assessment (LCA) as the compilation and evaluation of a product system's inputs, outputs and potential environmental impacts throughout its life cycle (ISO 14040, 2006). LCA aims to assess the environmental load of products and processes created throughout the life cycle, including raw material extraction and processing, manufacturing, transportation, maintenance, recycling and disposal. The following figure shows the life cycle stages frame work.

As it provides a framework for quantifying the environmental performance of alternative solid waste management strategies, LCA has been shown to be a useful tool for evaluating the environmental impact of End of Life management options [15]. Our assessment deals with the manufacturing of plastic recycling machines using reusable environmental materials to reduce waste. LCA conducted to formalize the manufacturing process of plastic recycling machines.

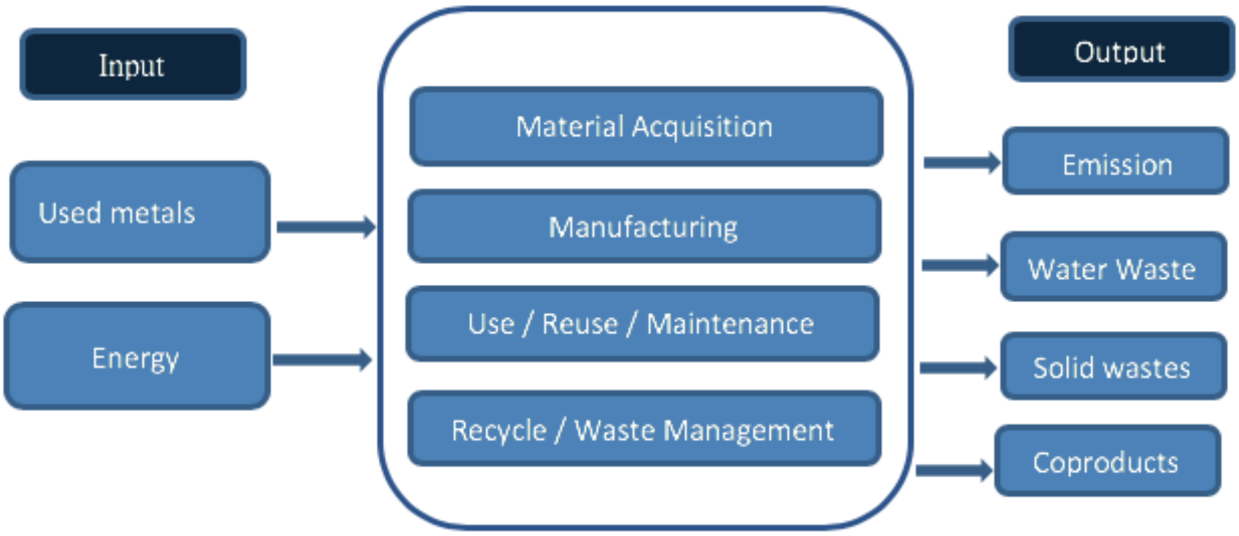


Figure 11. Life cycle atages framework (Curran ., M.A., pg 1, cited EPA, 1993)

Figure 12 shows the plastic recycling machine (shredder and extruder)'s production and life cycle process. The flow chart shows the material acquisition, production, transport for manufacturing of the product and usage of the product with an impact on the environment and also indicated with end of life for the product.

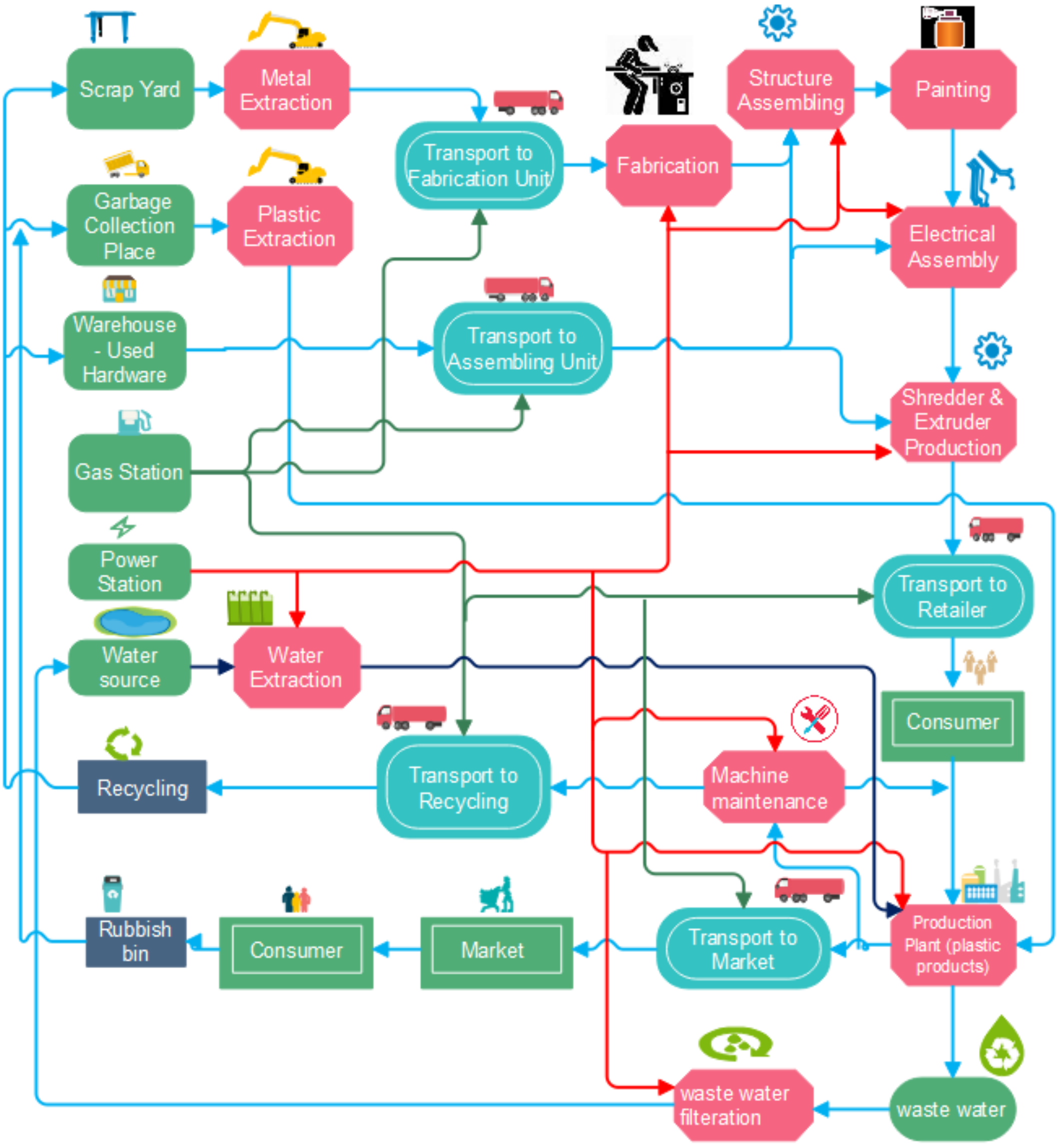


Figure 12. Life cycle stages of Manufacturing (Shredder and Extruder) and use for recycling plastics

3.8.2. Life Cycle Assessment Methodology

ISO's LCA methodology includes four steps: definition of goal and scope, analysis of inventory, impact assessment and interpretation [16] shown on Figure 13.

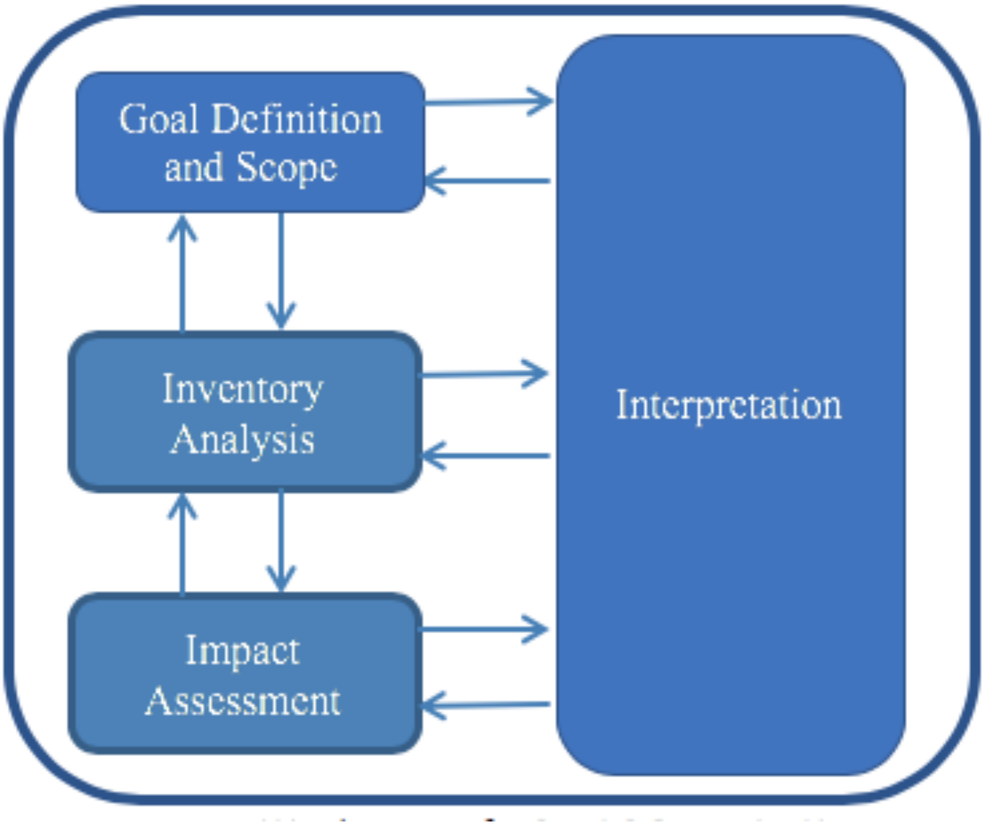


Figure 13. Phases of LCA (M. Finkbeiner et al, 2006)

3.8.3. Goal Statement

The goal of the study is to assess the environmental impacts through the life cycle of plastic recycling machine (shredder and extruder). The assessment includes the following life cycle stages: used material extraction, material transportation, machine manufacturing and recycling of domestic plastic waste for extend the life time of plastic materials on environment. The goal of this assessment is to produce plastic product without emission as per the LCA standard data.

3.8.4. Scope of the Study

The scope of this study is to analyze all parts of the process of plastic recycling using recycling machine to minimize environmental impact through the process. Figure 14 shows the total boundary of the plastic recycling system using recycling machines and we have to perform all the functional units of the process given bellow.

3.8.5. Functional Unit

The primary function of this study is to produce the plastic recycling machine for plastic waste recycling. As shown in Figure 14, we used a shredder and extruder machine to recycle plastic waste to plastic flakes and 3D plastic printing wires.

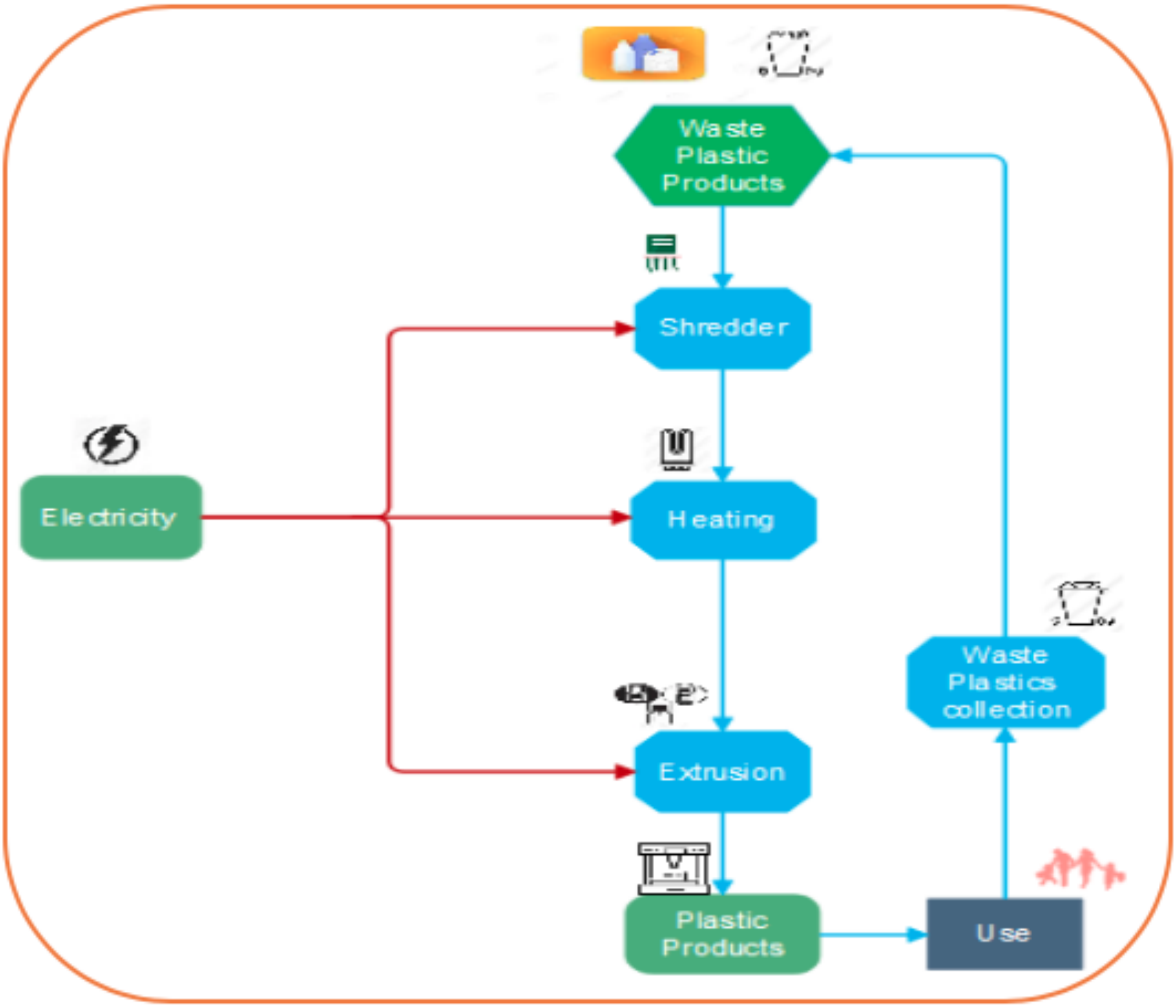


Figure 14. System boundary and process flow model for recycling of plastics

3.9. LCA: Inventory Analysis

Characterisation	Quantity	flow	flow type	category	subcategory	units	Conversion factor	units	Conversion Quantity	units
Electricity	5000	from power station	input	resources	in ground	kwh	1.08	kg CO_2/kwh	5400	kg CO2
Gas, petroleum	2.016	for transportation	input	resources	in ground	m³	-	-	2.016	m3 petroleum
							8.887	kg CO_2/gal	17.91619	kg CO2
Raw material, steel	22.2041	from scrap yard	input	resources	in ground	kg	-	-	22.2041	kg
Burned plastic	1	into air	output	resources	in ground	kg	950	mg toluene/kg plastic	950	mg toluene

Table 11. Data collection table

Total Material	Contribution	Accumulated contribution
Shredding axel	5%	5%
Shredding bracket bottom	3%	8%
Hopper	6%	14%
Hopper Bracket	3%	18%
electrics box	7%	25%
Frame Work	29%	54%
Barrel	10%	64%
Barrel support	1%	64%
Barrel Holder	2%	66%
Barrel Holder	3%	69%
Hopper Sheets	8%	77%
Hopper Sheets	1%	78%
electronics box	1%	78%
electronics box	1%	79%
frame work	15%	94%
frame work	1%	95%
barrel holder bearing shaft	4%	99%

Table 12. Cut-off criteria (mass)

3.9.1. LCA: Impact Assessment

Life cycle analysis impact assessment evaluates and measures the significance of environmental impacts of a product system. Every product system could potentially have a negative impact on the environment in many ways; such as consuming high amount fossil fuel or coal for energy, releasing hazardous sub-products or even by increasing carbon footprint from transportation. Hence, LCA Impact Assessment quantify every possible environmental impact into a comparable value. Following figure displays the potential environment impacts by using the shredder and extrusion system.

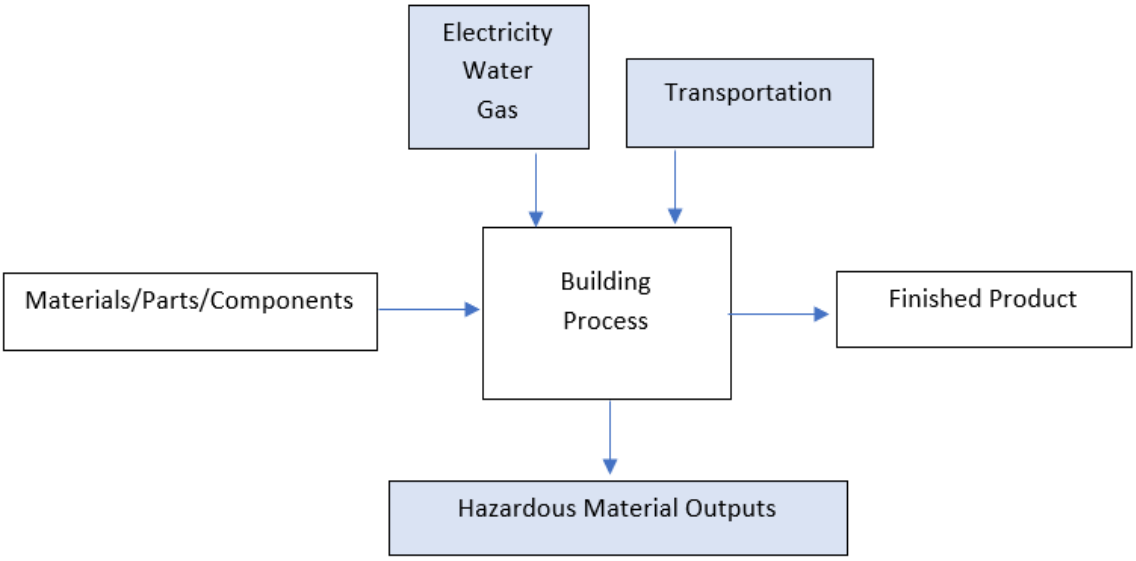


Figure 15. Potential impact assessment of the process

The idea of building our product is reusing scrap metals and materials. Hence, the specific metals or steels to use to build our product would be arbitrary to determine. For LCA impact assessment, buying new carbon steel would be assumed to calculate the amount of metals needed to build a single unit product. Power for operation such as gas and electricity, water consumption and transportation for raw materials and product shipment will contribute into impact assessment.

The product purpose is to melt plastic and could possibly release hazardous compound. Melting plastic such as polypropylene (PP), Polyethylene (PE), Polystyrene (PS) and Polyvinyl chloride (PVC) can release white fume/aerosol if plastic was accidentally burnt. The hazardous chemicals are styrene, aldehydes, alcohols, ketones, esters, dioxins and furans [17]. These compounds will be categorised under hazardous material outputs since extrusion will be to be tested and during customer usage. Table 13 shows the number of hazardous chemicals released into the air measure in mg of toluene/kg of plastic. Chemicals such as chloride, dioxins and furans are summarized under other in table 13.

Hazardous Chemicals	Emission factor (mg as toluene/kg plastic)
	Recycled PP/PE/PS/PVC
Aliphatic hydrocarbons	220
Aromatic hydrocarbons	10
Alcohols	20
Aldehydes	240
Ketones	80
Esters	70
Organic acids	170
Others	140
Total	**950**

Table 13. Heated plastic emission factor at 200C in air (Chang et al, 2014)

- Characterisation factors:

  To summarize the impact on environment, the potential factors such as hazardous chemicals and electricity are evaluate as shown in Figure 16.

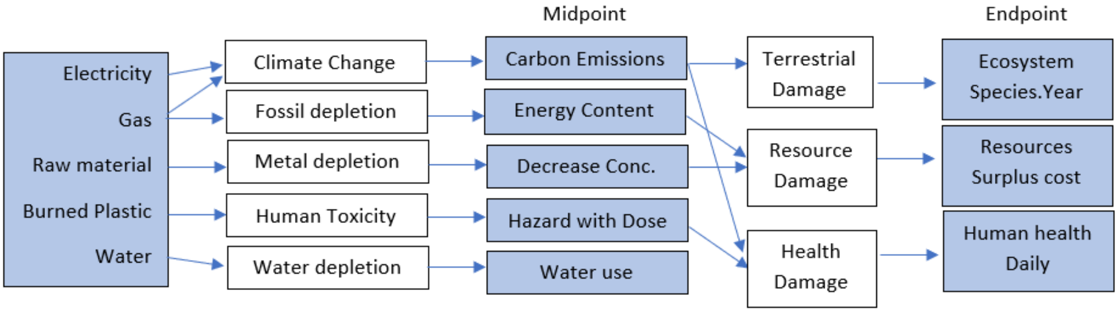


Figure 16. Characterisation factors of environmental impacts

- Impact Category Indicator Results:

  The input (electricity, gas, and steel as raw material) and output (hazardous chemicals) data were taken from the inventory analysis. The following table displays the appropriate conversion of the input and output data. For the analysis, power, fuel and water consumption values are measured per year meanwhile raw material, steel, is measured per unit.

Characterisation	Quantity	Units	Conversion factor	units	Conversion Quantity	Units	Citation
Electricity	5000	kwh/year	1.08	kg CO_2/kwh	**5400**	kg CO2	(Department of the Environment and Energy, 2017)
Gas, petroleum	2.016	m^3/year	-	-	**2.016**	m3 petroleum	-
			8.887	kg CO_2/gal	**0.068**	kg CO2	(EPA, 2018)
Raw material, steel	22.204	kg/unit	-	-	**22.204**	kg steel	-
Burned plastic	1	kg/year	950	mg toluene/ kg plastic	**950**	mg toluene	(Chang et al, 2014)

Table 14. Input and output data conversion values

Table 15 and 16 shows midpoint and endpoint indicators by using characterisation factors using ReCiPe by M. Goedkoop et al, 2014 [18]. The characterisation factors were found under hierarchic values for Climate Change (GWP), Fossil Depletion (FDP), Metal Depletion (MDP), Human Toxicity (TP), Water Depletion (WDP) and multiplied with the input and output quantities. Under the same impact categories, we can determine the endpoint indicator values. Water depletion does not have an endpoint value because it does not have a significant impact on the environment because wastewater is recyclable after treatment.

Characterisation	LCI	Quantity	units	Impact Category	Characterisation Factor	Midpoint Indicator	Unit Equivalent
Electricity	Carbon Dioxide	5400	kg	GWP	1.000	**5400**	kg CO_2 eq
Gas	Fossil	2.016	m^3	FDP	0.836	**1.685**	kg oil eq
	Carbon Dioxide	0.068	kg	GWP	1.000	**0.068**	kg CO_2 eq
Raw materials	Steel	22.204	kg	MDP	42.700	**948.111**	kg Fe eq
Burned Plastic	Toluene	9.500E-07	kg	TP	0.820	**7.786E-07**	kg 1,4-DB eq
Water	Water, processing	50.400	m^3	WDP	0.001	**0.050**	m^3

Table 15. Characterisation to midpoint indicator results

LCI	Midpoint Indicator	Unit Equivalent	Perspective Code	Characterisation Factor	Endpoint Indicator	Unit Equivalent
Carbon Dioxide	5400.068	kg CO_2 eq	CC	1.40E-06	**7.56E-03**	Daily
	5400.068	kg CO_2 eq	CC	7.93E-09	**4.28E-05**	species.yr
Fossil	1.685	kg oil eq	FRD	0.165	**0.279**	$
Steel	948.111	kg Fe eq	MRD	0.072	**67.790**	$
Toluene	7.786E-07	kg 1,4-DB eq	HT	7.00E-07	**5.45E-13**	Daily
Water	0.050	m^3	-	-	-	-

Table 16. Midpoint to endpoint indicator results

- Normalised Results:

  Table 17 shows the normalisation of the endpoint values for each LCI category. Normalisation explains the input and output values of our process effects on environmental impacts into relative perspective. The values of endpoint

Endpoint	LCI	Endpoint Indicator	Total	Normalisation Factor	Units	Normalisation Indicator (p/yr)
Human Health (Daily)	Carbon Dioxide	7.56E-03	7.56E-03	1.36E-02	DALY/p/yr	**0.554**
	Toluene	5.45E-13				
Ecosystem (species.yr)	Carbon Dioxide	4.28E-05	4.28E-05	9.17E-04	species.yr/p/yr	**0.047**
Resource ($)	Fossil	0.279	68.069	245.009	$/p/yr	**0.278**
	Steel	67.790				

Table 17. Normalisation indicator results

- Weighted Results:

  The next table analysed the weightage of the normalisation values that were found. Weighting is based on value choices or judgement and could determine which LCI has a significant impact. Hierarchic weightage factor was used to analyse the following data. Total weightage was found by multiplying normalisation factor with weightage factor and the grand total is the sum of all total weightage.

Endpoint	Normalisation Factor	Heirarchist Weightage factor	Total Weightage	Grand Total
Human Health	0.554	300	166.291	**268.313**
Ecosystem	0.047	400	18.675	
Resource	0.278	300	83.346	

Table 18. Weighted results

Based on the results human health impacts contributes the most in this impact assessment. This is mainly due to the high amount of power required to build our product which will contribute carbon emission. Hazardous chemicals output by melting plastic does not have a serious effect on the environment. However, burned plastic white fumes/aerosol can crucially damage our lungs and cause diseases [17]. Proper ventilation and gas masks are recommended when melting plastic.

3.10. Model Equations Analysis

In this project as explained before, the models used where based on a VRP and a TSP which equations will be explain in this section.

3.10.1. VRP Based Model

In the studied case the objection function is:

$$Min\left(\left[\sum_{i\in nodes}\sum_{j\in nodes} dist_{ij}x_{ij}\right]{}^{s_d}/_{v_{avg}}+\left[\sum_{i\in nodes} q_i\right]{}^{s_t}/_{r_o}\right)$$

Where $dist_{ij}$ is the distance between the nodes and x_{ij} takes binary values depending on whether the leg between those nodes is used or not, this way with the sum the global distance traveled can be known. Once the traveled distance is known, it is multiplied by the salary of a driver per hour and all of it divided by the average speed of the vehicle, so that we get the costs of transportation.
There is then another sum for the amount of plastic waste that needs to be picked up from each node and this multiplied by the salary of a technician per hour and divided by the processing rate of the old machine. This way the processing costs are known as well.
The sum of both is the quantity that needs to be minimize.

This objective function is subject to some constraints which are:

$$\sum_{i\in dest} x_{ij}=1,\ \ \forall j\in nodes$$

With this constraint it is assure that the route will only depart once from each destination node. The route can depart multiple times from the central node, that is why the constraint is only applied to the destination nodes and not to the whole network of them.

$$\sum_{j\in dest} x_{ij}=1,\ \ \forall i\in nodes$$

This constraint does the same as the other one but limiting the arrivals instead of the departures.

$$If\ x_{ij}=1\ \Rightarrow\ u_i+q_j=u_j, i,j\ \in nodes : i\neq cent_{node}, j \neq cent_{node}$$

$$q_i\leq u_i\leq Q,\qquad i\in dest$$

With these constraints making use of the MTZ formulation, the program assures that the vehicle will not take subtours and that it will not be overloaded.

3.10.2. TSP Based Model

In the studied case the objective function is:

$$Min\left(\left[\sum_{i\in nodes}\sum_{j\in nodes} dist_{ij}x_{ij}\right]^{s_d}\!/_{v_{avg}} + \left[\sum_{i\in nodes} q_i\right]^{s_d}\!/_{r_n}\right)$$

It tries and minimize the total costs as the one in the VRP, but this time the technician is the driver himself and the processing rate is from the new machine. As for the rest it keeps the same as VRP

The constraints similarly to the VRP ones:

$$\sum_{i\in nodes} x_{ij} = 1, \ \ \forall j \in nodes$$

$$\sum_{j\in nodes} x_{ij} = 1, \ \ \forall i \in nodes$$

The only difference with the VRP ones is that here the departures and arrivals are limited to one for all the nodes, as there is not a central one acting like a depot.

$$If\ x_{ij} = 1 \implies d_i + 1 = d_j, \qquad i,j \in nodes : j \neq 0$$

This is gets rid of subtours, as it assigns a value to every node where the route goes through, so that when the route tries to go through there again, it cannot do so, as that node already has a value assigned, so it cannot adapt another one.

3.11. Code Analysis

The first section of the code is oriented to create the instances that the program will work with.

```
n=10
nodes= [x for x in range(n)]
Q=2000
pop_m=155732/n

import random
pop={i:random.uniform(0, pop_m) for i in nodes}
q={i:pop[i]*0.0849 for i in nodes}
print(q)

loc_x=[]
loc_y=[]
for i in nodes:
    loc_x.append(random.uniform(0,30))
    loc_y.append(random.uniform(0,30))

import matplotlib.pyplot as plot

legs=[(i,j)for i in nodes for j in nodes if i != j]

import numpy as np
dist={(i,j):np.hypot(loc_x[i]-loc_x[j],loc_y[i]-loc_y[j])
           for i in nodes for j in nodes if i!=j}
```

Figure 17. Instances creation code

As seen in figure, first of all the number of nodes is set to 10 just to have a reasonable network and still get result in a reasonable time. A string of nodes is generated just to have a string with equal length to the number of nodes we have. The capacity of the vehicles is set to 2000 Kg, as it is the capacity of a mid-small size truck which is the one planned to be used.

In order to create the string with the amount of plastic waste in each node, there was a research about the plastic recycling process in Spain. That got to the conclusion that, as there are 600 plastic recycling plants in Spain [19], and its population is 46.72 Million inhabitants, there was a plastic recycling plant per every 77,866 inhabitants. As the average European plastic waste production is 31 Kg per person per year [20], it comes down to 84.9 grams per person per day.

Having these data, there is a random population string created for to represent the population in each node. This random number will go from 0 to double the inhabitants per plastic recycling plant and divided by the number of nodes, so that in average, the population per plastic recycling plant is similar to the real one.

With the population string there is only one step left to create the plastic waste production string and it is to multiply de population by the average plastic waste production per person per day.

Once these are done, the location for each node has to be created. For that two empty string are created and with a loop that runs as many times as nodes are, there are random number between 0 and 30 added to each string

every time the loop runs, so that they ended up having the coordinates for x and y axis for every node.
The upper bound of 30 Km is made because as mentioned before, there are 600 plastic recycling plants in Spain, and as its size is 505,990 square Km, this comes down on average to squares of 30 by 30 Kms per every plastic recycling plant.

There is a library imported for a later use of it plotting graphs. This library comes standard.
A string is created with all the different arcs from one node to another.
Importing numpy, that is another standard library, the use of hypothenuse function allows to create a dictionary with all the distances between one node to another.

Once this is done the instances to be used in the program are done and the next part of the process will be performed.

```
min=10000
for i in nodes:
    sum=0
    for j in nodes:
        if i!=j:
            sum+=dist[i,j]
    if sum < min:
        min=sum
        cent_node=i
```

Figure 18. Central node search code

This step is meant to find the central node of the network, the one from which the distance to all of the others is minimum, so that it can be used as the plastic recycling plant when simulating the present process of collecting the plastic waste.

In order to get this central node, there is a pair of loops created, so that one sums de distance from one node to all of the others and once this is done, the main node is changed and the distances from that one to all the others are summed as well. If the second sum is lower than the first one, the second node will be taken as the central one, otherwise the first one will still be considered the central one. As the loop runs, this comparison is made every run, so in the end the node which distance to all other nodes summed up together is the minimum will be set as the central node of the network.

```
plot.figure(figsize=(12,5))
for i in nodes:
    if i != cent_node:
        plot.scatter(loc_x[i],loc_y[i],color="green")
        plot.annotate('$q_{%d}=%d$'%(i,q[i]),(loc_x[i]+0.5,loc_y[i]-0.25))
    else:
        plot.scatter(loc_x[i],loc_y[i],color="red")
        plot.annotate("Central node", (loc_x[i]+1,loc_y[i]))
plot.show()
```

Figure 19. Plot instances for VRP

This section aims to plot the network of nodes created locating the central node and showing the amount of plastic waste at each location. For that the special commands for that library are used, using a for loop and representing all the nodes that are not the central one in one way and separating the central one so that it can be shown differently. The result is the following:

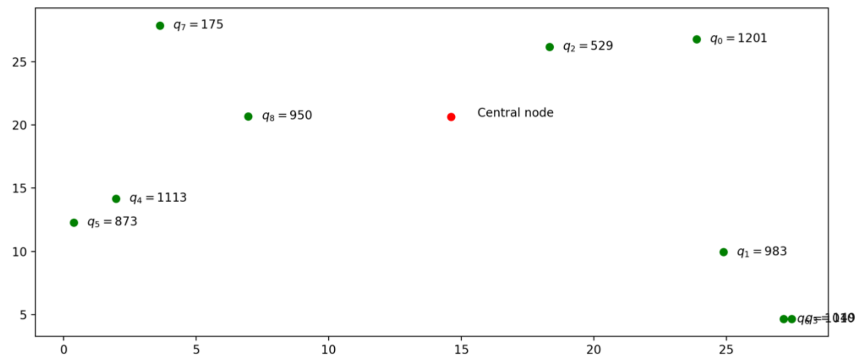


Figure 20. Instances graph for VRP

```
dest=[x for x in range(n)]
dest.remove(cent_node)

from docplex.mp.model import Model
mdl=Model('CVRP')

x=mdl.binary_var_dict(legs,name='x')
u=mdl.continuous_var_dict(nodes,ub=Q,name='u')

mdl.minimize(mdl.sum(dist[i,j]*x[i,j] for i,j in legs)*9/50+mdl.sum(q[i]for i in nodes)*15/1652)

mdl.add_constraints(mdl.sum(x[i,j] for j in nodes if i != j)==1 for i in dest)
mdl.add_constraints(mdl.sum(x[i,j] for i in nodes if i != j)==1 for j in dest)
mdl.add_indicator_constraints([mdl.indicator_constraint(x[i,j],u[i]+q[j]==u[j])for i,j in legs if i!=cent_node if j!=cent_node])
mdl.add_constraints(u[i]>=q[i] for i in dest)

mdl.parameters.timelimit=120
sol=mdl.solve(log_output=True)

mdl.get_solve_status()

sol.display()

route=[l for l in legs if x[l].solution_value>0.9]
```

Figure 21. VRP program code

In this section, firstly, there is a string created so that it contains only the destinations and not the central node. For that, we create a string as we created the string for the nodes, and then we proceed to remove which was found to be the central node. With this string created, the optimization program can be written after importing the optimization package of Cplex for Python.

Two variables are created as explained in the model, a binary variable, that will take the unity value if the route goes through that leg, or a value of zero if that is not the case. The second variable is the sum of the plastic waste collected since the departure from the plastic recycling plant, so that the vehicle does not overload.

With this done, the objective function and its constraints are written as showed earlier with the specific Cplex commands.

Once the constraints are written, a time limit of 120 seconds is set, so that the process does not take excessively long.

As the program just gives back the binary variable with zeros or ones depending on the route, a string is created only with the ones, so that the actual route is reflected there.

As the program is asked to display the solution, it is displayed as follows:

```
solution for: CVRP
objective: 94.297
x_0_2 = 1
x_1_9 = 1
x_2_9 = 1
x_3_9 = 1
x_4_5 = 1
x_5_9 = 1
x_6_3 = 1
x_7_8 = 1
x_8_9 = 1
x_9_0 = 1
x_9_1 = 1
x_9_4 = 1
x_9_6 = 1
x_9_7 = 1
u_0 = 1201.144
u_1 = 983.844
u_2 = 1730.913
u_3 = 1159.884
u_4 = 1113.359
u_5 = 1986.529
u_6 = 1010.675
u_7 = 175.452
u_8 = 1125.701
```

Figure 22. VRP solution

The two variables created are displayed, for the binary one only the values that are not zero, and for the loading variable, the sum of plastic waste up to the point where the route is going through.

```
plot.figure(figsize=(12,5))
for i in nodes:
    if i != cent_node:
        plot.scatter(loc_x[i],loc_y[i],color="green")
        plot.annotate('$q_{%d}=%d$'%(i,q[i]),(loc_x[i]+0.5,loc_y[i]-0.25))
    else:
        plot.scatter(loc_x[i],loc_y[i],color="red")
        plot.annotate("Central node", (loc_x[i]+1,loc_y[i]))
for i,j in route:
    plot.plot((loc_x[i],loc_x[j]),(loc_y[i],loc_y[j]),color="red",alpha=0.2)
plot.show()
```

Figure 23. Plotting code of VRP route

The result route is plotted in the graph.

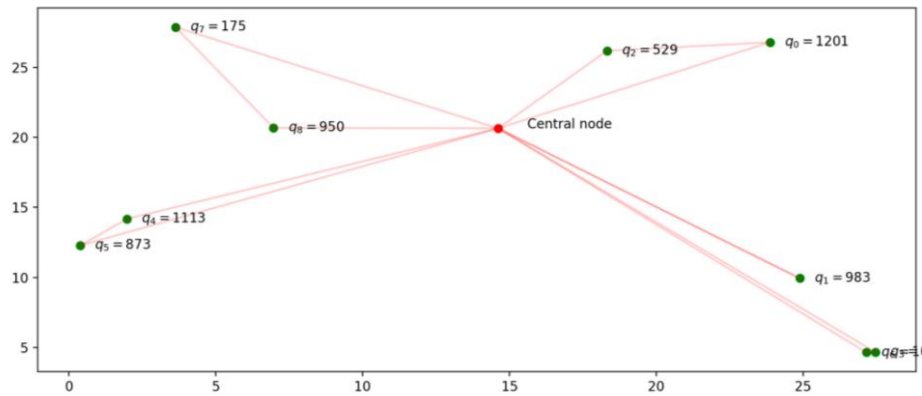


Figure 24. VRP route graph

```
plot.figure(figsize=(12,5))
plot.scatter(loc_x,loc_y,color="green")
for i in nodes:
    plot.annotate('$q_{%d}=%d$'%(i,q[i]),(loc_x[i]+0.5,loc_y[i]-0.25))
plot.show()
```

Figure 25. Plotting code for TSP instances

Now the network is plotted as it is for the TSP part of the project, as there is no central node and the vehicle has no need to go back.

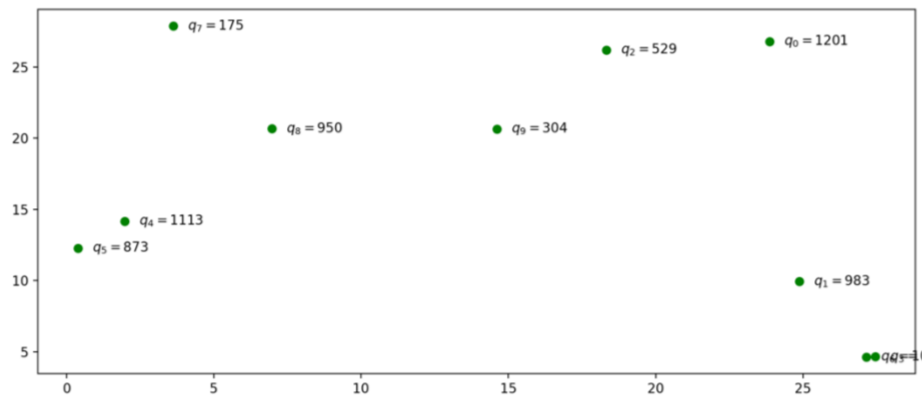


Figure 26. Instances graph for TSP

Now the TSP part is written.

```
mdl1=Model('TSP')

x1=mdl1.binary_var_dict(legs,name='x1')
d=mdl1.continuous_var_dict(nodes,name='d')

mdl1.minimize(mdl1.sum(dist[i]*x1[i] for i in legs)*9/50+mdl.sum(q[i]for i in nodes)*9/1101)

mdl1.add_constraints(mdl1.sum(x1[(i,j)] for i,j in legs if i==p)==1 for p in nodes)
mdl1.add_constraints(mdl1.sum(x1[(i,j)] for i,j in legs if j==p)==1 for p in nodes)

mdl1.add_indicator_constraints(mdl1.indicator_constraint(x1[(i,j)],d[i]+1==d[j])for i,j in legs if j!=0)

mdl1.parameters.timelimit=120
mdl1.parameters.mip.strategy.branch=1
mdl1.parameters.mip.tolerances.mipgap=0.15

sol1=mdl1.solve(log_output=True)

mdl1.get_solve_status()

sol1.display()

route1=[l for l in legs if x1[l].solution_value>0.9]
```

Figure 27. TSP program code

As previously, there are two variables created, a binary variable that acts as it does in the VRP part and a counting variable, that assigns a number to each node whenever the route goes through there so that it cannot go back and hence no subtours are created.
As done in the previous section, the program just gives back the binary variable with zeros or ones depending on the route, a string is created only with the ones, so that the actual route is reflected there.
And again, the solution display is as follows:

```
solution for: TSP
objective: 77.110
x1_0_2 = 1
x1_1_3 = 1
x1_2_9 = 1
x1_3_6 = 1
x1_4_5 = 1
x1_5_1 = 1
x1_6_0 = 1
x1_7_4 = 1
x1_8_7 = 1
x1_9_8 = 1
d_1 = 7.000
d_2 = 1.000
d_3 = 8.000
d_4 = 5.000
d_5 = 6.000
d_6 = 9.000
d_7 = 4.000
d_8 = 3.000
d_9 = 2.000
```

Figure 28. TSP solution

The only two variable created for the program are displayed only if they take any values, which in the case of the binary value is only when the route goes through that arc or the network, while in the second variable all of them have values which correspond with the place the node takes in the route, although is not relevant in that sense, the variable's main concern is to avoid subtours from happening.

```python
plot.figure(figsize=(12,5))
plot.scatter(loc_x,loc_y,color="green")
for i in nodes:
    plot.annotate('$q_{%d}=%d$'%(i,q[i]),(loc_x[i]+0.5,loc_y[i]-0.25))

for i,j in route1:
    plot.plot((loc_x[i],loc_x[j]),(loc_y[i],loc_y[j]),color="blue",alpha=0.2)
plot.show()
```

Figure 29. Plotting code for TSP route

Now the found route is to be displayed.

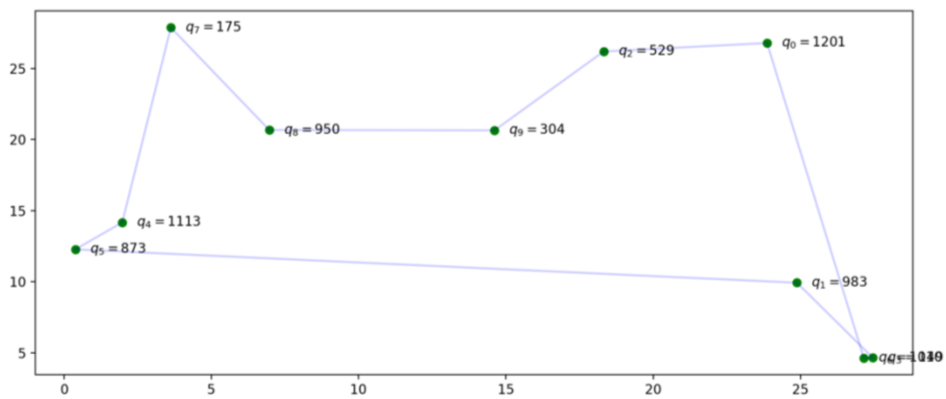


Figure 30. TSP route graph

```
plot.figure(figsize=(12,5))
plot.scatter(loc_x,loc_y,color="green")
for i in nodes:
    if i != cent_node:
        plot.scatter(loc_x[i],loc_y[i],color="green")
        plot.annotate('$q_{%d}=%d$'%(i,q[i]),(loc_x[i]+0.5,loc_y[i]-0.25))
    else:
        plot.scatter(loc_x[i],loc_y[i],color="red")
        plot.annotate("Central node", (loc_x[i]+1,loc_y[i]))

for i,j in route:
    plot.plot((loc_x[i],loc_x[j]),(loc_y[i],loc_y[j]),color="red",alpha=0.2)

for i,j in route1:
    plot.plot((loc_x[i],loc_x[j]),(loc_y[i],loc_y[j]),color="blue",alpha=0.2)
plot.show()
```

Figure 31. Plotting code to show both routes together

The last part of the code is to plot both given answers in the same graph.

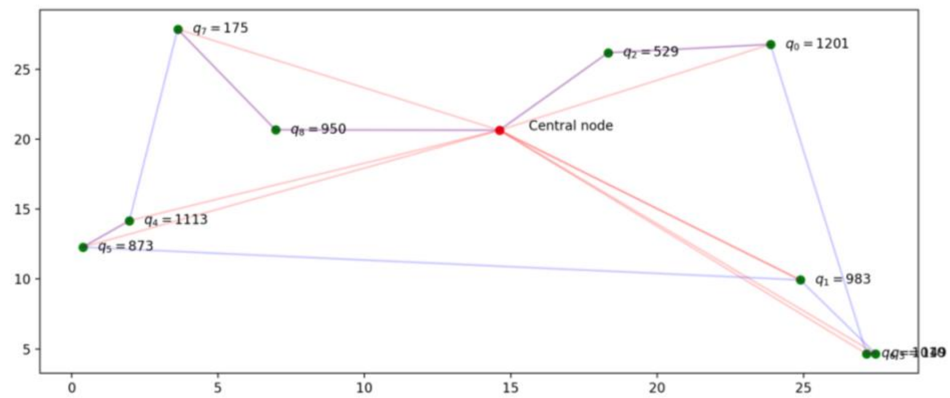


Figure 32. TSP and VRP routes graph

4. Results Analysis

4.1. LCA: Interpretation

“The objectives of the life cycle interpretation are to analyses results, reach conclusions, explain limitations and provide recommendations based on the findings of the preceding phases of the LCA or LCI study and to report the results for the cycle interpretation in a transparent manner”.
The aim of this portion of this study - as per goal and scope- is evaluate the environmental side effects by quantifying the magnitude of different factors and processes contributing to emissions, pollutants, etc, from different data collected.
Based on the findings, a transparent conclusion on the environment side effects will be stated, as well as recommendation.
This section of LCA study will be divided in the following sub-analysis:

Contribution analysis:

- Analysing data collected in the previous sections, to determine the main contributors by means of percentages in the different areas of the study from processes, materials, transportation, etc

Uncertainty analysis:

- To clarify any vague or ambiguous data that might affect the validity of the evaluation.

Sensitivity analysis:

- To examine the results from previous steps and validate them.
- To draw conclusions, re-assess and modify any of the pervious parts of the LCA if required.

4.1.1. Contribution Analysis

The contribution factors have been considered for this product as a whole instead of analysing them per stage, because the build of this product relies heavily on reusable materials. The data in the contribution table below is based on approximation of the LCI.

LCI i.p/o.p	manufcaturing	Use phase	others	total
CO2	5400	2160	0.68	7560.68
fossil	-	-	-	1.68
Toluene (burned plastic)	-	0.95	-	0.95
Water(processing)	50.4	-	-	50.4
Grand total	5452.08	2160.95	0.68	7613.71

Table 19. Contribution data approximated from LCI

LCI I.p/o.p	Manufacturing process	Use phase	others	total
CO_2	71.42214721	28.568859	0.00899	100
Fossil	100	0	0	100
Toluence(burned plastic)	0	100	0	100
Water(processing)	100	0		100

Table 20. Contribution data approximated from LCI in percetages

As it is noticed from both tables the major contributor is the CO2 emissions, in particular during the manufacturing process.

4.1.2. Uncertainty Factors

To examine the validity of the data the below equation is used.

So, for CO2 emissions
U1=1.2, U3=1, U4=1, U4=1, U2=1.1 & Ub=1.05.
Substituting the values in the equation above **σ2 = 1.24**

$$\sigma_g^{\ 2} = \exp^{\sqrt{[\ln(U_1)]^2+[\ln(U_2)]^2+[\ln(U_3)]^2+[\ln(U_4)]^2+[\ln(U_5)]^2+[\ln(U_b)]^2}}$$

LCI I.p/o.p	U1	U3	U4	U2	U5	Ub	**σ2**
CO2	1.2	1	1	1	1.1	1.05	1.24
fossil	1.05	1	1	1	1.05	1.05	1.09
Toluene	1.05	1.03	1.02	1	1.05	1.5	1.51
water	1.05	1.03	1.001	1	1.05	1	1.08

Table 21. Uncertainty factors

Over all the data are quite reliable for as per collected from LCI, since they have been collected from official resources and recent studies published by official bodies.

4.1.3. Sensitivity

As per the tables produced so far in the contribution analysis and as per LCI study, it is clearly the major impact is caused by the CO2 air emission into the air as a side effect of manufacturing the product.
Since this product is a design concept there is no need to conduct a comparison as the shredder and extrusion machine combination is already designed to recycle plastic with minimum waste –in concept.

4.1.4. LCA over all Conclusions

Even though the data collected are from reliable resources, the product LCA study has relied heavily on arbitrary references since there are no definite absolute design references when it comes to choosing the components and the materials.
Also, the data from LCA inventory to LCI can vary from one region to another, as prices and regulations of environment restrictions differ. However still based on the findings in the last stage, the goal and the scope are achieved, the product itself does not pose any environmental threat and the only concern is the source of energy mainly during the manufacturing process which can be minimized by means of finding alternative energy resources to power the assembly facility.

4.2. Optimization Results Analysis

The code was set for the development and for the ease of having quick results to have 10 nodes, and that is how it mainly stayed, anyway, some runs were made with 15 and 20 nodes as well.

The first network created is made with 10 nodes, which will be used to optimize the route.

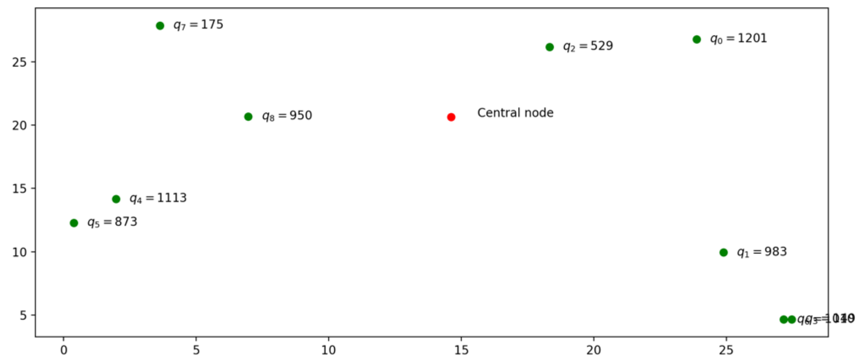


Figure 33. VRP instances for 10 nodes

The solution display and plot for the present part of the process, collecting the plastic waste in the different nodes and take all back to the plastic recycling plant, are the following.

```
solution for: CVRP
objective: 94.297
x_0_2 = 1
x_1_9 = 1
x_2_9 = 1
x_3_9 = 1
x_4_5 = 1
x_5_9 = 1
x_6_3 = 1
x_7_8 = 1
x_8_9 = 1
x_9_0 = 1
x_9_1 = 1
x_9_4 = 1
x_9_6 = 1
x_9_7 = 1
u_0 = 1201.144
u_1 = 983.844
u_2 = 1730.913
u_3 = 1159.884
u_4 = 1113.359
u_5 = 1986.529
u_6 = 1010.675
u_7 = 175.452
u_8 = 1125.701
```

Figure 34. VRP solution for 10 nodes

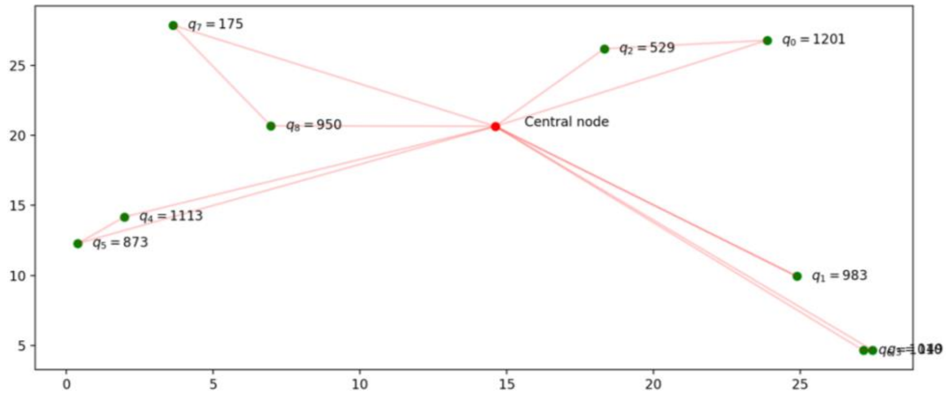


Figure 35. VRP route graph for 10 nodes

As it can be seen, the optimized cost of collecting and processing the plastic with the present process is of 94.297 euros per day. And the route taken by the vehicle is as showed, departing from the central node for several times, until the maximum capacity is about to be reached and arriving back to the central node to unload all the waste there.

The instance for the proposed collecting and processing process is the same, but without the central node as it is a continuous route and there is no need to drop the waste anywhere as it is process in the go.

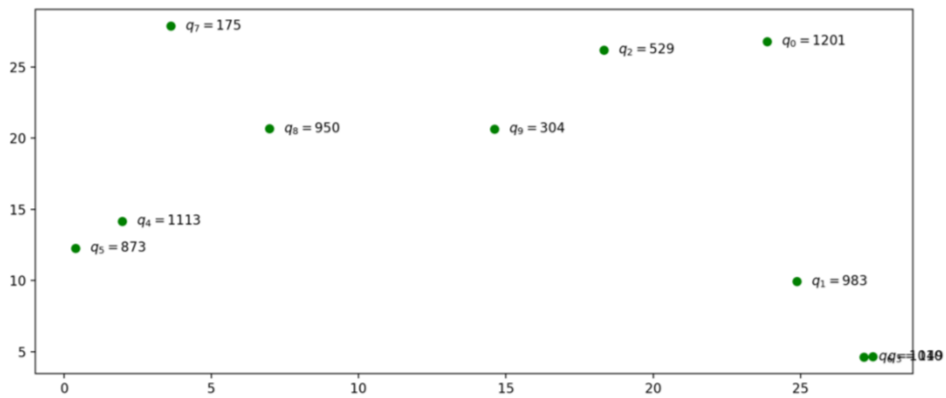


Figure 36. TSP instances for 10 nodes

The results given for this kind of process were the following.

```
solution for: TSP
objective: 77.110
x1_0_2 = 1
x1_1_3 = 1
x1_2_9 = 1
x1_3_6 = 1
x1_4_5 = 1
x1_5_1 = 1
x1_6_0 = 1
x1_7_4 = 1
x1_8_7 = 1
x1_9_8 = 1
d_1 = 7.000
d_2 = 1.000
d_3 = 8.000
d_4 = 5.000
d_5 = 6.000
d_6 = 9.000
d_7 = 4.000
d_8 = 3.000
d_9 = 2.000
```

Figure 37. TSP solution for 10 nodes

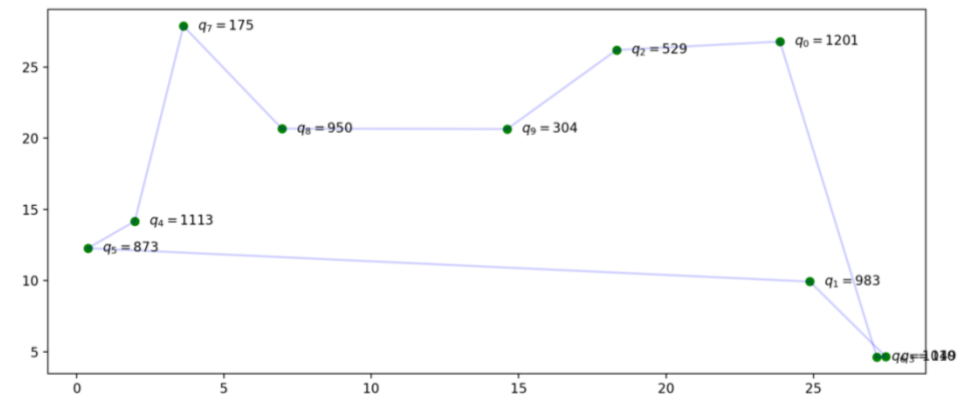


Figure 38. TSP route graph for 10 nodes

As showed in the figures, the cost of transportation and processing sums up to 77.11 euros per day and the route taken by the vehicle is the one displayed above.

As seen by the numbers, the proposed process makes some appreciable improvements for the cost of it and therefore, the concept being tried to proof is satisfactory up to now.

Anyway, a further research needs to be done to verify if the concept is actually good enough to be implemented and as a part of that, there have been made tests with 15 and 20 nodes as well.

For the 15 nodes, the network for the VRP based part is:

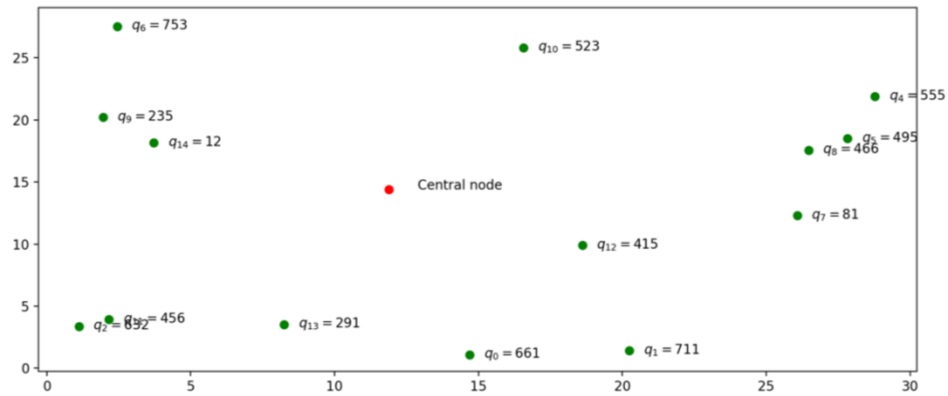


Figure 39. VRP instances for 15 nodes

With this network, the program was run, and the results obtain, in numbers and graph were as follows:

```
Total (root+branch&cut) =   13.48 sec.
solution for: CVRP
objective: 88.149
x_0_1 = 1
x_1_12 = 1
x_2_13 = 1
x_3_0 = 1
x_3_4 = 1
x_3_11 = 1
x_3_14 = 1
x_4_5 = 1
x_5_8 = 1
x_6_10 = 1
x_7_3 = 1
x_8_7 = 1
x_9_6 = 1
x_10_3 = 1
x_11_2 = 1
x_12_3 = 1
x_13_3 = 1
x_14_9 = 1
u_0 = 872.930
u_1 = 1584.801
u_2 = 1088.991
u_4 = 555.919
u_5 = 1050.963
u_6 = 1000.646
u_7 = 1599.115
u_8 = 1517.601
u_9 = 247.294
u_10 = 1524.579
u_11 = 456.831
u_12 = 2000.000
u_13 = 1380.134
u_14 = 12.124
```

Figure 40. VRP solution for 15 nodes

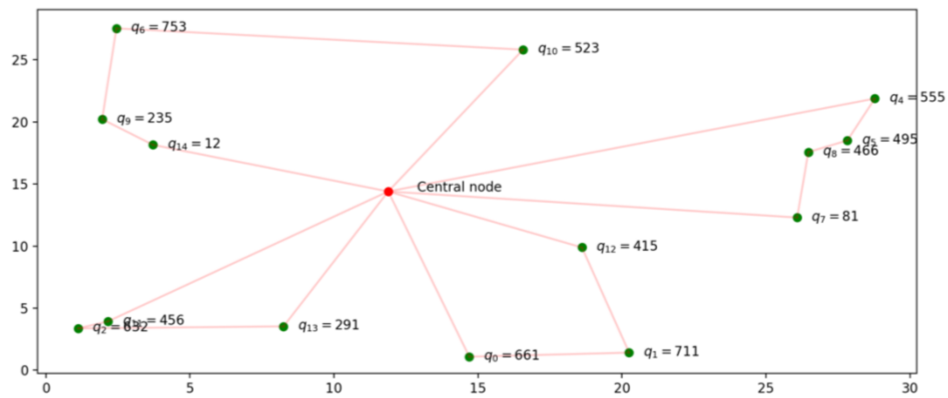


Figure 41. VRP route for 15 nodes

As showed in the figure, with this number of nodes, the time that takes to run the program is already noticeable, being it 13.48 seconds.
In this case the cost was 88.149 euros per day and the route can be seen in the graph.

For the TSP part, the network to be used is the same, with the central node acting like a normal node through where to route passes.

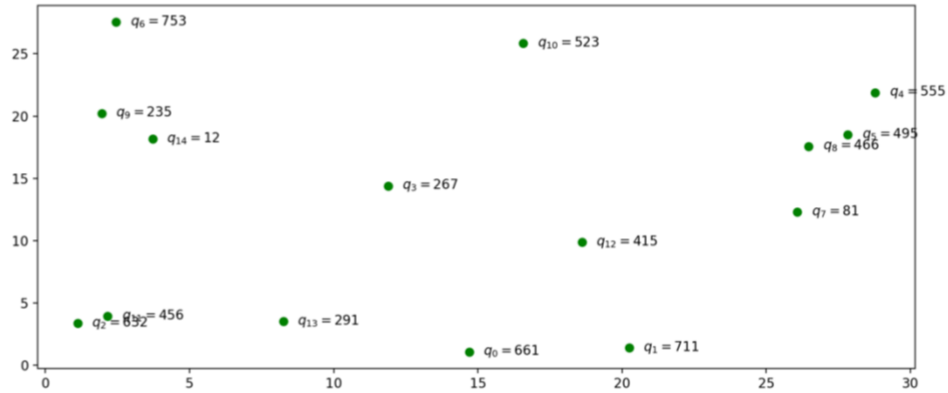


Figure 42. TSP instances for 15 nodes

With this network the results given by the program are:

```
Total (root+branch&cut) =     0.03 sec.
solution for: TSP
objective: 75.266
x1_0_1 = 1
x1_1_12 = 1
x1_2_0 = 1
x1_3_6 = 1
x1_4_10 = 1
x1_5_4 = 1
x1_6_9 = 1
x1_7_8 = 1
x1_8_5 = 1
x1_9_14 = 1
x1_10_3 = 1
x1_11_2 = 1
x1_12_7 = 1
x1_13_11 = 1
x1_14_13 = 1
d_1 = 1.000
d_2 = 14.000
d_3 = 8.000
d_4 = 6.000
d_5 = 5.000
d_6 = 9.000
d_7 = 3.000
d_8 = 4.000
d_9 = 10.000
d_10 = 7.000
d_11 = 13.000
d_12 = 2.000
d_13 = 12.000
d_14 = 11.000
```

Figure 43. TSP solution for 15 nodes

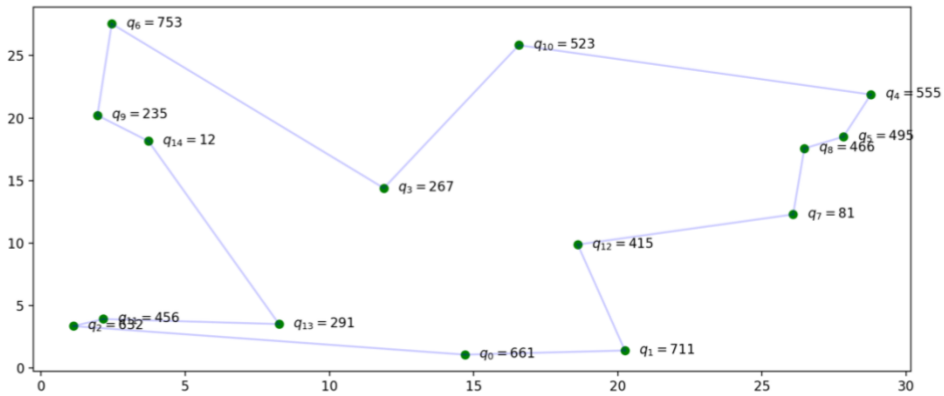


Figure 44. TSP route graph for 15 nodes

For the TSP part, as it is much less complex than the VRP, the processing time is not noticeable, and the cost for the process is 75.266 euros per day and the route is as showed.

Now again, the proposed system shows an improvement over the present one, the next step is to analyze it with 20 nodes.

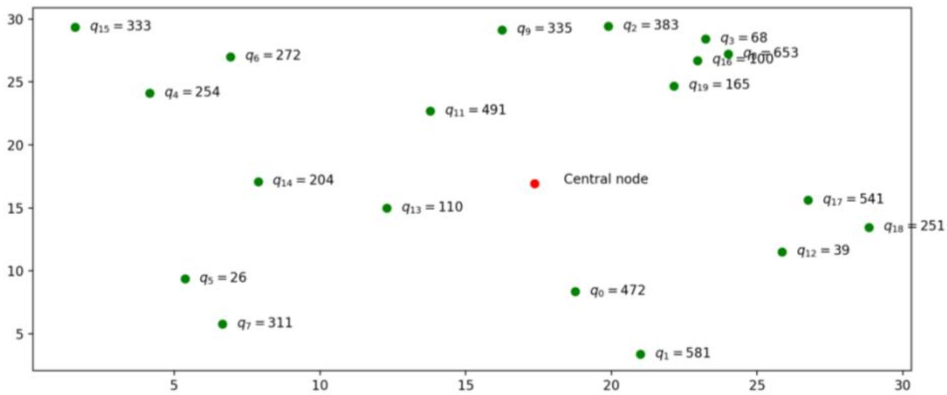


Figure 45. VRP instances for 20 nodes

With this network the results given are:

```
Total (root+branch&cut) =  600.07 sec.
solution for: CVRP
objective: 79.752
x_0_13 = 1
x_1_0 = 1
x_2_3 = 1
x_3_8 = 1
x_4_15 = 1
x_5_14 = 1
x_6_11 = 1
x_7_5 = 1
x_8_16 = 1
x_9_2 = 1
x_10_7 = 1
x_10_9 = 1
x_10_17 = 1
x_11_10 = 1
x_12_1 = 1
x_13_10 = 1
x_14_4 = 1
x_15_6 = 1
x_16_19 = 1
x_17_18 = 1
x_18_12 = 1
x_19_10 = 1
u_0 = 1885.417
u_1 = 1413.200
u_2 = 719.227
u_3 = 787.488
u_4 = 903.095
u_5 = 444.792
u_6 = 1508.666
u_7 = 417.829
u_8 = 1441.379
u_9 = 335.363
u_11 = 2000.000
u_12 = 832.142
u_13 = 1996.352
u_14 = 648.834
u_15 = 1236.488
u_16 = 1541.968
u_17 = 541.099
u_18 = 792.492
u_19 = 1707.099
```

Figure 46. VRP solution for 20 nodes

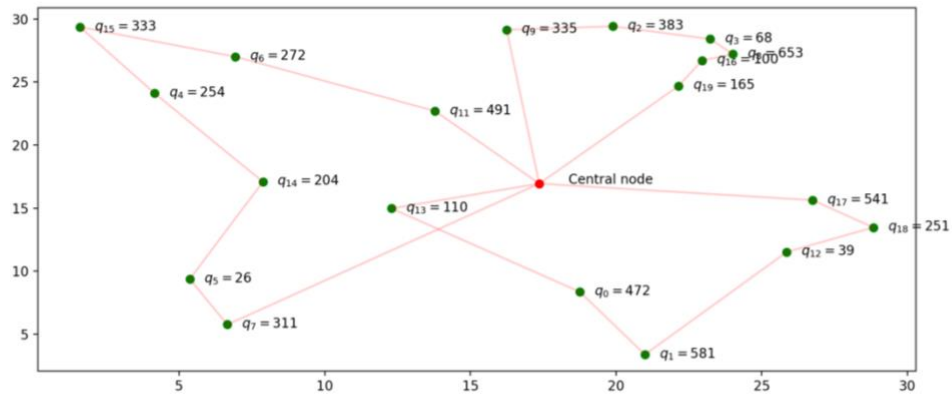


Figure 47. VRP route graph for 20 nodes

As before, the time is noticeable, but this time is reaching long times, therefore this can only be run a few times, as it is really inconvenient to run a 10 minutes program, which was limited by the code, it has been proved that it can take up to 40 minutes to perform the code if no time limit is applied.

The cost this time is of 79.752 euros per day.

For the TSP the network is:

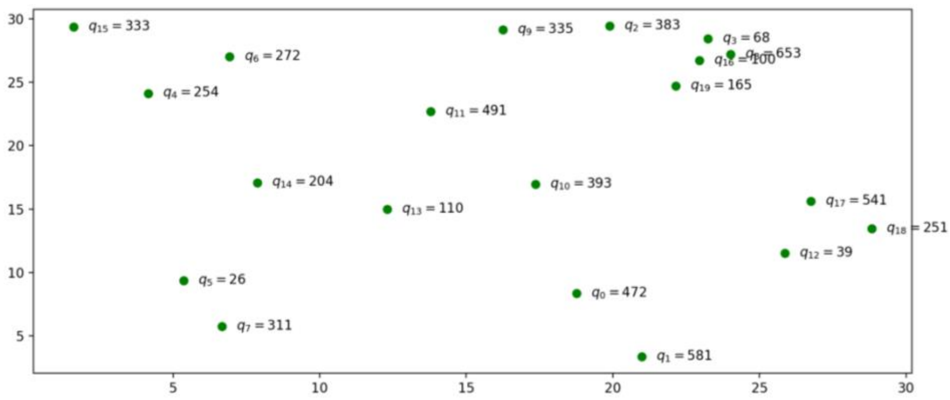


Figure 48. TSP instances for 20 nodes

The results given for it are:

```
Total (root+branch&cut) =    0.07 sec.
solution for: TSP
objective: 71.248
x1_0_12 = 1
x1_1_0 = 1
x1_2_9 = 1
x1_3_8 = 1
x1_4_15 = 1
x1_5_7 = 1
x1_6_11 = 1
x1_7_1 = 1
x1_8_2 = 1
x1_9_4 = 1
x1_10_13 = 1
x1_11_10 = 1
x1_12_18 = 1
x1_13_14 = 1
x1_14_5 = 1
x1_15_6 = 1
x1_16_19 = 1
x1_17_16 = 1
x1_18_17 = 1
x1_19_3 = 1
d_1 = 19.000
d_2 = 8.000
d_3 = 6.000
d_4 = 10.000
d_5 = 17.000
d_6 = 12.000
d_7 = 18.000
d_8 = 7.000
d_9 = 9.000
d_10 = 14.000
d_11 = 13.000
d_12 = 1.000
d_13 = 15.000
d_14 = 16.000
d_15 = 11.000
d_16 = 4.000
d_17 = 3.000
d_18 = 2.000
d_19 = 5.000
```

Figure 49. TSP solution for 20 nodes

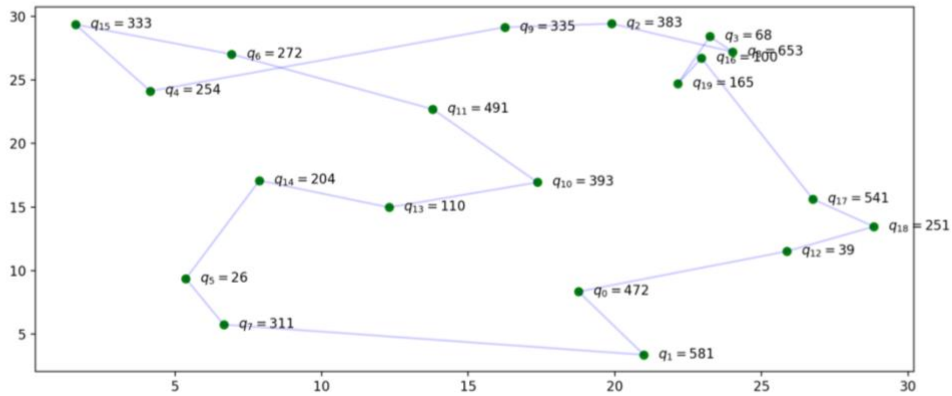


Figure 50. TSP route graph for 20 nodes

Again, this time the cost is 71.248 euros per day, so it is improving the present process, although it seems like the improvement decreases when the number of nodes increases.

Multiple cases with different number of nodes are added in the appendix, to prove that the improvement is constant.

As per now, the concept is proved to save transportation and processing costs with the data and the research available. For a final decision on whether to implement a full system or not, a much more detailed report is needed.

5. Conclusions

5.1. Sustainable Conclusions

The main objective of the project is achieved which is to redesign a plastic recycling machine with improve practicality and sustainability. Hence the following:

- The product is a solution in many to reduce the negative impact of plastic waste.
- The product is energy efficient, compact, and portable and with some imagination can be put together at a fraction of the cost of some bigger machines.
- This product can help a lot of communities utilized unused resources and re-purpose them, potentially creating beneficial economic impacts to their lives.
- Discount payback period is 2 years.
- The environmental impact is quite low, due to the product material selection and the waste is minimum.
- As per LCA the product meets its goal and scope. Mainly due to its simplicity.
- As per LCA, the highest contributor to the environment is the CO_2 emissions from power generation (electricity from power station)

5.2. Optimization Conclusions

For the initial objective of the project that was, as the name of the subject suggests, an approach to the industry with mathematics and a use of them more similar to how they are use in reality, the project was successful. As it applied the knowledge learned through this semester to the project in a coding way.

This means, not only the mathematics learned during the semester were used with an industry related goal, but they were applied through programming, which is another step on applicating the theoretical knowledge in a more realistic way.

Results wise, the project has been satisfactory as it has come to prove what it was supposed to prove. Although it may not be the most in-depth report, it is a solid first approach to the idea, and thanks to it, the possibility of further research is open.

This was useful as a first test, to simply decide on whether or not the idea deserved the time and funds needed to be put into the process of developing it.

One of the most visible aspects, is the fact that while the number of nodes increases the savings decrease, so that could be a good start in future projects with more processing capacity, to know if at a certain point, when the network gets bigger and bigger, the savings stop to occur, so that at that point and onwards, it is better to keep the process as it was before.

Although for the sake of industry appliance the research done in terms of size of the network is enough, as on average a plastic recycling plant only receives waste from 13 municipalities.

6. References

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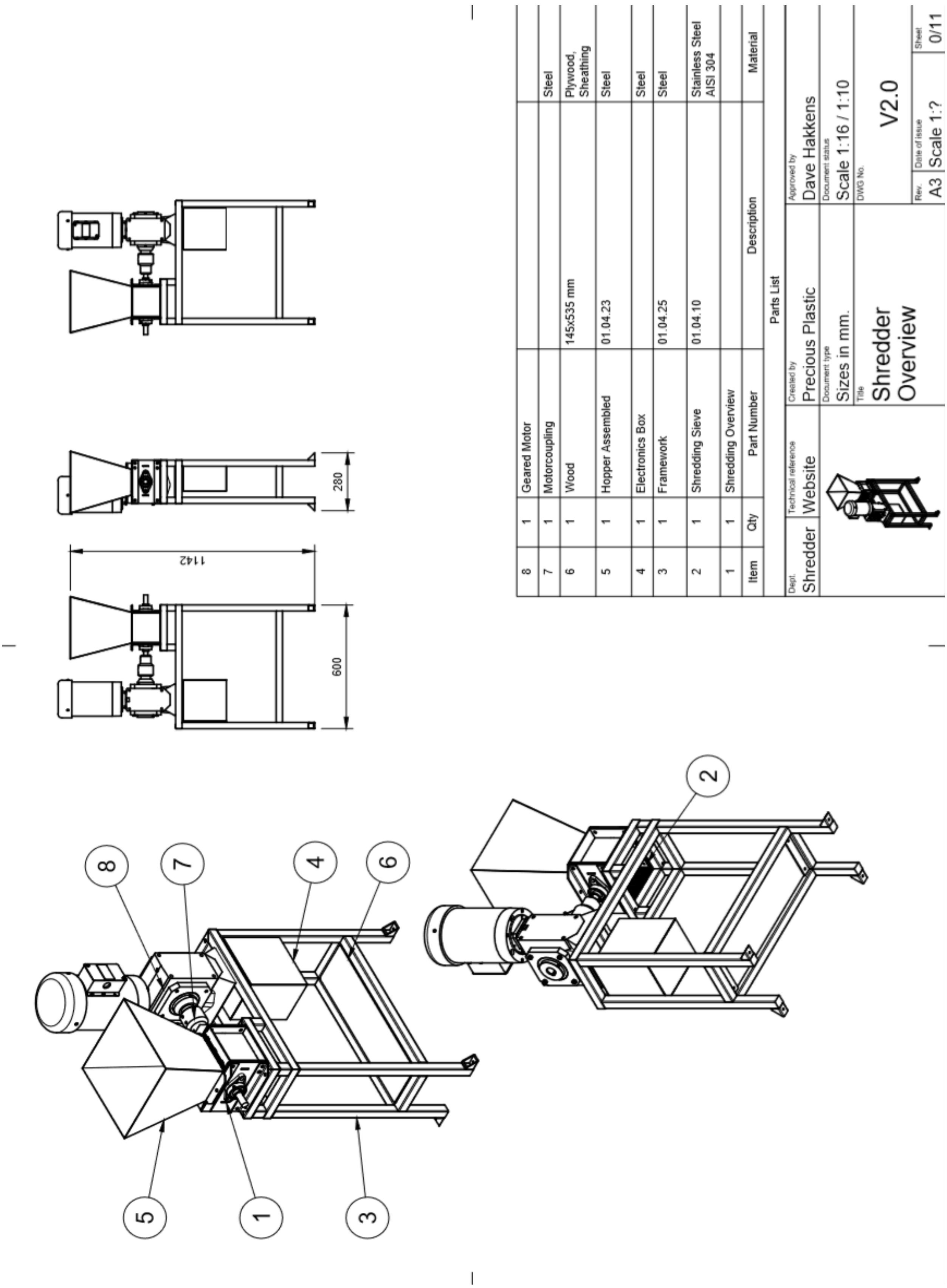
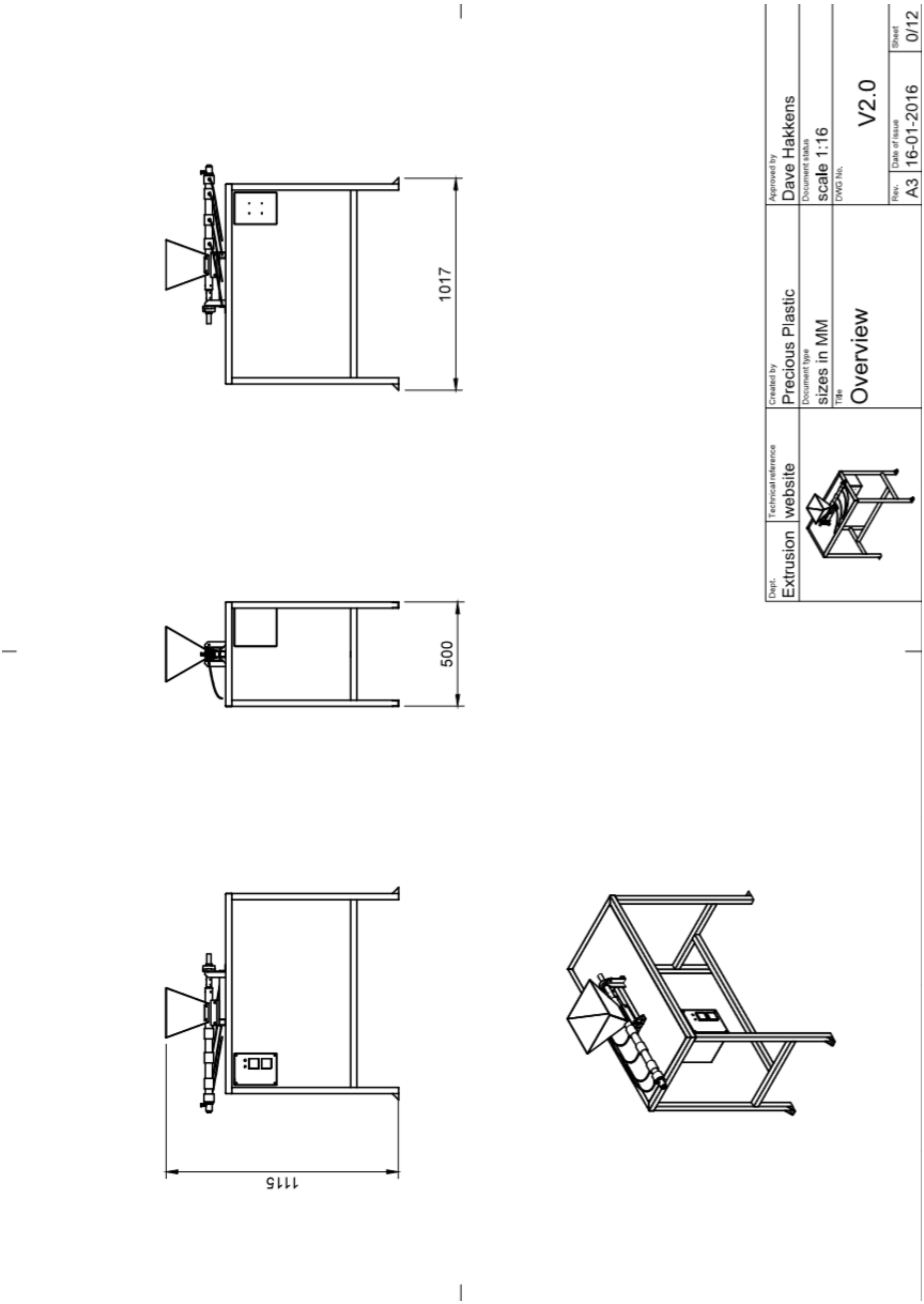
7. Appendix

Appendix A. Blueprint of a plastic shredder (Presciousplastic 2018)

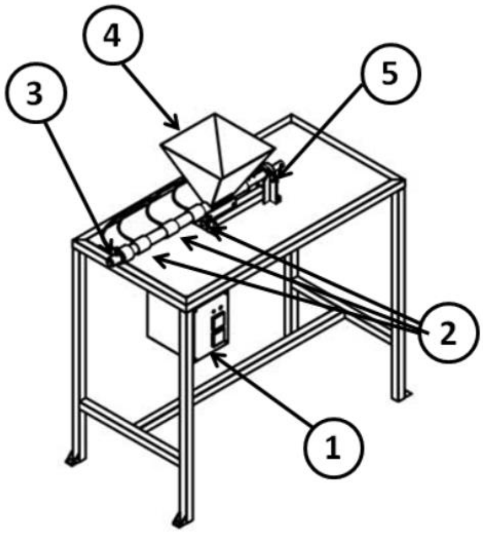


Appendix B. Blueprint of plastic extrusion (Preciousplastic 2018)



Appendix C. Plastic extrusion with labels

The extrusion machine



1. Electric control box
2. Heating elements
3. Nozzle
4. Hopper
5. Screw compressing shaft.

Appendix D. Cost for parts and materials

Standardized Item Name	**Unit**	**AUD/Unit**
fuel, petrol	ltr	$1,38
utilites, water	ltr	$0,00
utilites, electrical	kw/h	$0,28
ppe, welding mask	pcs	$27,99
ppe, welding gloves	pair	$43,75
ppe, standard goggles	pair	$7,15
ppe, ear miffs	pair	$12,99
ppe, rubber gloves	pair	$2,74
ppe, respirator (no filters)	pcs	$26,60
ppe, p95 filters (pair)	pcs	$46,55
ppe, fire extinguisher	pcs	$37,00
office, safe	pcs	$93,39
office, cash box	pcs	$32,25
office, whiteboard	pcs	$69,00
office, A4 paper (500pcs)	pack	$3,75
office, pens	pcs	$1,29
office, whiteboard markers	pcs	$3,96
office, scissors	pair	$3,96

office, stapler	pcs	$13,87
office, staples (pack 1000)	pack	$3,96
office, reciept book	pcs	$4,75
services, laser cutting	pcs	$152,95
steel, hexagonal bar (27 x 318mm)	pcs	$53,20
steel, angle bar (30 x 30 x 3mm)	m	$16,61
steel, mesh 10mm hole 1.5mm thick	m2	$165,92
steel, 1mm sheet	m2	$116,74
steel, 2mm sheet	m2	$199,17
steel, flat bar 30 x 3mm	m	$2,79
steel, box tube 30 x 30 x 3mm	m	$4,68
steel, tube 32 x 26ID x 3mm	m	$33,25
steel, round bar 25mm	m	$26,60
steel, flat bar 60 x 3m	m	$3,49
steel, auger bit 25.8mm	pcs	$332,50
steel, drill bit 26 x 600mm	pcs	$39,90
motor, 2kh 70rpm	pcs	$465,50
bearing, 22mm UCFL204	pcs	$7,71
electrical, power switch	pcs	$2,66
electrical, led indicator	pcs	$0,00
electrical, power cord	m	$0,00
electrical, SSR 25V	pcs	$3,17
electrical, PDI temp control 0-400c	pcs	$15,96
electrical, thermocouple k-type	pcs	$6,64
electrical, band heater 35x60mm	pcs	$3,94
electrical, band heater 40x45mm	pcs	$7,74
scales, digital hanging	pcs	$13,77
corded, angle grinder 4"	pcs	$86,14
corded, drill	pcs	$120,60
corded, stick welder 150	pcs	$551,30
saw, hand saw	pcs	$13,87
saw, hack saw	pcs	$7,61
spanner, adjustable spanner	pcs	$8,61
drill bit, metal assorted (25pcs)	set	$33,25
drill bit, metal steel tap assorted (6pcs)	set	$13,30
hammer, claw hammer	pcs	$13,78
tape measure, 8m (metric)	pcs	$6,89
tape measure, set sqaure 30cm	pcs	$11,03
broom, push broom	pcs	$5,15
brush, steel wire	pcs	$1,72
cable, extension cord 15m	pcs	$28,43
clamps, c 4"	pcs	$8,96
generator, 6.5kw	pcs	$1.205,96
consumerables, hack saw blades	pcs	$0,34
consumerables, grinding disk 4"	pcs	$3,96
consumerables, cutting disk 4"	pcs	$1,36
consumerables, welding rods	lb	$2,08

container, plastic barrel 55gal	pcs	$27,56
container, bag 1m3	pcs	$11,31
bucket, 20l	pcs	$20,33
machines, shredder	pcs	$922,55
machines, extrusion	pcs	$748,95
pliers, needle	pcs	$7,67
pliers, adjustable	pcs	$10,68
sand paper	sheet	$1,33
screwdriver, philips head	pcs	$5,51
shovel, spade	pcs	$23,77
Container, 20 ft	pcs	$2.067,36
Container, 40 ft	pcs	$2.756,48
first aid kit, small	pcs	$26,60
printing, A4 colour	pcs	$0,52
printing, A4 b&w	pcs	$0,34
printing, poster 24x36"	pcs	$40,83
printing, lables	pcs	$2,24
printing, lamitated A4 colour	pcs	$2,07
printing, lamitated A3 colour	pcs	$7,41
Vechicle Rental, Pickup	day	$51,68
services, fabrication	item	$172,28
services, mould making	pcs	$332,50

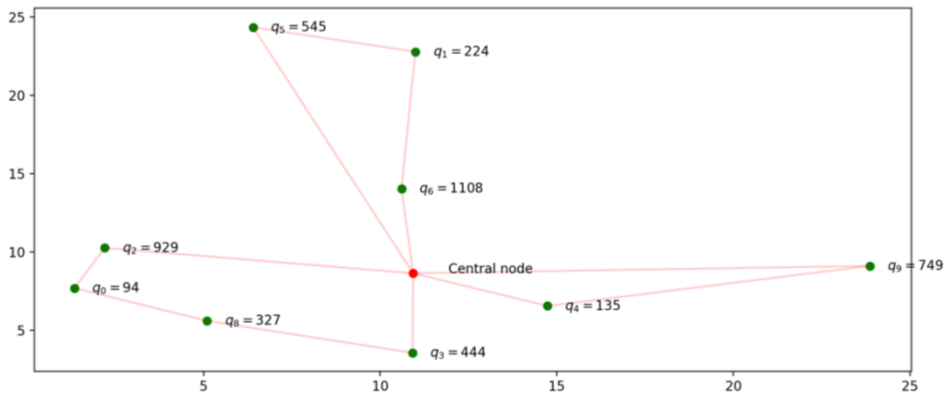
Item	Qty	RRP	Total Sales	% of Material Cost	Cost of Materials	Gross Profit	Kg Per Item	Total KG	Notes
Jewelry	200	$7,00	$1.400,00	0,1%	$1,25	$1.398,75	0,0625	12,5	Based on a 5x5x1cm volume of plastic.
Tiles/Coasters	70	$1,00	$70,00	1,6%	$1,12	$68,88	0,16	11,2	Based on a 14cm hex tile 0.5cm thick
Beam	60	$12,00	$720,00	10,0%	$72,00	$648,00	12	720	Based on a 2x4" beam 12ft long.
Door Handle	150	$1,50	$225,00	0,9%	$1,95	$223,05	0,13	19,5	Based on a standard handle
Misc	150	$1,88	$282,00	0,6%	$1,80	$280,20	0,12	18	Based on a 125cm3 of plastic
			Total Sales	**Average %**	**Total Material Cost**	**Total Gross Profit**	**Total Operations $/Month**	**KG/Month**	**Cost per Kilo**
			$2.697,00	2,90%	$78,12	$2.618,88	$1.012,37	781,2	$0,10
							Net Profit		
							$1.606,51	158,69%	

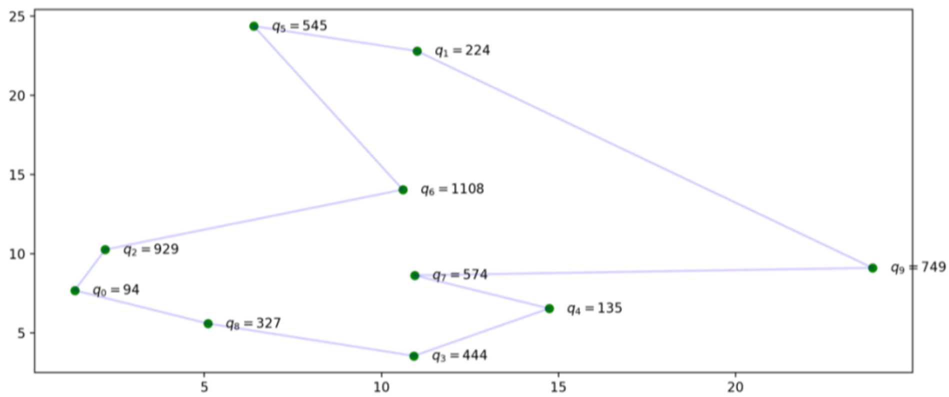
Appendix E. Examples with different number of nodes to show continuity in results.

For 10 nodes:

```
Total (root+branch&cut) =    0.07 sec.
solution for: CVRP
objective: 62.716
x_0_2 = 1
x_1_5 = 1
x_2_7 = 1
x_3_8 = 1
x_4_7 = 1
x_5_7 = 1
x_6_1 = 1
x_7_3 = 1
x_7_6 = 1
x_7_9 = 1
x_8_0 = 1
x_9_4 = 1
u_0 = 867.264
u_1 = 1333.711
u_2 = 1797.131
u_3 = 444.664
u_4 = 885.699
u_5 = 1879.115
u_6 = 1108.760
u_8 = 772.578
u_9 = 749.726
```

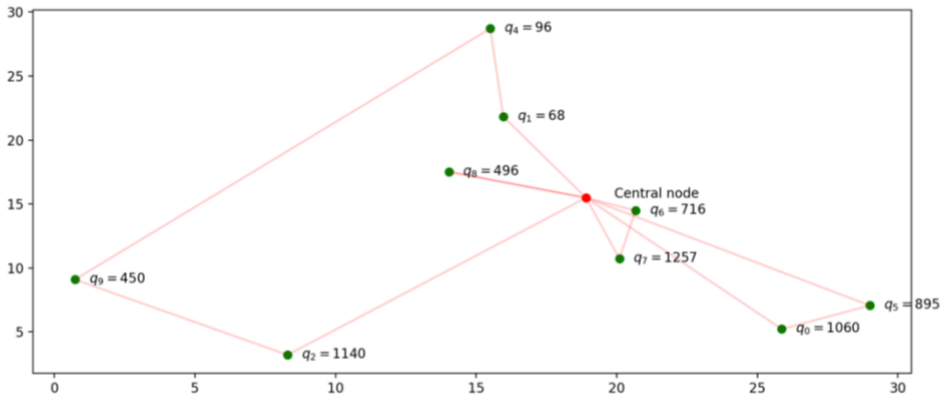
```
Total (root+branch&cut) =    0.01 sec.
solution for: TSP
objective: 56.265
x1_0_8 = 1
x1_1_5 = 1
x1_2_0 = 1
x1_3_4 = 1
x1_4_7 = 1
x1_5_6 = 1
x1_6_2 = 1
x1_7_9 = 1
x1_8_3 = 1
x1_9_1 = 1
d_1 = 6.000
d_2 = 9.000
d_3 = 2.000
d_4 = 3.000
d_5 = 7.000
d_6 = 8.000
d_7 = 4.000
d_8 = 1.000
d_9 = 5.000
```

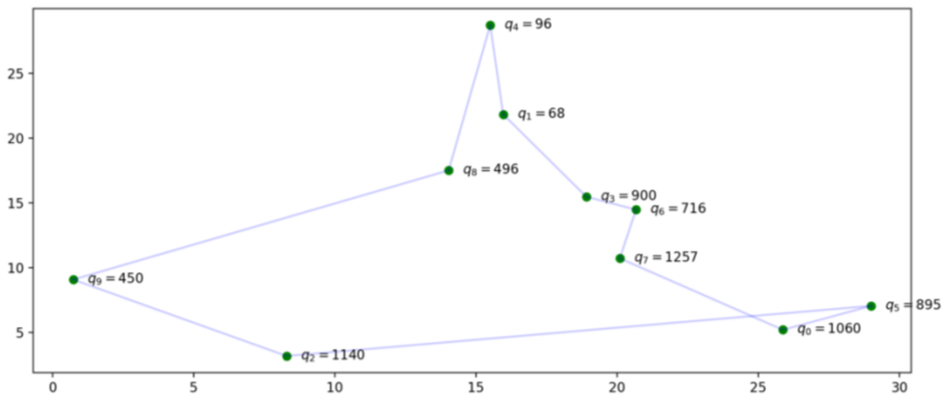




```
Total (root+branch&cut) =     0.02 sec.
solution for: CVRP
objective: 84.973
x_0_5 = 1
x_1_3 = 1
x_2_9 = 1
x_3_0 = 1
x_3_2 = 1
x_3_6 = 1
x_3_8 = 1
x_4_1 = 1
x_5_3 = 1
x_6_7 = 1
x_7_3 = 1
x_8_3 = 1
x_9_4 = 1
u_0 = 1060.490
u_1 = 1756.403
u_2 = 1140.699
u_4 = 1687.451
u_5 = 1955.715
u_6 = 716.499
u_7 = 1973.811
u_8 = 496.814
u_9 = 1591.095
```

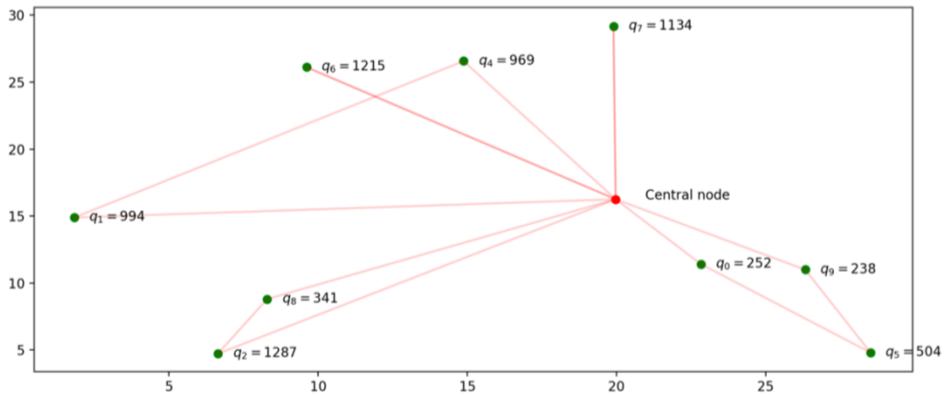
```
Total (root+branch&cut) =     0.01 sec.
solution for: TSP
objective: 73.929
x1_0_7 = 1
x1_1_4 = 1
x1_2_5 = 1
x1_3_1 = 1
x1_4_8 = 1
x1_5_0 = 1
x1_6_3 = 1
x1_7_6 = 1
x1_8_9 = 1
x1_9_2 = 1
d_1 = 4.000
d_2 = 8.000
d_3 = 3.000
d_4 = 5.000
d_5 = 9.000
d_6 = 2.000
d_7 = 1.000
d_8 = 6.000
d_9 = 7.000
```

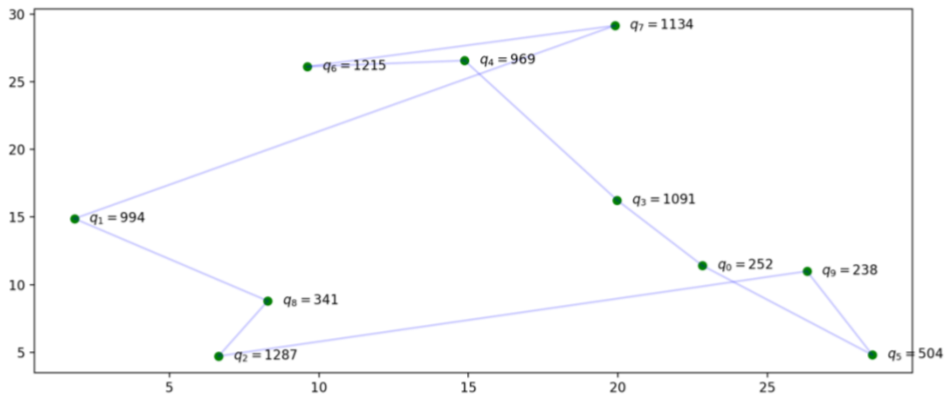




```
Total (root+branch&cut) =    0.02 sec.
solution for: CVRP
objective: 102.914
x_0_5 = 1
x_1_4 = 1
x_2_8 = 1
x_3_0 = 1
x_3_1 = 1
x_3_2 = 1
x_3_6 = 1
x_3_7 = 1
x_4_3 = 1
x_5_9 = 1
x_6_3 = 1
x_7_3 = 1
x_8_3 = 1
x_9_3 = 1
u_0 = 252.265
u_1 = 994.798
u_2 = 1287.314
u_4 = 1964.544
u_5 = 756.481
u_6 = 1215.815
u_7 = 1134.398
u_8 = 1628.339
u_9 = 994.511
```

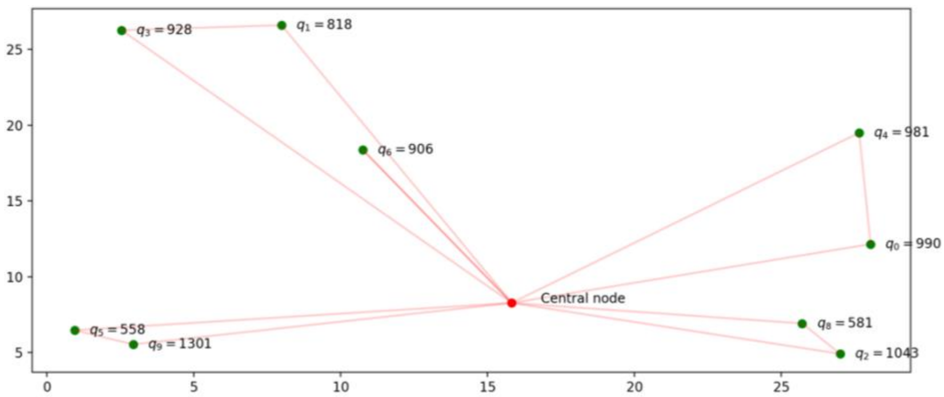
```
Total (root+branch&cut) =    0.02 sec.
solution for: TSP
objective: 84.608
x1_0_3 = 1
x1_1_8 = 1
x1_2_9 = 1
x1_3_4 = 1
x1_4_6 = 1
x1_5_0 = 1
x1_6_7 = 1
x1_7_1 = 1
x1_8_2 = 1
x1_9_5 = 1
d_1 = 5.000
d_2 = 7.000
d_3 = 1.000
d_4 = 2.000
d_5 = 9.000
d_6 = 3.000
d_7 = 4.000
d_8 = 6.000
d_9 = 8.000
```

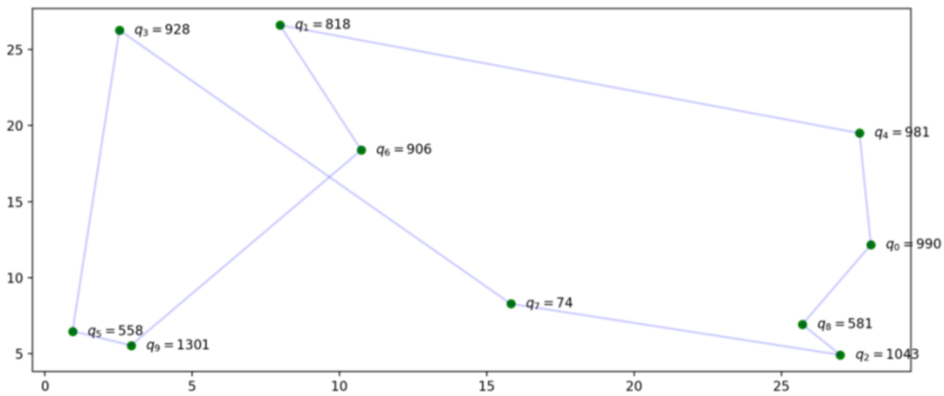




```
Total (root+branch&cut) =      0.03 sec.
solution for: CVRP
objective: 103.339
x_0_4 = 1
x_1_3 = 1
x_2_7 = 1
x_3_7 = 1
x_4_7 = 1
x_5_9 = 1
x_6_7 = 1
x_7_0 = 1
x_7_1 = 1
x_7_5 = 1
x_7_6 = 1
x_7_8 = 1
x_8_2 = 1
x_9_7 = 1
u_0 = 990.724
u_1 = 818.287
u_2 = 1624.987
u_3 = 1746.765
u_4 = 1971.800
u_5 = 558.151
u_6 = 906.439
u_8 = 581.716
u_9 = 1859.437
```

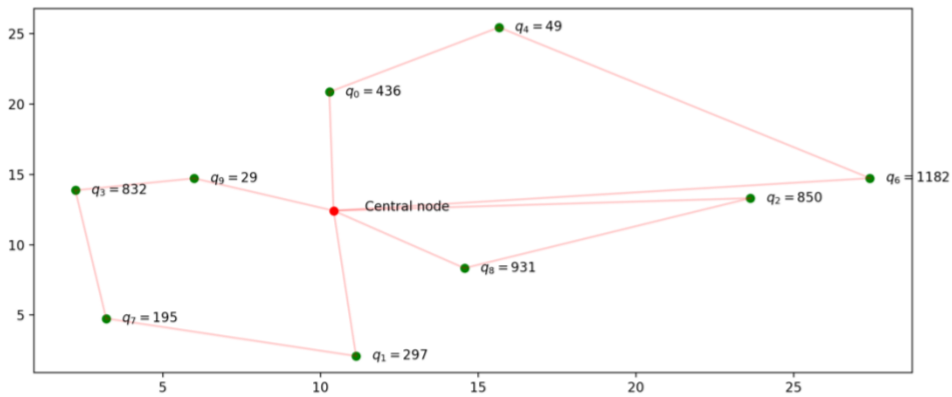
```
Total (root+branch&cut) =      0.02 sec.
solution for: TSP
objective: 87.812
x1_0_8 = 1
x1_1_4 = 1
x1_2_7 = 1
x1_3_5 = 1
x1_4_0 = 1
x1_5_9 = 1
x1_6_1 = 1
x1_7_3 = 1
x1_8_2 = 1
x1_9_6 = 1
d_1 = 8.000
d_2 = 2.000
d_3 = 4.000
d_4 = 9.000
d_5 = 5.000
d_6 = 7.000
d_7 = 3.000
d_8 = 1.000
d_9 = 6.000
```

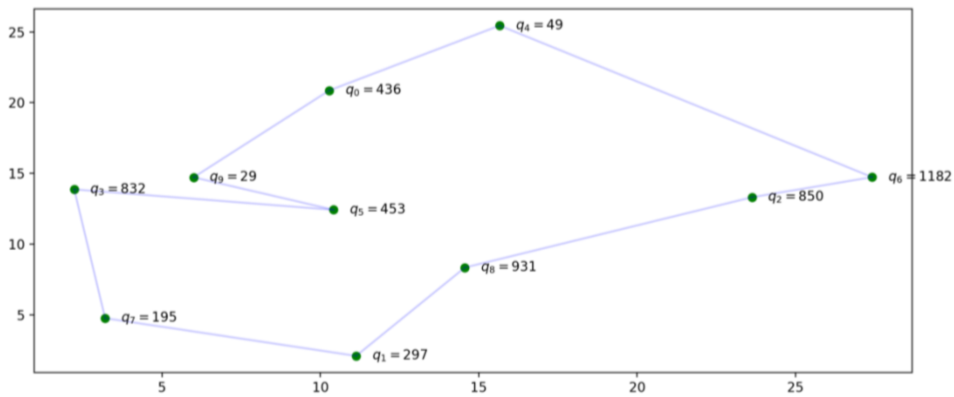




```
Total (root+branch&cut) =    0.04 sec.
solution for: CVRP
objective: 68.393
x_0_4 = 1
x_1_7 = 1
x_2_8 = 1
x_3_9 = 1
x_4_6 = 1
x_5_0 = 1
x_5_1 = 1
x_5_2 = 1
x_6_5 = 1
x_7_3 = 1
x_8_5 = 1
x_9_5 = 1
u_0 = 436.850
u_1 = 297.594
u_2 = 850.637
u_3 = 1325.410
u_4 = 486.444
u_6 = 1668.926
u_7 = 492.909
u_8 = 1781.778
u_9 = 1354.665
```

```
Total (root+branch&cut) =    0.02 sec.
solution for: TSP
objective: 57.889
x1_0_9 = 1
x1_1_8 = 1
x1_2_6 = 1
x1_3_7 = 1
x1_4_0 = 1
x1_5_3 = 1
x1_6_4 = 1
x1_7_1 = 1
x1_8_2 = 1
x1_9_5 = 1
d_1 = 5.000
d_2 = 7.000
d_3 = 3.000
d_4 = 9.000
d_5 = 2.000
d_6 = 8.000
d_7 = 4.000
d_8 = 6.000
d_9 = 1.000
```

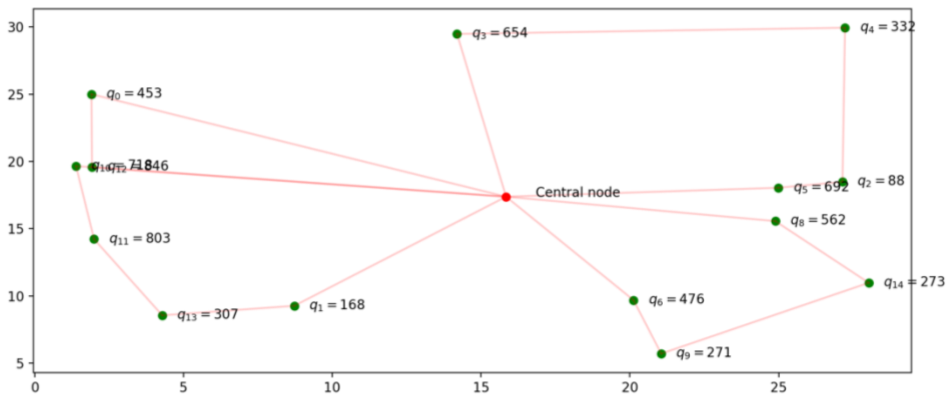


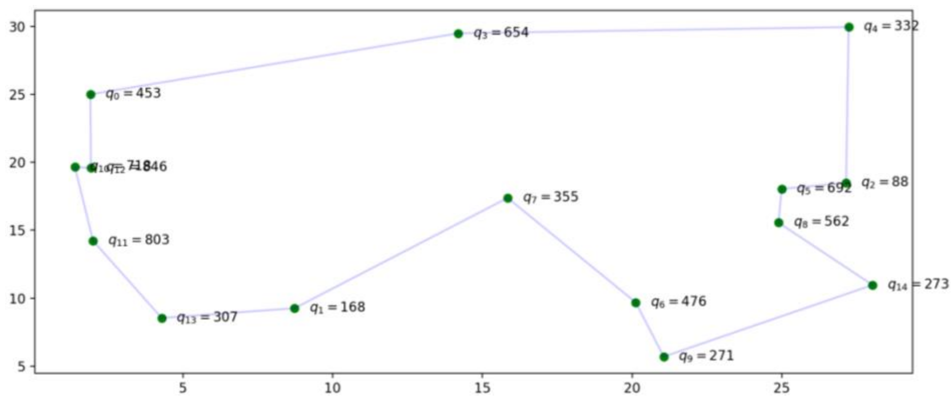


For 15 nodes:

```
Total (root+branch&cut) =   34.09 sec.
solution for: CVRP
objective: 92.678
x_0_12 = 1
x_1_7 = 1
x_2_4 = 1
x_3_7 = 1
x_4_3 = 1
x_5_2 = 1
x_6_9 = 1
x_7_0 = 1
x_7_5 = 1
x_7_6 = 1
x_7_10 = 1
x_8_7 = 1
x_9_14 = 1
x_10_11 = 1
x_11_13 = 1
x_12_7 = 1
x_13_1 = 1
x_14_8 = 1
u_0 = 453.234
u_1 = 2000.000
u_2 = 1012.971
u_3 = 2000.000
u_4 = 1345.823
u_5 = 924.173
u_6 = 892.083
u_8 = 2000.000
u_9 = 1163.670
u_10 = 719.552
u_11 = 1523.358
u_12 = 1299.492
u_13 = 1831.278
u_14 = 1437.596
```

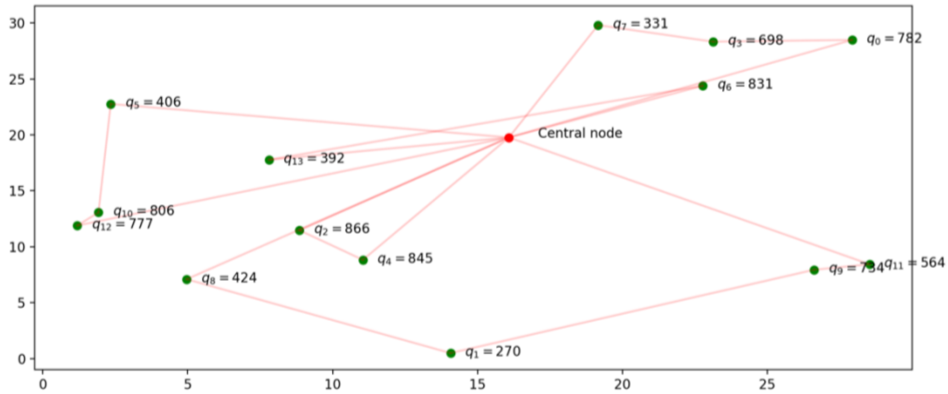
```
Total (root+branch&cut) =    0.02 sec.
solution for: TSP
objective: 75.691
x1_0_3 = 1
x1_1_13 = 1
x1_2_5 = 1
x1_3_4 = 1
x1_4_2 = 1
x1_5_8 = 1
x1_6_7 = 1
x1_7_1 = 1
x1_8_14 = 1
x1_9_6 = 1
x1_10_12 = 1
x1_11_10 = 1
x1_12_0 = 1
x1_13_11 = 1
x1_14_9 = 1
d_1 = 10.000
d_2 = 3.000
d_3 = 1.000
d_4 = 2.000
d_5 = 4.000
d_6 = 8.000
d_7 = 9.000
d_8 = 5.000
d_9 = 7.000
d_10 = 13.000
d_11 = 12.000
d_12 = 14.000
d_13 = 11.000
d_14 = 6.000
```

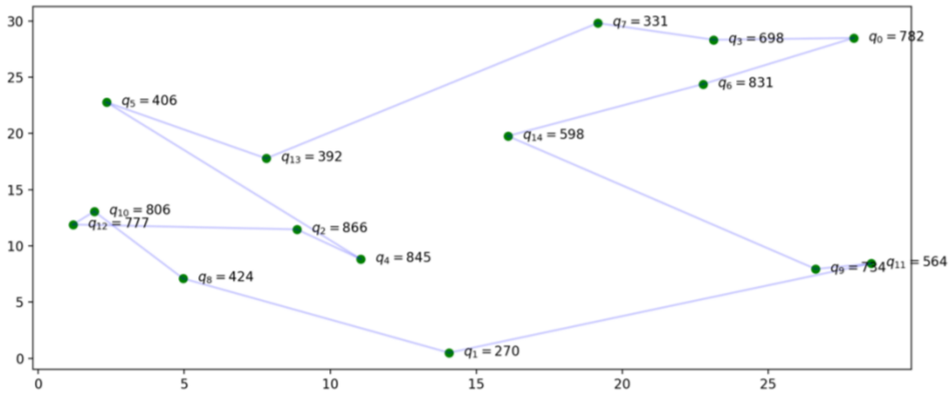




```
Total (root+branch&cut) =   87.58 sec.
solution for: CVRP
objective: 120.236
x_0_3 = 1
x_1_9 = 1
x_2_4 = 1
x_3_7 = 1
x_4_14 = 1
x_5_10 = 1
x_6_13 = 1
x_7_14 = 1
x_8_1 = 1
x_9_11 = 1
x_10_12 = 1
x_11_14 = 1
x_12_14 = 1
x_13_14 = 1
x_14_0 = 1
x_14_2 = 1
x_14_5 = 1
x_14_6 = 1
x_14_8 = 1
u_0 = 782.236
u_1 = 695.619
u_2 = 1154.724
u_3 = 1480.237
u_4 = 2000.000
u_5 = 406.982
u_6 = 1607.224
u_7 = 1811.400
u_8 = 424.730
u_9 = 1430.348
u_10 = 1213.554
u_11 = 1994.653
u_12 = 1991.182
u_13 = 2000.000
```

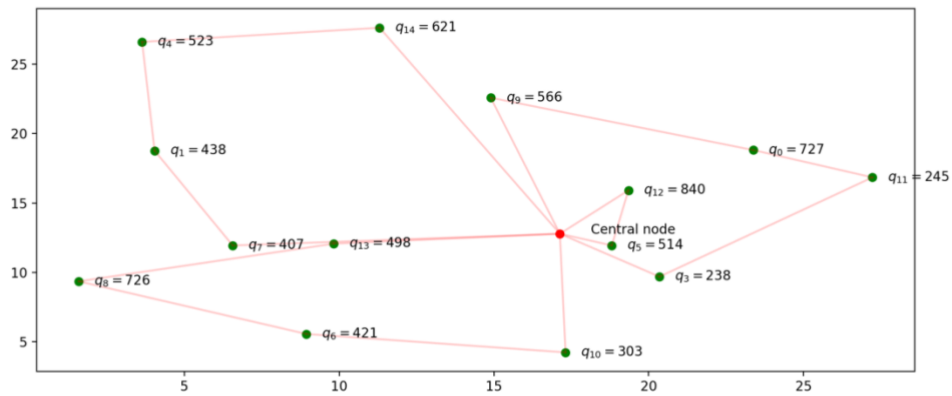
```
Total (root+branch&cut) =    0.02 sec.
solution for: TSP
objective: 99.478
x1_0_6 = 1
x1_1_8 = 1
x1_2_4 = 1
x1_3_0 = 1
x1_4_5 = 1
x1_5_13 = 1
x1_6_14 = 1
x1_7_3 = 1
x1_8_10 = 1
x1_9_11 = 1
x1_10_12 = 1
x1_11_1 = 1
x1_12_2 = 1
x1_13_7 = 1
x1_14_9 = 1
d_1 = 5.000
d_2 = 9.000
d_3 = 14.000
d_4 = 10.000
d_5 = 11.000
d_6 = 1.000
d_7 = 13.000
d_8 = 6.000
d_9 = 3.000
d_10 = 7.000
d_11 = 4.000
d_12 = 8.000
d_13 = 12.000
d_14 = 2.000
```

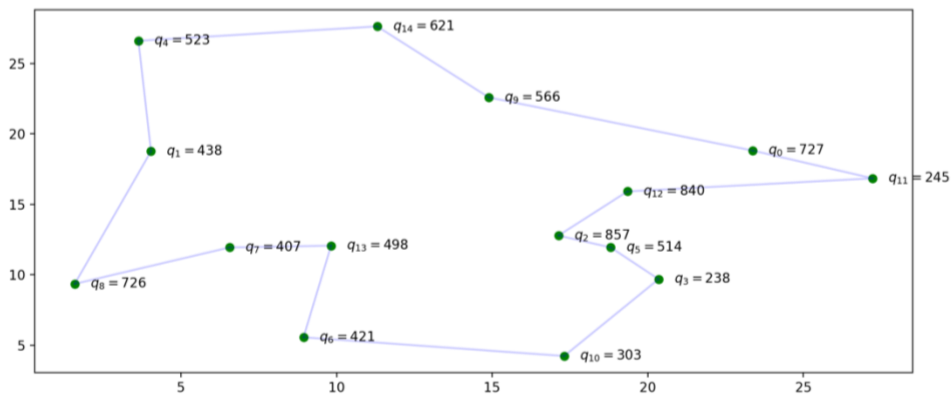




```
Total (root+branch&cut) =    12.43 sec.
solution for: CVRP
objective: 96.934
x_0_11 = 1
x_1_7 = 1
x_2_9 = 1
x_2_12 = 1
x_2_13 = 1
x_2_14 = 1
x_3_2 = 1
x_4_1 = 1
x_5_2 = 1
x_6_10 = 1
x_7_2 = 1
x_8_6 = 1
x_9_0 = 1
x_10_2 = 1
x_11_3 = 1
x_12_5 = 1
x_13_8 = 1
x_14_4 = 1
u_0 = 1293.291
u_1 = 1583.993
u_3 = 1776.918
u_4 = 1145.347
u_5 = 1355.542
u_6 = 1645.811
u_7 = 1991.523
u_8 = 1224.718
u_9 = 566.196
u_10 = 1948.847
u_11 = 1538.868
u_12 = 840.689
u_13 = 498.080
u_14 = 621.918
```

```
Total (root+branch&cut) =    0.03 sec.
solution for: TSP
objective: 81.320
x1_0_11 = 1
x1_1_4 = 1
x1_2_5 = 1
x1_3_10 = 1
x1_4_14 = 1
x1_5_3 = 1
x1_6_13 = 1
x1_7_8 = 1
x1_8_1 = 1
x1_9_0 = 1
x1_10_6 = 1
x1_11_12 = 1
x1_12_2 = 1
x1_13_7 = 1
x1_14_9 = 1
d_1 = 11.000
d_2 = 3.000
d_3 = 5.000
d_4 = 12.000
d_5 = 4.000
d_6 = 7.000
d_7 = 9.000
d_8 = 10.000
d_9 = 14.000
d_10 = 6.000
d_11 = 1.000
d_12 = 2.000
d_13 = 8.000
d_14 = 13.000
```

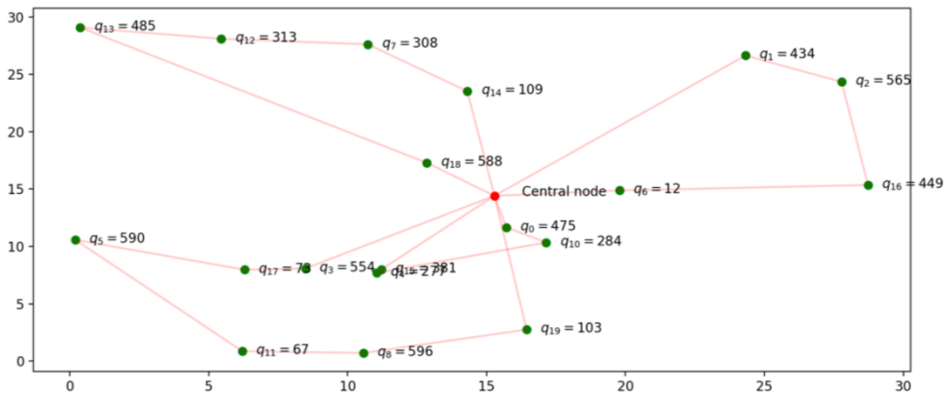


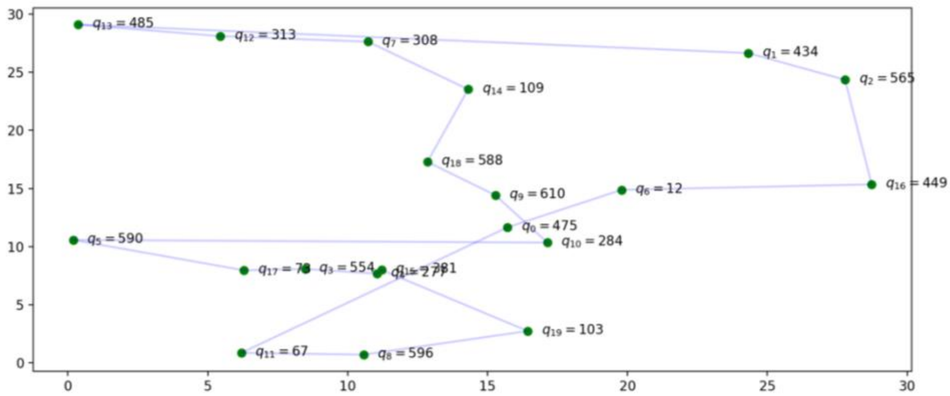


For 20 nodes:

```
Total (root+branch&cut) = 1240.27 sec.
solution for: CVRP
objective: 94.759
x_0_10 = 1
x_1_9 = 1
x_2_1 = 1
x_3_17 = 1
x_4_15 = 1
x_5_11 = 1
x_6_16 = 1
x_7_12 = 1
x_8_19 = 1
x_9_0 = 1
x_9_3 = 1
x_9_6 = 1
x_9_14 = 1
x_10_4 = 1
x_11_8 = 1
x_12_13 = 1
x_13_18 = 1
x_14_7 = 1
x_15_9 = 1
x_16_2 = 1
x_17_5 = 1
x_18_9 = 1
x_19_9 = 1
u_0 = 1056.825
u_1 = 1461.904
u_2 = 1027.336
u_3 = 568.725
u_4 = 1618.833
u_5 = 1232.423
u_6 = 12.119
u_7 = 612.314
u_8 = 1896.481
u_10 = 1341.693
u_11 = 1299.818
u_12 = 925.425
u_13 = 1411.424
u_14 = 303.589
u_15 = 2000.000
u_16 = 462.011
u_17 = 642.110
u_18 = 2000.000
u_19 = 2000.000
```

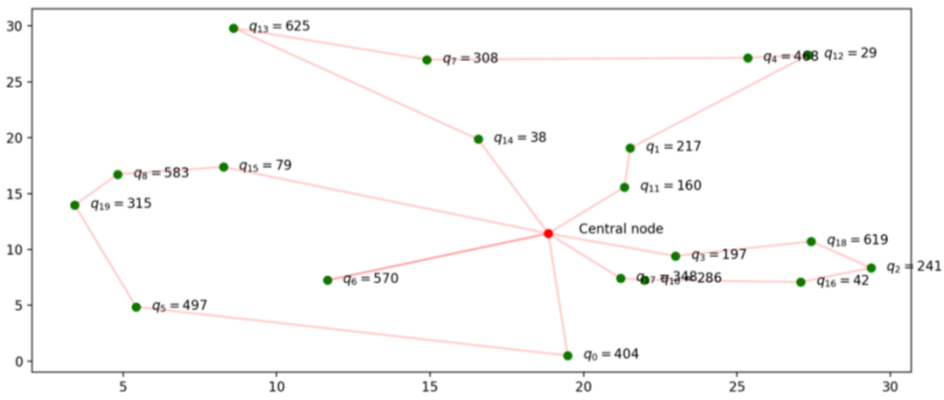
```
Total (root+branch&cut) =    0.04 sec.
solution for: TSP
objective: 85.284
x1_0_6 = 1
x1_1_13 = 1
x1_2_1 = 1
x1_3_4 = 1
x1_4_15 = 1
x1_5_17 = 1
x1_6_16 = 1
x1_7_14 = 1
x1_8_11 = 1
x1_9_10 = 1
x1_10_5 = 1
x1_11_0 = 1
x1_12_7 = 1
x1_13_12 = 1
x1_14_18 = 1
x1_15_19 = 1
x1_16_2 = 1
x1_17_3 = 1
x1_18_9 = 1
x1_19_8 = 1
d_1 = 4.000
d_2 = 3.000
d_3 = 14.000
d_4 = 15.000
d_5 = 12.000
d_6 = 1.000
d_7 = 7.000
d_8 = 18.000
d_9 = 10.000
d_10 = 11.000
d_11 = 19.000
d_12 = 6.000
d_13 = 5.000
d_14 = 8.000
d_15 = 16.000
d_16 = 2.000
d_17 = 13.000
d_18 = 9.000
d_19 = 17.000
```

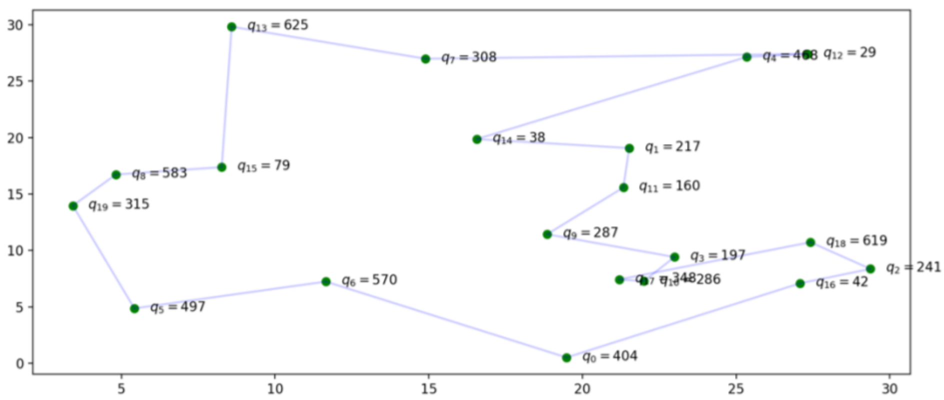

$q_{13} = 485$
$q_{12} = 313$
$q_7 = 308$
$q_1 = 434$
$q_2 = 565$
$q_{14} = 109$
$q_{18} = 588$
Central node
$q_6 = 12$
$q_{16} = 449$
$q_0 = 475$
$q_5 = 590$
$q_{10} = 284$
$q_3 = 554$
$q_{19} = 103$
$q_{11} = 67$
$q_8 = 596$


$q_{13} = 485$
$q_{12} = 313$
$q_7 = 308$
$q_1 = 434$
$q_2 = 565$
$q_{14} = 109$
$q_{18} = 588$
$q_9 = 610$
$q_6 = 12$
$q_{16} = 449$
$q_0 = 475$
$q_5 = 590$
$q_{10} = 284$
$q_3 = 554$
$q_{19} = 103$
$q_{11} = 67$
$q_8 = 596$

```
Total (root+branch&cut) = 2566.86 sec.
solution for: CVRP
objective: 85.368
x_0_9 = 1
x_1_11 = 1
x_2_16 = 1
x_3_18 = 1
x_4_12 = 1
x_5_0 = 1
x_6_9 = 1
x_7_4 = 1
x_8_19 = 1
x_9_3 = 1
x_9_6 = 1
x_9_14 = 1
x_9_15 = 1
x_10_17 = 1
x_11_9 = 1
x_12_1 = 1
x_13_7 = 1
x_14_13 = 1
x_15_8 = 1
x_16_10 = 1
x_17_9 = 1
x_18_2 = 1
x_19_5 = 1
u_0 = 2000.000
u_1 = 1689.302
u_2 = 1322.633
u_3 = 461.720
u_4 = 1441.965
u_5 = 1595.637
u_6 = 2000.000
u_7 = 972.968
u_8 = 782.696
u_10 = 1651.214
u_11 = 1850.246
u_12 = 1471.606
u_13 = 664.100
u_14 = 38.209
u_15 = 198.820
u_16 = 1364.867
u_17 = 2000.000
u_18 = 1081.396
u_19 = 1097.911
```

```
Total (root+branch&cut) =    0.05 sec.
solution for: TSP
objective: 73.670
x1_0_6 = 1
x1_1_11 = 1
x1_2_16 = 1
x1_3_10 = 1
x1_4_14 = 1
x1_5_19 = 1
x1_6_5 = 1
x1_7_12 = 1
x1_8_15 = 1
x1_9_3 = 1
x1_10_17 = 1
x1_11_9 = 1
x1_12_4 = 1
x1_13_7 = 1
x1_14_1 = 1
x1_15_13 = 1
x1_16_0 = 1
x1_17_18 = 1
x1_18_2 = 1
x1_19_8 = 1
d_1 = 11.000
d_2 = 18.000
d_3 = 14.000
d_4 = 9.000
d_5 = 2.000
d_6 = 1.000
d_7 = 7.000
d_8 = 4.000
d_9 = 13.000
d_10 = 15.000
d_11 = 12.000
d_12 = 8.000
d_13 = 6.000
d_14 = 10.000
d_15 = 5.000
d_16 = 19.000
d_17 = 16.000
d_18 = 17.000
d_19 = 3.000
```


$q_{13} = 625$
$q_7 = 308$
$q_{12} = 29$
$q_{14} = 38$
$q_1 = 217$
$q_8 = 583$
$q_{15} = 79$
$q_{11} = 160$
$q_{19} = 315$
Central node
$q_{18} = 619$
$q_3 = 197$
$q_2 = 241$
$q_6 = 570$
$q_{16} = 42$
$q_5 = 497$
$q_0 = 404$
0
5
10
15
20
25
30


$q_{13} = 625$
$q_7 = 308$
$q_{12} = 29$
$q_{14} = 38$
$q_1 = 217$
$q_8 = 583$
$q_{15} = 79$
$q_{11} = 160$
$q_{19} = 315$
$q_9 = 287$
$q_{18} = 619$
$q_3 = 197$
$q_2 = 241$
$q_6 = 570$
$q_{16} = 42$
$q_5 = 497$
$q_0 = 404$
0
5
10
15
20
25
30