UNIVERSITAT DE BARCELONA

MASTER FINAL PROJECT
MASTER OF ENVIRONMENTAL ENGINEERING

DESIGN OF AN INNOVATIVE COLLECTION SYSTEM FOR THE ORGANIC FRACTION OF MUNICIPAL SOLID WASTE

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Summary

Climate change is one of the biggest challenges humanity is actually facing. This is why the European Union has recently issued a more restrictive waste management Directive, which establishes a minimum percentages of selective waste collection for the coming years. To achieve these objective is necessary to improve the current selective collection methods. This is why organic matter becomes important, due to the large amount that is generated as well as its subsequent valorization possibilities.

In this final master project a study of the current collection systems is made to find out which are their main characteristics that allow improving the separation efficiency. In addition, the existing technologies that allow differentiating organic matter from other types of materials are reviewed.

Succeeding, an innovative organic matter collection system based on X-ray technology is designed. This prototype is design to reject the organic matter waste bags that have an amount of improper materials greater than the desired maximum limit. In this way, citizens can be rewarded for making good use of the system.

Subsequently, due to the high cost of the X-ray based system a second system was designed. It is a system where users are identified by QR codes on the waste bags. This allows a subsequent bag inspection to benefit or fine the user.

Finally, a preliminary economic comparison of both systems and the current one is carried out. In addition to the environmental advantages and compliance with the European Directive, better separation of organic waste at source reduces the cost of pre-treating it. With this framework, the economic feasibility of both designs is studied.

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1. INTRODUCTION

1.1 INTRODUCTION

One of the biggest challenges that humanity is currently facing is climate change. To combat it, it is necessary to act in various fields. One of them is the management of household waste. The management of household waste involves large investment by the municipalities, reaching quite high figures. For example, in Barcelona 453 million € were spent in the environment in 2017, of which 323 731 070 € were for waste management (approximately 71%). This represents about 200 € per inhabitant per year [1].

The European Union has recently reinforced its commitment to the environment by issuing a more restrictive Directive (Directive (EU) 2018/851 of the European Parliament on waste) [7]. It sets a minimum recycling levels that must be reached by member states. This new Directive aims to reach a recycling level of 55% for the year 2025 (for the year 2030 it marks a recycling level of 60% and 65% for the year 2035). In addition, this Directive also states that member states shall ensure, by December 31 of 2023, that organic waste is either separated and recycled at its source or collected separately and not mixed with other types of waste.

To achieve the recycling figures set by the EU Directive, waste management is involved in constant change, with the aim of finding a more effective method. Currently there are various procedures for citizens to deposit their waste, in addition to multiple technologies for their separation in specialized plants.

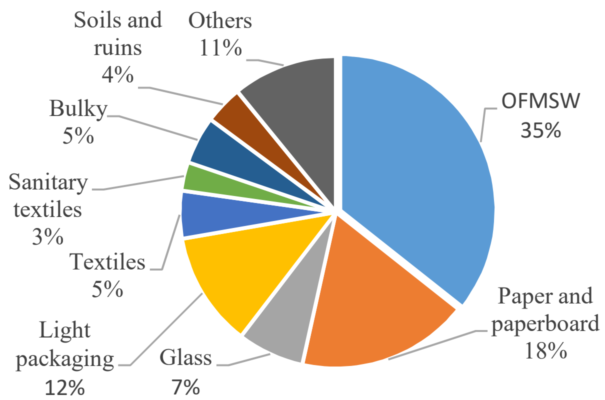


Fig. 1. Proportion in percentage of each fraction of municipal waste generated in Catalonia [10].

To date, 38% of the generated domestic waste is recycled in Catalonia [2]. This implies that the rejected fraction represents 62% of the total municipal waste. If the selective collection was perfect, the remaining fraction should only represent 11%. In order to reverse this situation, organic matter source-separation becomes important due to its abundance, reaching 35% of municipal wastes produced by weight (Fig. 1).

The Agencia de Residuos de Cataluña defines the Organic Fraction of Municipal Solid Waste (OFMSW) as the biodegradable organic waste of plant and/or animal origin, susceptible to biological degradation, consisting mainly of: food preparation remains, leftover remains of food and food in poor condition, and plant remains of small size and non-woody type (grass, leaf litter, bouquets, etc.) [13]. A high-quality OFMSW with a low percentage of impurities (< 5%) is compatible with a biological treatment of maximum technological simplicity and, consequently, at a lower investment and treatment cost [3]. This, added to its great recovery potential, makes this study particularly relevant to further improve the current collection systems.

1.2 OBJECTIVES

The main objective of this project is to design an innovative OFMSW collection system. This system must encourage the collection of most of this fraction as well as reduce the percentage of improper material.

To achieve this, the following secondary objectives are established:

- Study the current waste collection systems to know their strengths and weaknesses.
- Review the existing methods and technologies applicable to the system for the detection of improper materials.
- Conduct a preliminary design of the system, considering the revised information.
- Define the main characteristics of the designed system.
- Conduct a preliminary economic assessment of the new system to compare it with existing systems.

2. STATE OF ART

There are various methods for separating waste. In some municipalities, it is the citizen who carries out the separation, depositing the residue in bags in containers differentiated by fractions. In other municipalities, physical and mechanical separation systems are used to divide the fraction of waste that interests us from the improper or other types of waste. The first option is the one that the European Directive [7] wants to promote since it reaches higher recovery efficiency.

This chapter discusses the most relevant selective collection systems, in addition to the most relevant interesting waste separation technologies for this project.

2.1 SELECTIVE COLLECTION SYSTEMS

Selective collection is the type of collection in which the citizen is in charge of separating their waste according different types. Generally, a difference is made between paper and cardboard, light packaging, glass, organic fraction, the rejected fraction and others. The most important selective collection methods used are reviewed below.

2.1.1 Collection through dumpster on the sidewalk

It is the most common waste collection system worldwide. These are containers located on the sidewalk in which the citizen deposits their waste. These containers are emptied by the corresponding collection services at a specific time and frequency, according to the type of waste [20].

Some modifications to this system have emerged, trying to improve its efficiency, in terms of the quality of the collected waste (low improper percentage) and its subsequent transport.

2.1.1.1 Smart Containers

Smart containers have already been incorporated in some pioneering municipalities, such as Urgellet, and La Garrotxa (Catalonia, Spain) Sasieta (Basque country, Spain) [27]. These are containers similar to the sidewalk ones with the difference that in order to open them you must have an identification card [2]. In this way, it is possible to know who throws the waste in the container and to be able to act on it. This technology stimulates the minimization of improper waste in selective collection.

2.1.1.2 Underground containers

It is a system of dumpsters where they are underground, leaving only an entrance or mailbox outside so that users can deposit their waste. This design reduces the visual impact of the dumpsters, in addition to its volume on the sidewalk. It is implemented especially in certain more tourist areas or with more transit. In the article *Development of a mechanical device for concealing underground urban solid residual containers* [6] a preliminary design of one of these dumpsters can be found.

2.1.1.3 Pneumatic collection

This type of collection focuses on the transport of the bags from the container mailbox where the user deposits the bag to another point, which may be the treatment place or another intermediate place [15]. This container mailbox can be placed at the sidewalk or inside of residential buildings. Hydraulic systems suck the bags through adapted pipes. It is a sophisticated but quite expensive collection system [19].

2.1.2 Door to door collection

Door-to-door collection is a system of selective collection of municipal waste based on the fact that the holder, instead of depositing wastes in a container on the sidewalk, it will be collected at the point of generation (homes or shops) according to a pre-established schedule and on which an exhaustive control and monitoring can be carried out [3].

In this type of collection, selective collection rates of more than 80% are reached, being the maximums of all the types of collection analysed [2]. Due to this, the organic fraction of the rejected fraction is highly reduced while the OFMSW improper percentage is have been highly reduced down up to 2% [3]. The main problem is that it is difficult to apply this system to areas of high population density with multi-family dwellings.

2.1.3 DRS (Deposit-Refund Systems)

They are based on leaving a deposit when buying a container (bricks, cans, and glass or PET bottles). A machine returns the deposit when the container is deposited in it by the user. In this way, the user considers the container as a consumer good and not as a waste to be eliminated. Implementing a DRS system would increase the recycling rate, but would also suffer a considerable increase in costs [12].

Although it is not a system for collecting organic matter (currently it only works with containers), the idea of leaving a deposit that is returned to the user appears interesting in order to improve the recycling rate.

2.2 WASTE SEPARATION SYSTEMS

Sometimes it is necessary to separate the waste in a triage plant after collection. This is the case of the triage of the rejected fraction or when there are improper in some of the other fractions. The higher the improper percentage, the higher the cost of pre-treatment and the worse the quality of the final product. Regarding to the organic fraction, there are multiple studies that point out the importance of a low percentage of improper organic matter for the valuation processes to be efficient, both for composting [26] and anaerobic digestion [11].

This section studies the different technologies currently available that allow differentiating between different types of materials. Some of them are currently implanted to separate other types of fractions, but none of them is widely developed in the detection of improper material within domestic organic waste.

2.2.1 Manual separation

Manual separation is based on the ability of operators to detect improper or desirable materials within waste. It consists of the manual separation of waste by the operators. These wastes circulate thanks to conveyor belts. The operators can also use other systems, such as magnets, to easily detect iron residues [21]. In addition to being expensive, manual separation is dangerous for operators. This is the reason why this type of triage is the one to be eliminated, making the user responsible for separating their waste.

2.2.2 Optical separation

Optical separation replaces manual triage in some waste separation plants. It is a system that, using high-resolution infrared and colour cameras and scanners, analyses all the components of the waste [23]. Then, a system of high-precision air injectors propels each element in a suitable direction and distance to move it to its corresponding conveyor belt, so that the required components can be separated.

One of the main disadvantages of this system is organic matter. This, due to its high humidity, is very sticky and adheres to residues such as plastics or metals. Because of this, the system may fail to properly separate the material and reduce its performance. In addition, it is difficult to blow some heavier materials, such as glass.

2.2.3 X-ray technology

As an alternative to previous technologies, X-rays are studied. It is a system that is not widely used for the detection of organic wastes, although there are some models available in the market. For example, the Tomra x-tract 1200 is a system capable of separating organic waste in a triage plant for subsequent treatment [17]. According to manufacturer, this system would be able to recover up to 95% of the interesting materials from OFMSW.

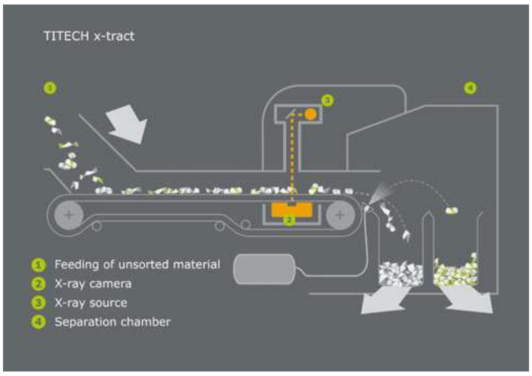


Fig. 2. Operating scheme of the Tomra x-tract 1200 equipment for the improper separation of the OFMSW.

X-rays are a type of electromagnetic radiation, like radio waves or infrared. These radiations are of the ionizing type, because when interacting with the matter it produces the ionization of its atoms, that is, it originates charged particles (ions) [5]. There are several detection systems for X-rays. When X-rays interact with matter, they can be partly absorbed and partly transmitted. This feature is used to take radiographic images. Diffraction is used, for example, in airport scanners for baggage inspection. The only limitation is the density of the material to be examined. For materials denser than lead no transmission is achieved, but there is not limitation for bio-waste.

The X-ray system consists of two main elements, as can be seen in Fig. 2:

- An X-ray generator, which projects the rays into the object to be analysed.
- An X-ray receiving board. The receiving board receives the X-rays sent by the generator. This signal is modified when crossing the object to be analysed and depending on the diffraction, they classify the crossed objects in different classifications, for example, inorganic and organic.
- An air blower system to separate the waste in two streams and divert the materials to different conveyor belts.

3. DESIGN OF A SIDEWALK X-RAY BASED SYSTEM

As explained previously on Section 2.2.3, X-rays allow us to pass through opaque bodies and see what is on the other side through a radiography. This system explained below is based on the use of X-ray technology at the waste collection point. This allows to observe what there is inside the organic waste bag that users deposit in the container. A hallmark of the designed device is its ability to accurately estimate the percentage of improper in the bag. Knowing this, the user will receive a reward for correctly separating the bag of OFMSW. Annex 1 contains all the plans, element by element and the whole system, with their main measurements.

3.1 LOCATION

The possibility of locating the new system at various points, such as inside supermarkets, in the hall of residential buildings or combining it with existing containers of various types was considered and evaluated.

Based on the Table 1 it is chosen to design a modification of the waste bags introduction system to the current containers. This is done to take advantage of the current facilities of these containers and reduce investment, since it is not necessary to modify the collection model of trucks by the waste management company. In this case an inbox for underground containers is designed, although it is also valid for the inlets of the pneumatic collection. This choice is because, even knowing that they are less extended than surface containers, citizens cannot move them freely. Furthermore, these containers have an inbox that facilitates the implementation of the system.

Table 1. Pros and cons of different possible locations for the X-ray collection system.

	PROS	CONS
Supermarkets	- Vigilance -No damage from atmospheric agents	- Potential bad smells - Leachates - The search for an establishment that allows the system - Spread of vectors - Limited collection time
Hall of residential buildings	- Vigilance - Less impact of atmospheric agents - Extensive collection time	- Little dispersion of possible bad smells - Fouling and leachates - Spread of vectors
Existing containers	- Leachates already controlled - Currently extended system - Extensive collection time	- Less controlled - Possible manipulation by citizens - Impact of atmospheric agents
Sidewalk dumpsters	- Very extended	- Easily to manipulate - Occupation of the public sidewalk
Underground containers	- Implanted in multiple municipalities - Difficult to manipulate (attached to the ground)	- Less extended than sidewalk containers - Expensive implementation
Pneumatic systems	- Difficult to manipulate (attached to the ground)	- Minimum extension. - High energy consumption - Complex infrastructure

3.2 SYSTEM DESIGN

The realization of this project includes the design of the waste reception system. Its design consisted of a creative process but always based on the information reviewed in the State of Art Section of this project (Section 2). This system needs certain essential elements to ensure its correct operation.

These are:

- A frame
- A cover
- A lead envelope
- A bag reception box
- A bag weighing system
- An X-ray detection system
- An identification system

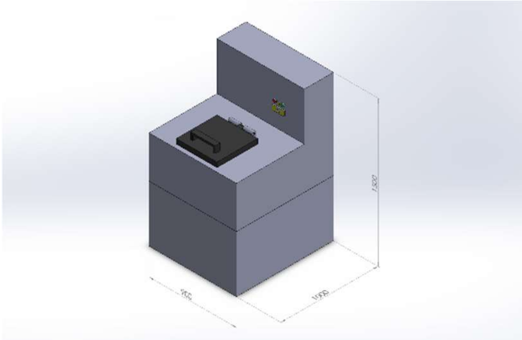


Fig. 3. Picture of the whole system designed in SolidWorks.

The conceived system can be seen in the Fig. 3.

The elements of which its location is not defined in the following sections are within the frame (X-ray battery, alert delivery system, etc.).

3.2.1 Frame and cover

The frame is made of recycled plastic (recycled high density polyethylene), due to its lightness, in addition to promoting circular economy. There are information and identification systems in it that are explained later (see Section 3.2.6).The cover (in darker colour in Fig. 3) and the frame must protect the system from atmospheric agents, preventing internal components from being damaged, which would increase maintenance costs. Based on the standard UNE-EN 60529:2018 *Degrees of protection provided by the enclosures* [30] is determined that the frame has to be in possession of a degree of protection IP 55. This means, quoting the standard:

- *The entrance of dust is not totally prevented, but without the dust entering in a sufficient quantity that could affect the satisfactory operation of the equipment.*
- *The water sprayed with the help of a nozzle, in all directions on the enclosure, must not have harmful effects on the equipment.*

In addition, the cover must have an inner layer of lead to prevent leakage of ionizing radiation from the system to the exterior, for the same reasons as the lead envelope (see Section 3.2.2). This cover will close by gravity, in case some user may leave it open, so that the components are not affected by possible rain.

3.2.2 Lead envelope

As explained later in Section 3.3.1, X-rays can cause damage to human health. This envelope, together with the cover, are the measures of protection against X-rays.

Inside the frame there is thick lead envelope that prevents leaks to the outside of the system radiation (see Fig. 4).

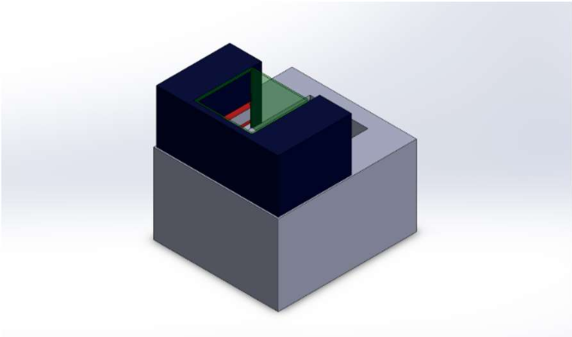


Fig. 4. Lead envelope (coloured black) wrapping the main components.

3.2.3 Bag reception box

Various designs of a receptor mechanism for introducing the bag into the system have been considered. It must be an element that allows the introduction of the bag, its transfer to the container and its removal by the user. Furthermore, it must be able to coexist with the weighing and X-ray systems and allow them to function properly.

Existing systems have been studied [6] in addition to designing new ones. Some of the latter consisted of a hatch that made the scale move to drop the bag or pneumatic systems that pushed the bag in one direction or another. All these designs were discarded for several reasons, such as the fact that the scale was a mobile element, since it would be more likely to damage it and would require increased maintenance. At the end of various designs, one was found that stands out for its simplicity (Fig.5), which is explained below.

Fig. 5. Image showing the movement of the box (coloured green) from its initial position (left) at the moment the user deposits the bag and its final position (right), where the bag would fall through the hole until reaching the container.

When the bag is introduced by the user it is deposited in a square container called “the box”. This box fulfils the following functions:

- Having a top hole allows the introduction of the bag by the user. In addition, it maintains the waste bag in the same position in which it was inserted so that, in case it has to be removed by the user, the user can access the bag handle easily.
- Allows the displacement of the bag, moving it to the hole where it will fall to the container if necessary.
- Being emptied laterally allows the correct functioning of the X-ray equipment.
- The lower hole allows the bag to be placed on top of the weighing machine so that it can be accurately weight, in addition to allowing the bag to fall into the container.

The box is designed to fit on rails to allow its movement. In addition, its design together with the design of the lead envelope prevents the user from accessing dangerous elements of inside the system.

3.2.4 Bag weighing system

The system must have a weighing element for the inserted bag. The reason of this component is that the user will receive a benefit based on the amount deposited. In addition, this weighing will ensure that the user does not introduce any other type of unwanted organic matter, such as unwanted vegetable fraction, since it is less dense than the bio-waste and will not receive the same profit.

It is not necessary for the scale to have a very high resistance against water and external agents because it is not located outdoors so it is not in direct contact with atmospheric agents continuously, but it must resist the leakage of residues from the bags, which contain a high degree of humidity and weak acids.

The weighing system consists of a bench scale. This weighing system is chosen because it has small dimensions, suitable for the system, and because they are suitable for working with organic products, (many are designed to work with food). In addition, an abundant diversity of models and prices can be found on the market.

The bench scale is placed at the bottom of the box, as shown in Fig. 6, allowing the bag to be placed on top of it and the box to drag the bag if necessary. An example is the My Weigh HDSC parcel scale, with an accuracy of 20 grams [22], although many models could be used. Its plate is 400 mm long and 350 mm wide, with an approximate height of 50 mm.

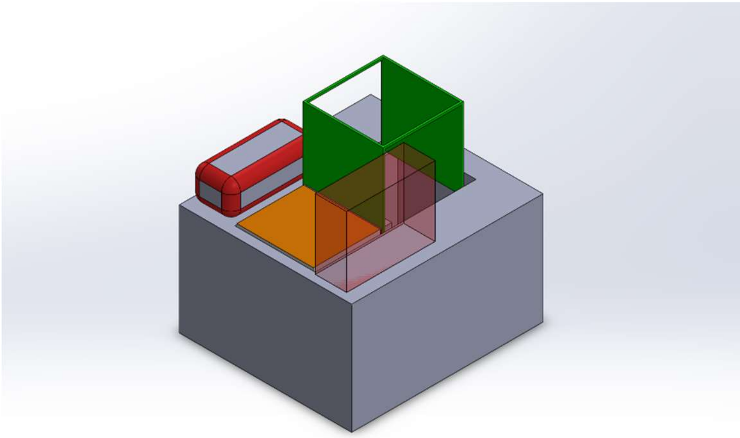


Fig. 6. The scale (the orange element) is placed under the box to be able to weigh the bag.

3.2.5 X-ray detection system

As explained above in Section 2.2.3, an X-ray generator and receiver are required for the use of this technology. An example is the portable generator SPX-6046P from the company SecuPlus. As shown in Annex 2 it is a small system that can work in a reasonable temperature range (between -15 ºC and 50 ºC). The dimensions of the generator are 480 mm long, 215 mm wide and 175 mm high and those of the detection plate are 462 mm long, 366 mm wide and 164 mm high. This X-ray system generates an image where the organic material is shown in orange and the inorganic material in blue. Also, depending on the amount of the material, the image will be obtained with higher contrasts (dense and deep objects) or lower (thinner objects). In this way, the ratio between inorganic fraction in the bag and the organic fraction can be estimated. This would be automatically analysed by an electronic system within the device.

As shown in Fig 7, the generator would be arranged to the left of the waste bag and the detection plate to the right.

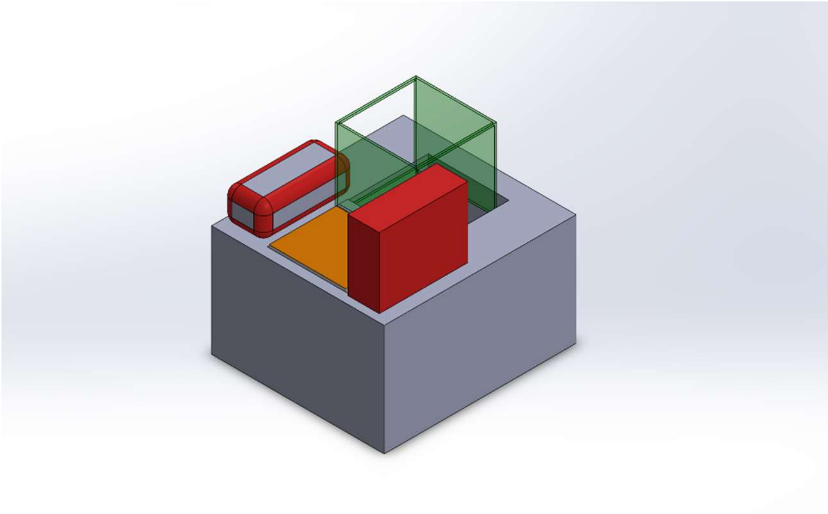


Fig. 7. Detail of the system where the X-ray generator is shown (red and grey) to the left of the scale (in orange) and the receiver plate to its right (in red).

In addition and as explained in Section 3.3.1, the system is provided with all the necessary elements to prevent X-rays from causing any type of damage to the health of users.

3.2.6 Identification and control

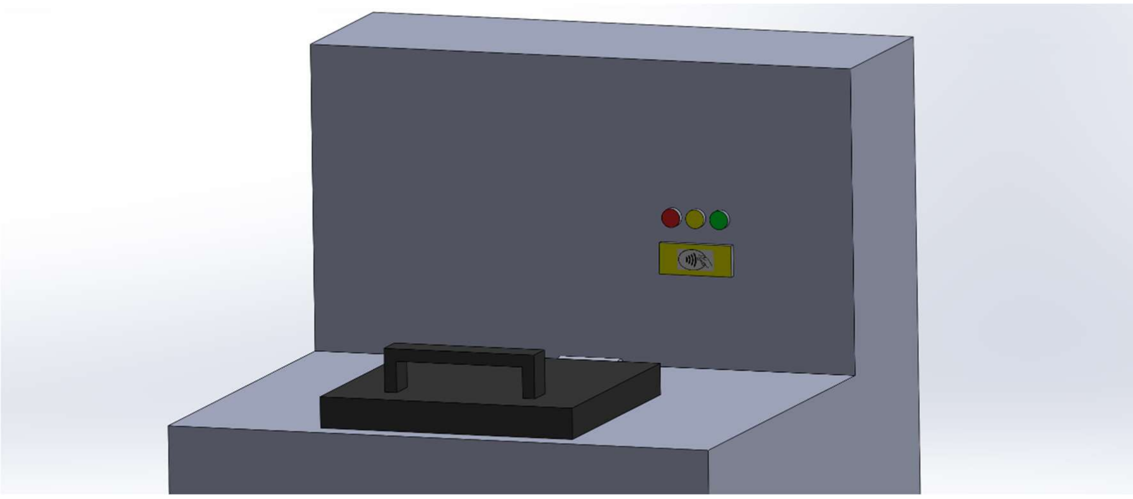


Fig. 8. Image of the upper part of the frame showing the slot for the insertion of the identification card, as well as the information lights for the user.

In the frame, and as shown in Fig. 8, there is a card reader (in yellow colour), as well as certain information signs. These signs consist of three lights that indicate to the user the procedure to follow. The information provided by each of the light signals is the following:

- Left red light: it will light up when the weight of the bag is higher than the maximum (> 7 kg) or it has an elevate percentage of improper (> 5%). The user will be instructed to proceed to remove the bag (see Section 3.6).
- Central yellow light: it will light up when the weight of the bag is lower than the minimum (< 1 kg). The bag will be sent to the container but the user will not receive any benefit (see Section 3.5).
- Green right light: it will light up when the weight and content of the bag are as desired, indicating to the user that he will be rewarded.

An explanatory sticker with the previous instructions will accompany each light. Also, next to these signs or next to the cover there will be a sticker with information for the user on what type of organic material is appropriate for this container, as well as a short list of the most common improper to find on the organic fraction. This information will help the user to better understand what can be deposited in this container.

In order to control de system properly, it is necessary to use a simple PLC (Programmable Logic Controller) system in addition to card reading and system control software. This system allows the identification of the user as well as the control of all the actions that the system must carry out.

3.3 SECURITY AND HEALTH

The system has been equipped with various elements for safety and hygiene, both for users and for workers who handle it. These elements are explained below.

3.3.1 X-ray

One of the main problems of working with X-rays is the exposure of the human being to its radiation. Ionizing radiation, as explained in various articles, can cause harmful effects on health, depending on the sensitivity of the organ and the amount of radiation to which the body is exposed [31]. These effects range from reddening of the skin to cancer.

To avoid these problems, the entire system must be properly insulated with a layer of lead. This lead layer can be found on the cover (Section 3.2.1) and on the lead envelope (Section 3.2.2). Lead prevents the spread of X-rays since, as explained above, it has a high enough density to avoid the transmission of radiation.

Lead, on the other hand, is a material that can cause various conditions to the human body. As explained in various investigations and articles, such as "*Lead poisoning and health*, 2020" by the World Health Organization [32], exposure to lead can be harmful if it is inhaled, ingested or introduced into the body through the skin (by using of cosmetic products, for example). In any case, there should be no problem working with a solid lead layer covered in plastic.

3.3.2 The cover

As mentioned previously (see Section 3.2.1 Frame and Cover) the cover closes autonomously by gravity. This ensures that the system remains closed even if the user does not close it. On the other hand, the system will not initiate any action if it is detected that the cover is not closed properly. This restrictions are made possible by a limit switch. In addition to this, the cover cannot be lifted during system operations. These restrictions protect the health of the users and the system from possible manipulations and failures.

3.3.3 Virus and bacteria

In order to further protect the health of the user, a type of contactless card has been chosen to avoid the spread of viruses and bacteria. This type of technology reduces the contact between cards and the system, and consequently, reduces the risk of contagion of diseases among users.

3.3.4 Alarm system

The system has a relay with a 2G antenna. This element allows sending a signal (SMS) to a computer or telephone to alert of any type of failure in the system. The range of alert situations is very wide. For example, when the X-ray system does not work or the cover is not closed properly.

One model would be the gsm Alarm System, Mini 8 CH. It allows sending the signal up to 6 devices [28]. Economical and small, it is a very appropriate and useful element.

Depending on the type of alert, the system will go into hibernation mode (for example, if the cover does not close properly). This means that users will not be able to use it. A maintenance staff should go to perform the necessary operations to fix the situation. Once the error is corrected, the system will return to service. This procedure ensures that no user is affected by a possible failure.

3.4 IDENTIFICATION CARDS

There are various technologies for user identification. The identification cards will have Radio-Frequency Identification (RFID) passive technology, so the container must have a RFID reader. When an Access key is held over the reader, the access tag is checked and, if approved, the container opens and waste can be deposited each use is recorded [27].

Two identification cards will be given per home. These cards will be associated with housing, and their loss must be notified immediately. The cards are accompanied by an environmental education campaign that informs users about what type of materials can be placed in the container, the environmental benefits of recycling organic matter, the system use procedure, the economic benefit that users receive for its correct use and which are the most common improper to ensure that they are not introduced.

As a future alternative would be the possibility of install a reader for the Smartphone in addition to the card reader. In this way, it would not be necessary to use the cards. Also, the user could take better control of the benefit that he has accumulated each month with an app. At this moment, it is discarded since the necessary NFC (Near-Field Communication) technology is not yet available in a large number of smartphones, although its presence is gradually increasing.

3.5 CRITERIA OF ACCEPTANCE

It is necessary to apply restrictions for the acceptance of the bags. In this case, they are applied to the improper percentage and the bag's weight.

As for the weight, assuming a maximum bag volume of 10 L and that the OFMSW density reaches 600 kg/m^3 [14] an upper limit of 7 kg is established per bag inserted. Bags higher than this amount are not accepted since a larger bag could affect the accuracy of the X-ray system. However the user can enter several bags repeating the procedure but one at a time. It is known that on average a citizen generate about 450 grams of organic matter [3] and that in households with several occupants and on special occasions (Christmas, etc.) larger quantities can be produced.

As a restriction, since the citizen is going to obtain a benefit from the delivery of the OFMSW, it is decided that the bag must contain at least 1 kg of organic matter. If the bag weights less than that no benefit will be given. Therefore, if the weighing system detects a bag that is not inside the range of 1000 grams to 7000 grams the user will not obtain any type of benefit.

Another restriction is the percentage of improper. According to the "*Guía para la implantación de la recogida separada y tratamiento de la fracción orgánica*" [18], it is necessary to reach a level of improper less than 5%, which is within the range of efficacy of the X-ray technology. Therefore, when the system detects that this percentage is exceeded, the bag will be defined as unwanted, and the user will be asked to remove it. On the other hand, if the percentage of unwanted material is below this value, the bag will be defined as desirable and would be pushed into the container.

3.6 UTILIZATION PROCEDURE

The first step is the user identification. The user must bring the identification card close to the reader to open the cover (this action puts the system into operation mode). One of the purposes of this procedure is that the user cannot insert any element into the container without being identified. In this way, in the event of damage to the interior, the causer could be identified and penalized.

After identification, the user must open the cover for the introduction of the bag filled with organic material and close it again to continue with the procedure. In the event that the bag is not desired (too much weight or improper percentage) a red light on the panel will activate, signalling the user to remove the bag. At this time the user must open the cover and remove his bag. The user has 2 minutes to remove their waste bag (enough time to open and retrieve their bag). If it is not removed, the mechanism that move the bag to the container would be activated. This is done so that the other users do not find the system blocked and cannot deposit their waste. Finally, a fine will be sent to the user (identified with the help of the card) for not proceeding correctly.

In the event that the bag is fulfils the quality but its weight is lower than the minimum (< 1 kg) the system would activate the mechanism that would push the bag backwards (away from the user). The bag would fall through a hole destined for the container. At the same time, the yellow light on the panel would light up indicating that the procedure has been successfully completed but that the user will not receive any benefit for that bag.

In the event that the bag is desired (low improper percentage and weight between 1 kg and 7 kg) the system would activate the mechanism to push the bag towards. The bag would fall through the hole. Also the green light on the panel would light up indicating that the procedure has been successfully completed and the user can leave knowing that he will get a profit.

3.7 POWER SOURCE

Initially, the system was designed to be used with the energy provided by a solar panel. This design has been discarded due to the impossibility of installing a panel with sufficient surface area to provide the necessary power to the X-ray system. To solve this, it was decided to directly connect the system to the electrical network, in the same way as already it is made with other urban elements such as lampposts.

On the other hand, in the event of a power outage the X-ray system has a battery capable of operating the system (see Annex 2). In addition, card readers are designed to last 2 to 3 years [27] without having to be connected to any power source.

3.8 USER REWARD

As explained in Section 2.1.3, DRS systems reduce the percentage of improper that are found in the collected fraction. This is because its rewarding motivates the users to make a good separation of their waste. After evaluating different ways to reward users who make appropriate use of the system a financial reward has been chosen in the form of discounting the annual waste rate.

The user must deposit at least two desired bags a week (see Section 3.6). For each week that the user makes a correct use of the system, he will receive a 2 € discount. The maximum discount is 60 € per year. In the event that at any time the system detects an improper presence above what is established, the user will not receive their corresponding discount of that month, regardless of whether they deposit other bags with the amount of improper admitted during the rest of the month. This is a reward already used in other selective collection tests, as in the municipality of Urgellet in Spain (where the maximum discount is 50% of the annual waste rate) [27] that has shown to arouse the interest of users.

3.9 ECONOMIC VALUATION

The purpose of this section is to clarify what the construction cost of this system would be, taking into account all the components previously explained. In Table 2 an estimated price for each element of the X-ray based system is shown.

Table 2. Estimated price for each element of the X-ray system.

Element	Quantity	Observations	Price
Plastic elements	x 1	Recycled High Density Polyethylene	100 €
The box	x 1	-	10 €
Lead elements	x 1	Lead envelope and part of the cover	138 €
X-ray generator + detector	x 1	Model Portable X-ray Scanner SPX-6046P	16 630 €
Weigh system	x 1	My Weigh HDSC	115 €
Mechanisms	-	Motor, sensors, etc.	60 €
Alarm system	x 1	Gsm, Mini 8 CH model	41 €
RFID reader	x 1	-	20 €
Identity cards	x 300	0,3 € / unit	90 €
Software	x 1	-	4000 €
PLC system	x 1	-	80 €
Others (lights, etc.)	-	-	30 €
		TOTAL	**21 314 €**

Maintenance and installation costs are not taken into account in Table 2. Only the prices of the elements that make up the system are shown. Consequently, the total economic estimate of the system as a whole amounts to 21 314 €.

3.10 SWOT ANALISYS

A SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis is made in order to study the system. This type of analysis allows to detect the own pros and cons of the system and to foresee the negative situations that could happen when implementing it.

Table 3. SWOT analysis of the X-ray based system.

	Weaknesses	**Strengths**
Internal	- High initial investment	- Wide deposit time - Increase waste quality - Facelift of an extended but questioned system (underground containers)
	Threats	**Opportunities**
External	- Citizen rejection for its complexity - Poor discipline of citizens when using the system - Work with ionizing radiation and lead elements can be reflected in a rejection of the use of the system by users, even if the necessary measures are established for its control	- Higher quality of the other waste fractions - Decrease of the rejected fraction - Greater involvement of the population in waste

4. INSPECTION BASED SYSTEM

Due to the high cost of the X-ray based system, a modification of the design of the previous section (*3.X-ray System*) is studied. It is a simpler design but with a partial control of the improper materials. In this system, X-ray technology is dispensed with, leaving only the weighing system as detection of what is being introduced into the receptacle by the user. In order to ensure efficiency, a post-collection inspection of the container bags is added (in the triage plant). In order to achieve this, new bags with QR codes are introduced so the users can be identified in the inspection process.

The objective of this second system is to reduce the costs of the X-ray system trying to maintain efficiency and compare the systems later.

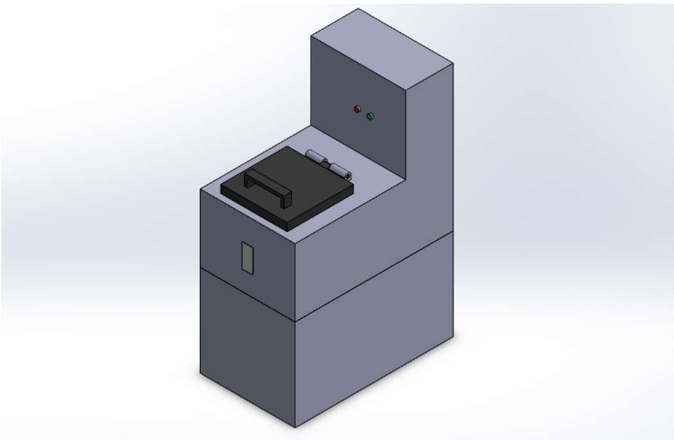


Fig. 9. Picture of the new system designed in SolidWorks.

Annex 3 contains all the plans of the system, element by element and as a whole, with their main measurements.

4.1 LOCATION

This system is placed as an inbox for underground containers so that it can be compared with the previous design. However, the structure can be modified to be used in other types of existing containers, without modifying its basic operating principles.

4.2 SYSTEM DESIGN

This system shares the design of the previous system (*see Section 3.X-ray based system)* except for certain exceptions that are detailed below:

- The use of an X-ray generator, as well as its receiver board, are dispensed with.
- The use of the lead envelope is disregarded, as well as the lead layer on the cover. This is because since there is no longer an X-ray generator, it is not necessary to use this material to isolate the system.
- The lateral recesses that "the box" had in the previous design were designed to allow the X-ray system to function properly. By dispensing with the X-ray system, the box does not need to be laterally hollow. The design of the new box can be seen in the Fig. 10.

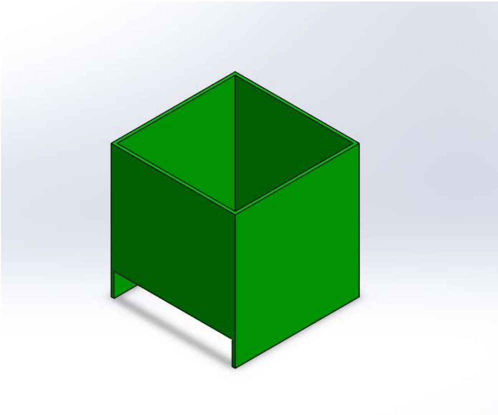


Fig. 10. Design of "the new box" without the side openings.

As observed in the previous figure, the upper recess of the box is maintained (for the introduction and removal of the bag by the user) as well as the lower recess (to allow the weighing of the bag, as well as its fall towards the container).

- One of the information signs is dispensed with, leaving only one red and one green light. The red light will come on when the weight of the bag is inappropriate (see Section 4.5), and the user will be instructed to proceed to remove the bag. The green light will indicate that the bag has the appropriate weight and that the procedure of moving the bag to the container is started.
- The RFID card reader is dispensed with. Instead, a QR reader is installed on the system to open the cover and identify the user. This will allow the system to read the codes on the bags.

In addition to the above differences, there is a resizing of the structure. The main reason is due to the fact that the absence of the generator and the X-ray receiver plate makes it possible to narrow them and this allows saving on material. Difference in sizes can be seen in Fig. 11.

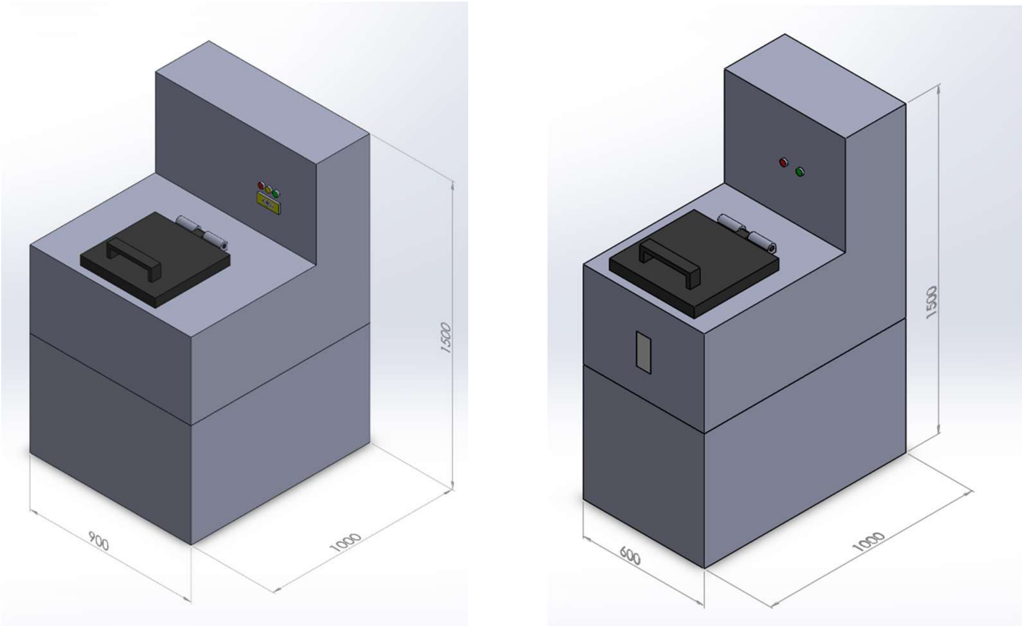


Fig. 11. Dimensions of the X-ray system design (left) versus those of the new system (right). The measures are in mm.

In the other hand the scale, frame and identification and control system (including the alarm system) are manteined. The scale now becomes more important since it is the only physical element that allows determining whether or not the bag is desirable for disposal in the container.

4.2.1 Bag identification

Various ways to identify the user have been studied, such as the test that has been carried out in Santa Pau and Can Blanch (Catalonia, Spain) [27]. In this test, users were identified thanks to an identification card that allowed them to use the system. In addition, the bags could be identified thanks to alphanumeric codes and thus be able to carry out subsequent inspections. In that system fraud was possible as containers were not locked and users could place regular garbage bags without any code. To avoid this, a system was designed which cannot be used without previous identification. A QR reader [8] detects the code of the bags to open the cover (see Fig. 12). In addition, this QR code allows the subsequent identification of the bags at the time of inspection.

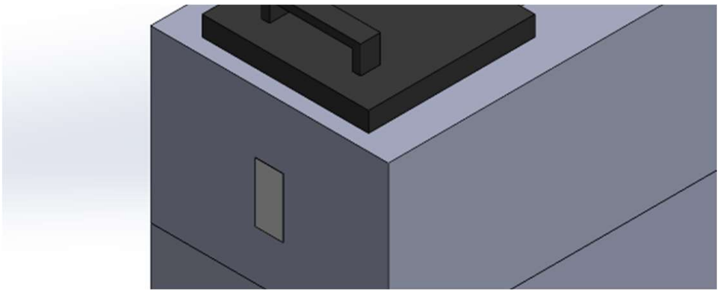


Fig. 12. QR code reader of the system (coloured white).

4.2.2 Bag inspection

To ensure that improper materials are not placed in the bags, there will be an inspection system. This task will be carried out by one or more workers at the triage plant. The tasks to be carried out consist of:

- Separation of a reduced number of bags, of random choice, for inspection.
- Subsequently and manually, the inspector will open the bag.
- Visually and quickly, it will carry out an inspection of the contents of the bag. The objective at this point is the detection of improper materials within it.
- If the bag does not contain a high quantity of improper materials it is returned to the plant process. In the event that too many improper items are observed, the inspector will perform a reading of the identification QR code of the bag and will issue a financial penalty to the user.

The objective of this inspection is to maintain efficiency by raising awareness. It is not a question of obtaining money thanks to the citizens disposing of their waste, but of promoting a responsible attitude among them, raising awareness and promoting a circular economy. With the system implemented in Santa Pau and Can Blanch, it was possible to reduce the improper percentage to 7% [27]. With the improvement of the identification and the incentive of the discount in the waste tax, it is expected to reduce this percentage even more.

4.3 SECURITY AND HEALTH

To maintain safety and hygiene, both for users and for workers, the elements of the previous system are maintained (see Section 3.3 Security and health), except those related to the effects produced by X-rays (the lead elements). In addition, this new system presents more safety for workers.

One of the main improvements in the security of this system compared to the current one is the transfer of personnel from a triage process to an inspection process. In triage, operators are exposed to high physical loads, blows and cuts with objects, falls of heavy weights, entrapment with moving objects, etc. However, inspections are safer processes as the workload is reduced (inspections are random on a small number of bags), and it is not as mechanical as conveyor triage process that can lead to increased operator fatigue and serious accidents such as entrapment.

4.4 IDENTIFICATION BAGS

The main purpose of these bags is to identify the user in order to grant the reward or, in case of incorrect use of the system, proceed to fine them. These are compostable bags that carried a QR code associated with a home, so they are for private use. These QR codes are different for each bag so the system can detect if a bag is used more than once. The bags are sent to the users but they are in charge of paying for the amount they need.

Fig. 13. Example of QR bags [27].

4.5 CRITERIA OF ACCEPTANCE

The weight limits are the same as in the previous system, and for the same reasons (see Section 3.5). Consequently, bags over 7 kg will be defined as undesirable and the user will be asked, using a red light, to remove it from the system. Bags weighing less than 1 kg will be accepted, but the user will not receive any compensation for them.

In this design there is no type of automatic detection of the amount of improper material present in the waste bag, so the percentage of improper will not determine if a bag is desirable or not in the system.

4.6 UTILIZATION PROCEDURE

The usage procedure is similar as in the previous design (Section 3.X-ray based system). The only difference is that, since there is no element that detects the amount of improper, a bag will not be rejected by the system due to the type of waste that is introduced. In addition, to be able to identify the users, the QR code of the bag must be brought close to the reader, instead of the identification cards of the previous design.

If the bag weighs less than 7 kg it is defined as desirable. The green light will come on, indicating that the user will receive a benefit. However, if the weight is less than 1 kg no light will come on. This indicates that the bag is accepted but no benefit is given by it.

In the event that the bag weighs more than 7 kg, the red light will illuminate, indicating to the user that the bag must be removed.

4.7 POWER SOURCE

To make a better comparison between the systems, it is decided that the energy source of this system is the same as that of the previous design (see Section 3.7). In any case, by dispensing with the X-ray system, the possibility of incorporating a solar panel into the system to provide the energy becomes feasible.

4.8 USER REWARD

Users will be rewarded in the same way as in the previous system (see Section 3.8). In addition, the penalty system comes into play in this system. In the event that a bag is found to contain a high percentage of improper material, an economic fine will be applied to the user (identified thanks to the QR code). In addition, the user will not receive the discount that would correspond to him that month for making an adequate separation.

4.9 ECONOMIC VALUATION

The purpose of this section is to clarify what the construction cost of this system would be, taking into account all the components previously explained. In the *Table 4* an estimated price for each element of the inspection based system is shown.

Maintenance and installation costs are not taken into account in Table 4. Only the prices of the elements that make up the system are shown. Therefore, the total estimate of the price of the elements to be able to build this system is estimated in 4462 €.

Table 4. Estimated price for each element of the inspection based system.

Element	Quantity	Observations	Price
Plastic elements	x 1	Recycled High Density Polyethylene	100 €
The box	x 1	-	10 €
QR reader	x 1	-	26 €
Weigh system	x 1	My Weigh HDSC	115 €
Mechanisms	-	Motor, sensors, etc.	60 €
Alarm system	x 1	Gsm, Mini 8 CH model	41 €
Software	x 1	-	4000 €
PLC system	x 1	-	80 €
Others (lights, etc.)	-	-	30 €
		TOTAL	**4462 €**

4.10 SWOT ANALISYS

A SWOT analysis is made in order to study the system.

Table 5. SWOT analysis of the inspection based system.

	Weaknesses	Strengths
Internal	- Non-automated improper detection process - Higher percentage of improper than in the X-ray based system	- Wide deposit time - Increase waste quality - Facelift of an extended but questioned system (underground containers) - Movement of workers to a less dangerous position
	Threats	**Opportunities**
External	- Poor discipline of citizens when using the system - Easy to trick the system	- Higher quality of the other waste fractions - Decrease of the rejected fraction - Higher involvement of the population in the matter of waste

5. PRELIMINARY ECONOMIC COMPARISON

In this section, an economic comparison of the two previously defined systems with the current system is made in order to subsequently reach certain conclusions about the viability of each one.

The main economic advantage of the proposed systems compared to the current system is the higher recovery efficiency and the saving of pre-treatment costs at the triage plants. Pre-treatments are the processes carried out to separate improper material from organic matter before composting or anaerobic digestion processes. These systems consume a large amount of energy that is reflected in the costs. Currently the treatment costs are in the gap of 50 – 70 €/t [16], depending on whether they will be used to make compost or biogas. Of these, it is taken as guidance that approximately 30% correspond to pre-treatment, about 18 €/t. The savings will be greater the more organic matter is collected. In practice, the incentive of money is expected to increase the amount collected, so that the rejected fraction decreases and it is also saved in the treatment of that fraction. In addition, a greater quantity and quality of compost and / or biogas would be generated, which is also economically valued. The X-ray based system is expected to obtain low enough percentages of improper materials (< 5%) to minimize pre-treatment so a very simple system can be assumed. Therefore, it is estimated that costs would be minimized (1 €/t approximately). On the other hand, a system based on inspections is known to decrease this percentage to 7% [27]. In the system proposed in this work, it is expected to reduce this figure thanks to the economic incentive. Pre-treatment costs are estimated to be reduced by 50% (9 €/t) in the inspection based system.

Table 6. Comparison of expected pre-treatment costs for the different systems.

	Actual system	**X-ray based system**	**Inspection based system**
Pre-treatment cost per tonne (€/t)	18 €/t	1 €/t	9 €/t
Pre-treatment cost per container	1183 €/year	66 €/year	591 €/year

To obtain the data of Table 6 an amount of 65.7 $t\ /year$ of OFMSW collection has been considered (see Annex 4). Compared to the current system, the X-ray system saves 1117 €/year in pre-treatment costs and the inspection system saves 591 €/year.

On the other hand, the lowering of the waste tax is obtained. As shown in Annex 4, each container will be available for approximately 125 homes. If each of them obtained the maximum annual discount of 60 € it would mean a maximum total reduction of 7500 € of waste rates. As explained above, this benefit is already provided to the user in other tests [27], but the same results were not always obtained. In this case it is expected to be able to balance this discount:

- Avoiding paying the landfill disposal costs of the organic fraction that is currently deposited in the rejected container.
- With the payments received for the collection and treatment of the organic matter.
- With the extra benefits acquired by obtaining a higher quality and quantity of compost, biogas and / or digestate of anaerobic digestion.
- With the lowering of maintenance costs due to the reduction of improper materials (they can cause damage to the equipment).

Taking into account just the saves of landfill costs and with the payments made by the Generalitat, the new systems obtain a positive balance of 3363 € per container per year (see Annex 4).

Regarding the cost of salaries no variation is taken into account. Personnel currently working at the triage plant would become part of the inspection team of the inspection based system. On the other hand, in the X-ray based system, these personnel should be transferred to the equipment maintenance team, since it has more delicate elements.

The rest of the costs can be seen in the Table 7. Maintenance costs reflected in this table include cleaning costs, as explained in Annex 4. Maintenance costs increase in the X-ray system due to its more delicate components.

Table 7. Comparison of expected costs for the different systems.

	Actual system	**X-ray based system**	**Inspection based system**
System	-	21 314 €	4462 €
Installation	-	2000 €	1000 €
Maintenance	93 €/year	606 €/year	93 €/year

Regarding the price of the current system and its installation, according to Table 7, it can be seen that it is zero. These are because the comparison is made between the assumption of installing the proposed systems and maintaining the current ones already installed. These are systems that provide a facelift to a current one already used.

Taking into account all the above costs, and as can be seen in Annex 4, the X-ray system obtains profitability from the thirty-ninth year (Table 13) while the inspection-based system obtains it from the tenth year (Table 14), both compared to the current system.

5.1 PRICE ESTIMATION FOR THE VIABILITY OF THE X-RAY BASED SYSTEM

The COVID-19 pandemic has limited the possibility to obtain information to carry out this project. Of all the companies contacted, only one has answered. For this reason, it is expected that, under normal conditions, lower prices could have been obtained for the components of the X-ray based system. In this subsection, an economic study is carried out to calculate what the price of the X-ray system would be so that this system would be profitable in less time. This study is carried out on this system because it is considered to be the most promising in terms of minimizing the percentage of improper material, as well as being the more innovative of the two proposed systems.

Table 8. Number of years in which the system shows a positive balance against different prices of the same.

System cost	Positive balance
10 078 €	20 years
7058 €	15 years
4039 €	10 years

Table 8 shows the price that the system should have to give profitability at different times. These calculations were carried out in the same way as in the previous section, simply modifying the initial investment of the system, but keeping the other costs the same.

As can be seen, it is necessary to reduce the cost of the system by 81% to reach a positive balance in 10 years. This is a fairly high percentage. The main costs that could be saved would be software (by manufacturing more than one system the unit price of the software is reduced) and the X-ray system. Assuming that the price of the software is kept to a minimum, the X-ray system would still have to cost 3355 €, implying a reduction in the price of this technology of almost 80%.

6. CONCLUSIONS

Literature review showed that the main characteristics that make an organic waste collection system work better are: (i) user identification, (ii) an economic reward for correctly carrying out waste separation, (iii) flexible hours and (iv) facility to use. The two systems designed in this project meet all these characteristics.

The X-ray based system is able to detect levels of improper low enough to lower the cost of pre-treatment at the triage plants and improve the quality the plant products. Besides that, its other main advantage is its automation, since it does not require personnel for its daily operation. On the contrary, it is an expensive system that requires a high initial investment.

On the other hand, the inspection based system does seem to have the necessary characteristics to reach the levels established by the European Directive and it has an economic balance that make it viable. Its main drawback compared to the previous system is the need for personnel to carry out the inspections. Even so, it is an innovative and viable system fit to meet the requirements.

6.1 RECOMMENDATIONS

Regarding future lines of research and study after this work, certain future research is proposed. First, carry out tests with real prototypes of both systems to verify their effectiveness. Regarding the X-ray system, it is necessary to test its real capacity to detect improper material inside an OFMSW bag before carrying out a field test. Moreover, carry out a deeper economic analysis of how the increase in the quality of the OFMSW (lower percentage of improper material) affects the final remuneration obtained through the generation of biogas or composting. Finally, study the implantation of the X-ray system in a location where the flow of organic waste is much higher (with larger containers), such as in a restoration area, in order to collect more waste and save more money with pre-treatment.

7. BIBLIOGRAPHY

1. Adjuntament de Barcelona. *Memoria de Costes 2017: INFORME CORPORATIVO* (p. 2). Barcelona, 2019.

2. AMB. *La recollida selectiva a la metròpolis arriba al màxim històric, mentre entren en funcionament els primers contenidors intelligents*, 2020, [Retrieved 14 April 2020]. Available at: http://www.amb.cat/ca/web/amb/actualitat/sala-de-premsa/notes-de-premsa/detall/-/notapremsa/la-recollida-selectiva-a-la-metropolis-arriba-al-maxim-historic--mentre/8797033/11696

3. Coll i Gelabert, E., Giró I Fontanals, F., Martín Gascon, P., Puig Ventosa, I., Álvarez Prado, L., Colomer I Missé, J., Salvans i Clusellas, C., Codina i Pujols, E., Segalés i Masmitjà, D., Aymemí i González, A., Llopart Gràcia, S. *Manual municipal de recollida selectiva porta a porta a Catalunya*. Barcelona: Associació de Municipis Catalans per a la Recollida Porta a Porta, 2007. ISBN: 978-84-932279-2-0.

4. Cuevas Asencio, P., González Cielos, N., Luna Sánchez, G., & Prior Hombrados, R. (2014). *Diseño de un sistema de recogida selectiva de materia orgánica* (Proyecto Fin de Master). Escuela de organización industrial.

5. Cullity, B. & Stock, S. *Elements of X-ray diffraction*. Pearson India Education Services, 2015.

6. Díaz, R. et al. *Development of a mechanical device for concealing underground urban solid residual containers*. Díaz, R., Sierra, J., Cortizo, J., Rodríguez, E. & Fernández, R. Materials and Design, 26 (2005), 602-608.

7. DIRECTIVA (UE) 2018/851 DEL PARLAMENTO EUROPEO Y DEL CONSEJO de 30 de mayo de 2018 por la que se modifica la Directiva 2008/98/CE sobre los residuos. 2018.

8. Docooler Escáner de código QR. (2020). Retrieved 9 June 2020, from https://www.amazon.es/Docooler-Esc%C3%A1ner-Escaneo-vers%C3%A1til-supermercados/dp/B07RVJXHZC/ref=sr_1_14?__mk_es_ES=%C3%85M%C3%85%C5%BD%C3%95%C3%91&dchild=1&keywords=lector+QR&qid=1591726141&sr=8-14

9. D'Onza, G., Greco, G., & Allegrini, M. (2016). Full cost accounting in the analysis of separated waste collection efficiency: A methodological proposal. *Journal Of Environmental Management*, *167*, 59-65. doi: 10.1016/j.jenvman.2015.09.002

10. Estudi de composició de residus municipals a Catalunya. (2009). Retrieved 22 March 2020, from http://residus.gencat.cat/ca/ambits_dactuacio/recollida_selectiva/residus_municipals/materia_organica_form_-_fv/generacio/estudi_de_composicio_de_residus_municipals_a_catalunya/

11. Font, X. et al. *Promoting circular economy in the surroundings of an organic fraction of municipal solid waste anaerobic digestion treatment plant: Biogas production impact and economic factors.* Abad, V., Avila, R., Vicent, T. & Font, X. Bioresource Technology 283 (2019) 10-17.

12. FVMP. *VALORACIÓN DE UN SISTEMA DE DEVOLUCIÓN, DEPÓSITO Y RETORNO AFECTACIÓN A LAS ENTIDADES LOCALES DE LA COMUNITAT VALENCIANA*. Valencia, 2016.

13. Gencat. *Definiciones*, 2009, [Retrieved 14 February 2020]. Available at: http://residus.gencat.cat/es/ambits_dactuacio/recollida_selectiva/residus_municipals/materia_organica_form_-_fv/que_es_la_form/definicions/

14. Gencat. *Densitat*, 2014, [Retrieved 13 March 2020]. Available at: <http://residus.gencat.cat/es/ambits_dactuacio/recollida_selectiva/residus_municipals/materia_organica_form_-_fv/que_es_la_form/densitat/>

15. Gencat. *Recogida neumática*, 2009, [Retrieved 9 April 2020].Available at: <http://residus.gencat.cat/es/ambits_dactuacio/recollida_selectiva/models_de_recollida/segons_sistema_de_recollida/recollida_pneumatica/>

16. Guerrero, T. (2013). *La gestión de la fracción orgánica de los residuos municipales en Cataluña*. Lecture, Barcelona.

17. Interempresas. *La tecnología de sensores de Titech x-tract recupera hasta el 95% de inertes de la basura orgánica*, 2013, [Retrieved 23 March 2020]. Available at: https://www.interempresas.net/Reciclaje/Articulos/110865-tecnologia-sensores-Titech-x-tract-recupera-hasta-95-por-ciento-inertes-basura-organica.html

18. Ministerio de Agricultura, Alimentación y Medio Ambiente. (2013). *Guía para la implantación de la recogida separada y tratamiento de la fracción orgánica*. Madrid.

19. Miteco. *Sistema de Recogida*, 2020, [Retrieved 13 April 2020]. Available at: https://www.miteco.gob.es/es/calidad-y-evaluacion-ambiental/temas/prevencion-y-gestion-residuos/flujos/domesticos/gestion/sistema-recogida/Neumatica.aspx

20. Miteco. *Sistemas de Recogida*, 2020, [Retrieved 17 March 2020]. Available at: <https://www.miteco.gob.es/es/calidad-y-evaluacion-ambiental/temas/prevencion-y-gestion-residuos/flujos/domesticos/gestion/sistema-recogida/Contenedores-superficie-soterrados.aspx>

21. Miteco. Sistemas de tratamiento. [Retrieved 14 April 2020]. Available at: https://www.miteco.gob.es/es/calidad-y-evaluacion-ambiental/temas/prevencion-y-gestion-residuos/flujos/domesticos/gestion/sistema-tratamiento/Tratamientos-mecanicos.aspx

22. My Weigh HDCS. (2020). Retrieved 28 March 2020, from https://www.balanzasdigitales.com/basculas-paqueteria/421-bascula-de-paqueteria-my-weigh-hdcs-60-kg.html

23. Picvisa. *Ecoglass Separador Óptico*. [Retrieved 16 April 2020]. Available at: https://picvisa.com/es/c/ecoglass-separador-optico-22#

24. Planchas de plomo. (2020). Retrieved 1 April 2020, from https://www.tucajadeherramientas.com/planchas-de-plomo-c-7_715.html

25. Retrieved 22 May 2020, from http://www.comansa.biz/pdf/14255.pdf

26. Rodrigues, L. et al. *The impact of improper materials in biowaste on the quality of compost*. Rodrigues, L., Puig-Ventosa, I., López, M., Martínez, F., Ruiz, A., & Bertrán. T. Journal of Cleaner Production, 251, (2020) 119601.

27. Saleh, D., Salova, M., Bulbena, B., Loderus, T., & Calaf Forn, M. *User identification for municipal waste collection in high-density contexts.* Barcelona, 2019.

28. Sistema de Alarma. (2020). Retrieved 23 May 2020, from https://www.amazon.es/Sistema-Llamada-inal%C3%A1mbrica-Inteligente-Seguridad/dp/B07MFSQPBF

29. Tarifas Punto Verde. (2020). Retrieved 1 May 2020, from https://www.ecoembes.com/es/empresas/ingresos-punto-verde/tarifa-punto-verde-por-material

30. UNE-EN 60529:2018 Grados de protección proporcionados por las envolventes (Código IP). 2018.

31. WHO. Ionizing radiation, health effects and protective measures. (2020). Retrieved 17 March 2020, from https://www.who.int/es/news-room/fact-sheets/detail/ionizing-radiation-health-effects-and-protective-measures

32. WHO. Lead poisoning and health. (2020). Retrieved 20 March 2020, from https://www.who.int/es/news-room/fact-sheets/detail/lead-poisoning-and-health

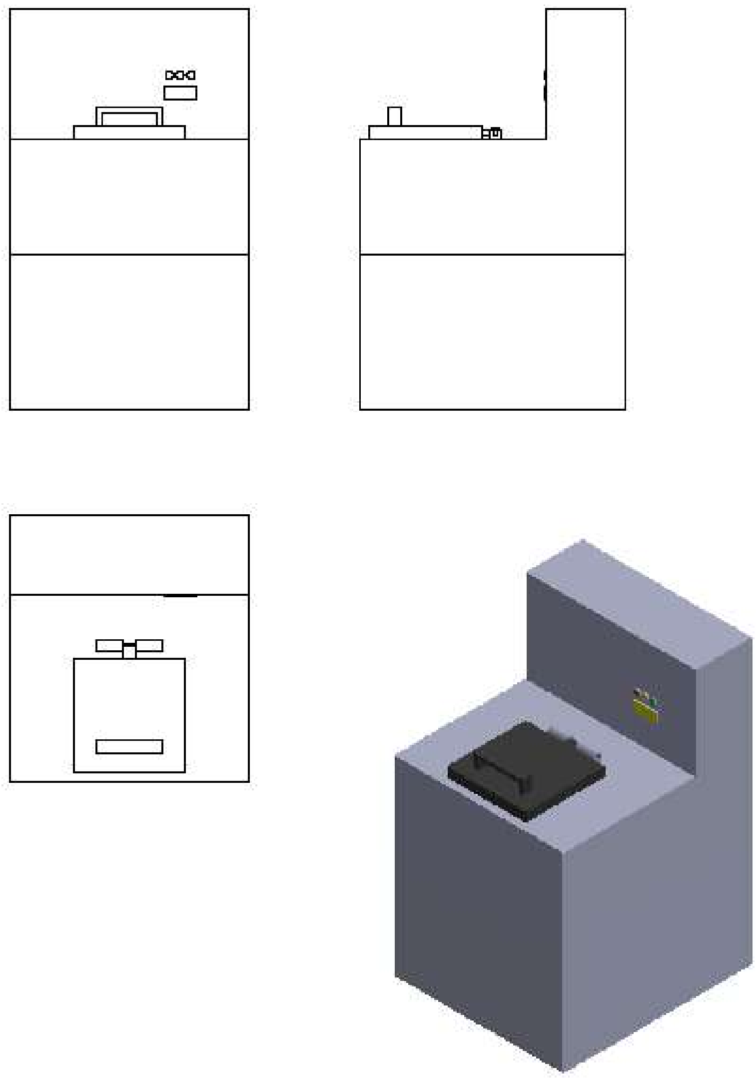
33. Agència de Residus de Catalunya, estadistiques. (2019). Retrieved 5 July 2020, from http://estadistiques.arc.cat/ARC/

34. Cánones sobre la disposición del desperdicio de los residuos municipales (2020). Retrieved 6 July 2020, from http://residus.gencat.cat/es/ambits_dactuacio/tipus_de_residu/residus_municipals/canons_sobre_la_disposicio_del_rebuig_dels_residus_municipals/index.html

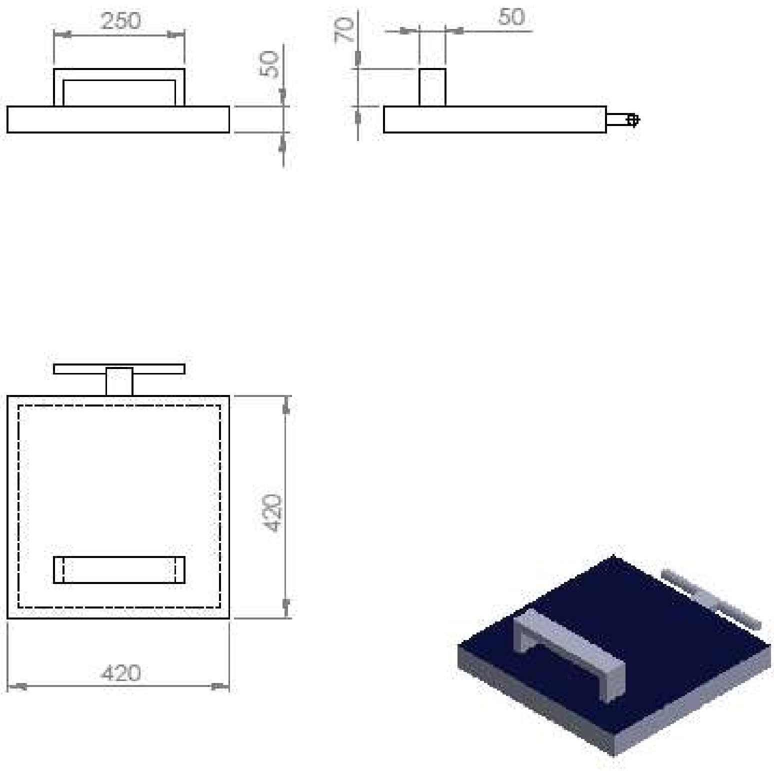
35. Agència de Residus de Catalunya. (2019). *Guia d'orientació als ens locals sobre l'aplicaciço del retorn dels cànons sobrel a disposició del rebuig dels residus municipals per l'any 2019.*

Annex 1

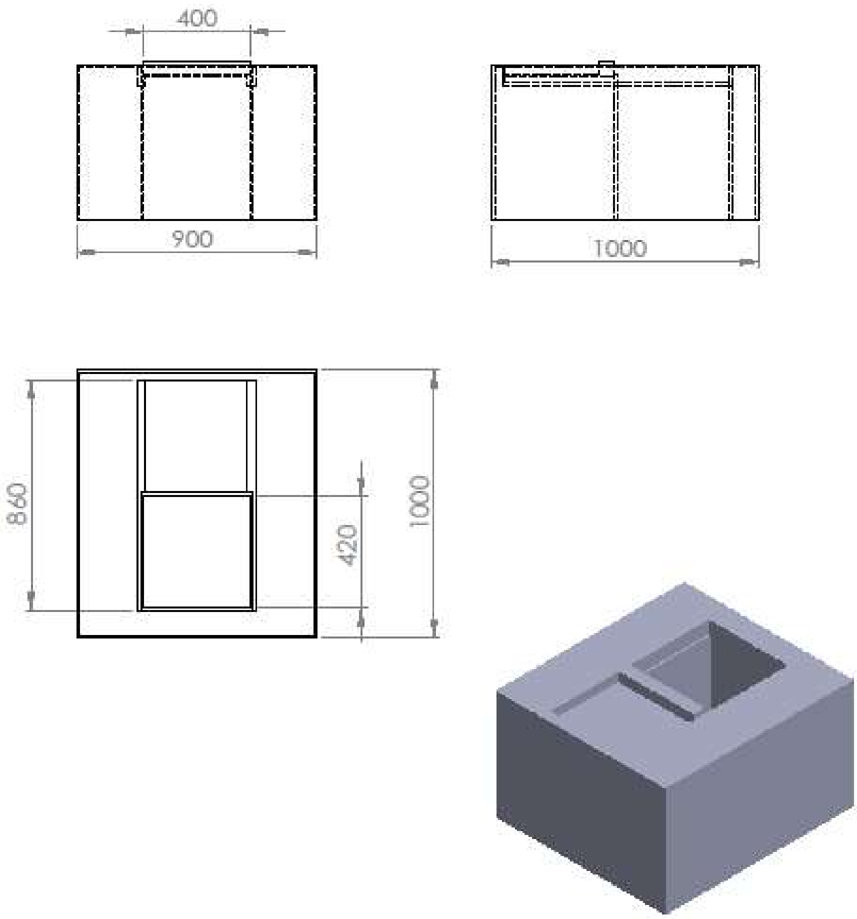
X-ray based system plans



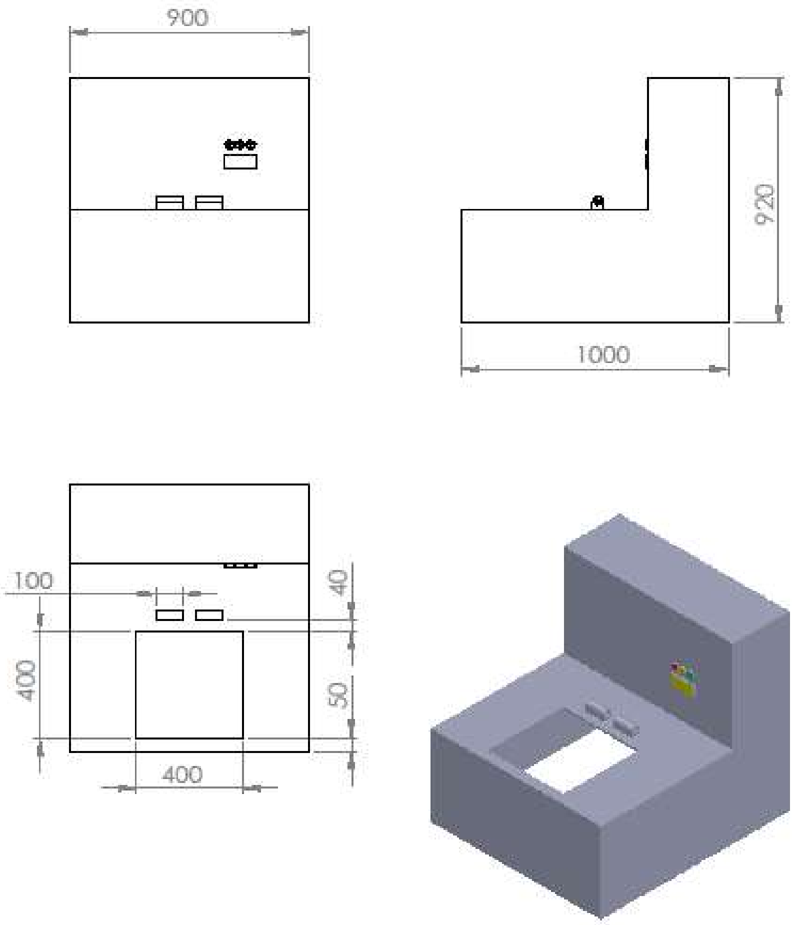
1:20 scale Measures are in mm	**X-ray based system: full system**	Plan 01



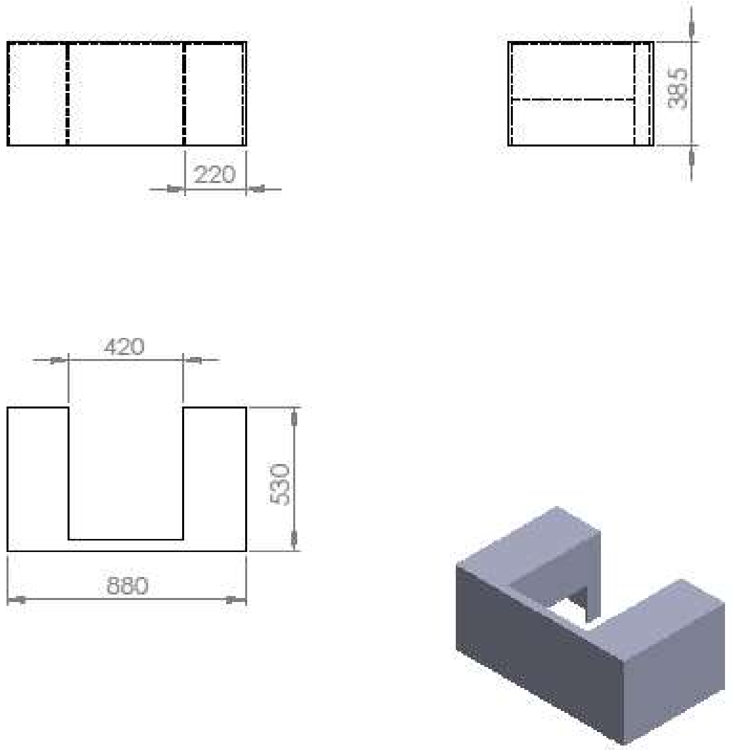
1:10 scale Measures are in mm	**X-ray based system: cover**	Plan 02



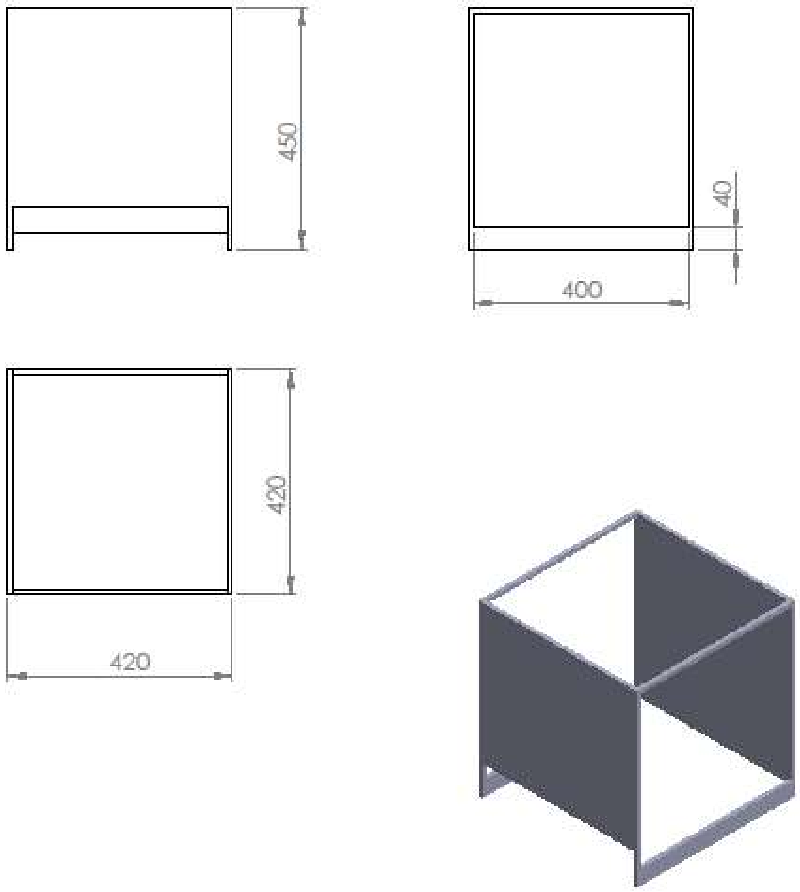
1:20 scale Measures are in mm	**X-ray based system: frame**	Plan 03



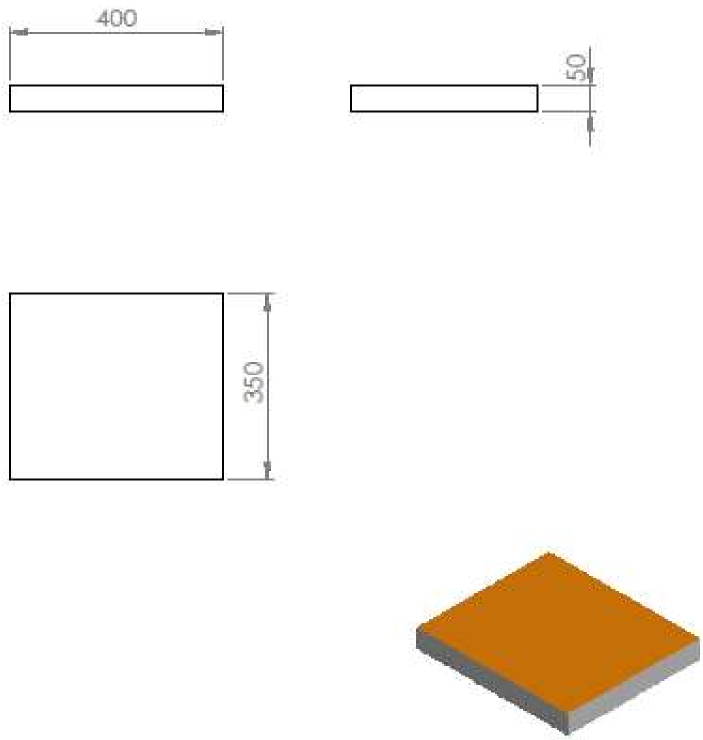
1:20 scale Measures are in mm	**X-ray based system: cover**	Plan 04



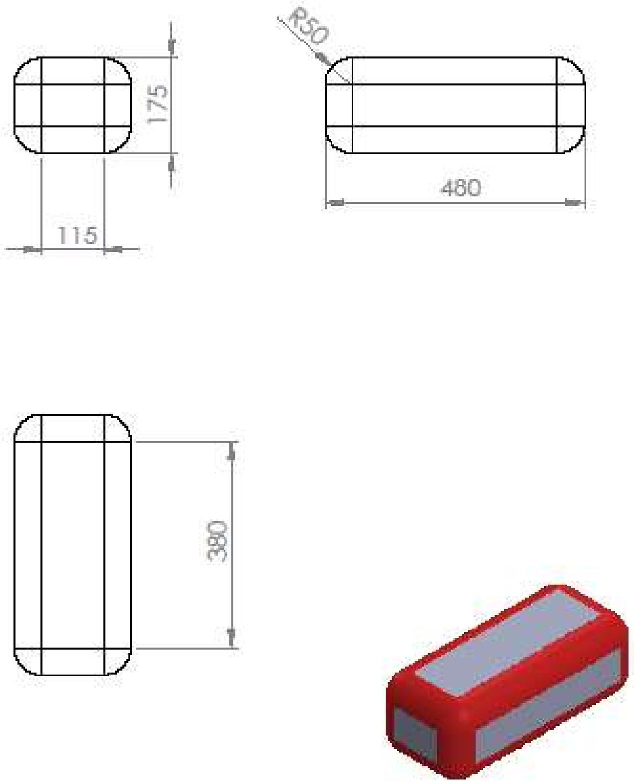
1:20 scale Measures are in mm	**X-ray based system: lead envelope**	Plan 05



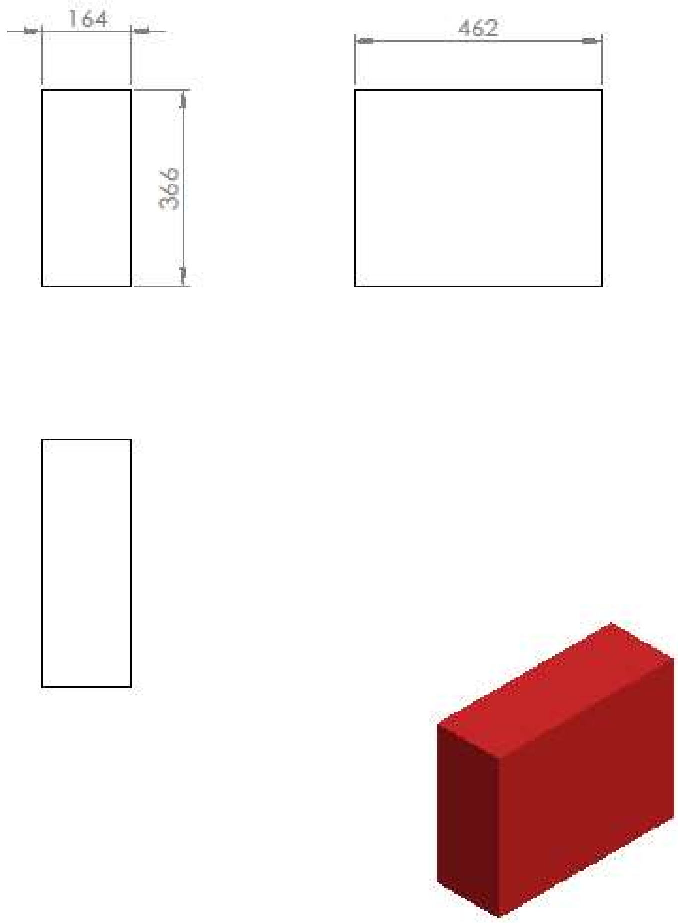
1:10 scale Measures are in mm	**X-ray based system: bag reception box**	Plan 06



1:10 scale Measures are in mm	**X-ray based system: weighing system**	Plan 07



1:10 scale Measures are in mm	**X-ray based system: X-ray generator**	Plan 08



1:10 scale Measures are in mm	**X-ray based system: X-ray repection board**	Plan 09

Annex 2

X-ray system specifications

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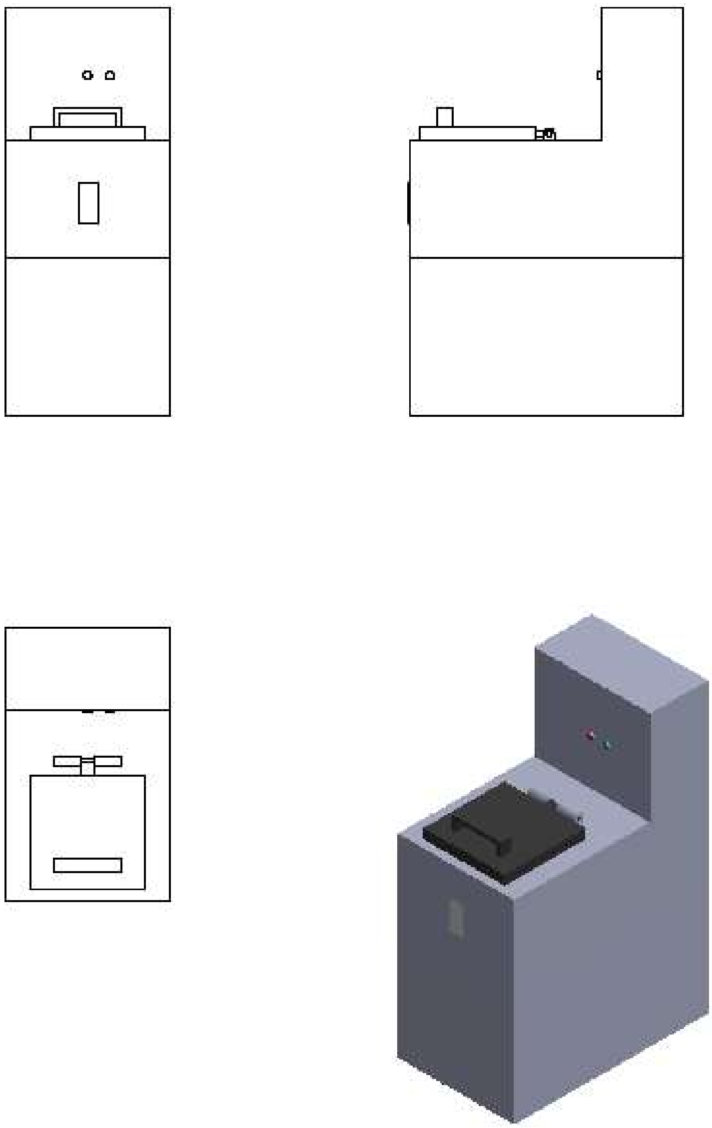
Table 9. X-ray generator and receiving board specifications.

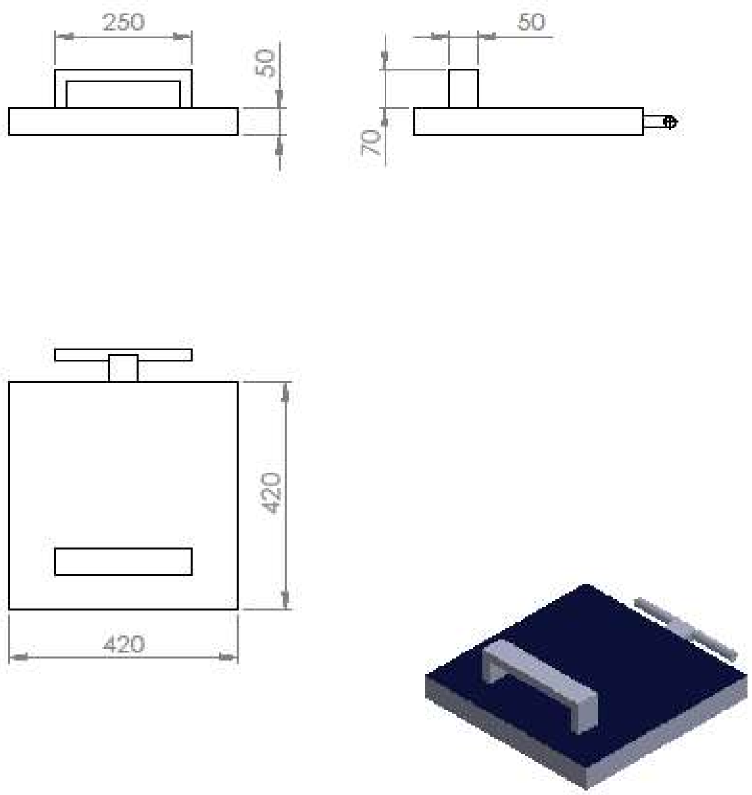
Portable X-ray scanner model SPX-6046P	
Wire resolution	40
Penetration	30 mm Steel / 140 m aluminium
Sensor type	Industrial CCD camera
Imaging array	1280*960 resolution
Effective imaging area	600 (w) *460 (h) mm
Image acquisition time	6 s
X-ray tube voltage	120 kV
X-ray source current	1 mA
Storage capacity	At least 10 000 images
Material classification	Dual energy colour display, organic exclusion, inorganic exclusion
X-ray generator dimensions	482 * 215 * 178 mm (L*W*G)
Detection board dimensions	462 * 366 * 164 mm (L*W*G)
Operating temperature	-15 ºC ~ + 50 ºC
Storage temperature	-40 ºC ~ + 70 ºC
charger features	Input: 100 V~240 V; 2.0 A Max Output: 42.0 V; 2.0 A
Battery	Rechargeable lithium ion battery (supports 500 images captures); 14.8 V; 5200 mAh

Annex 3

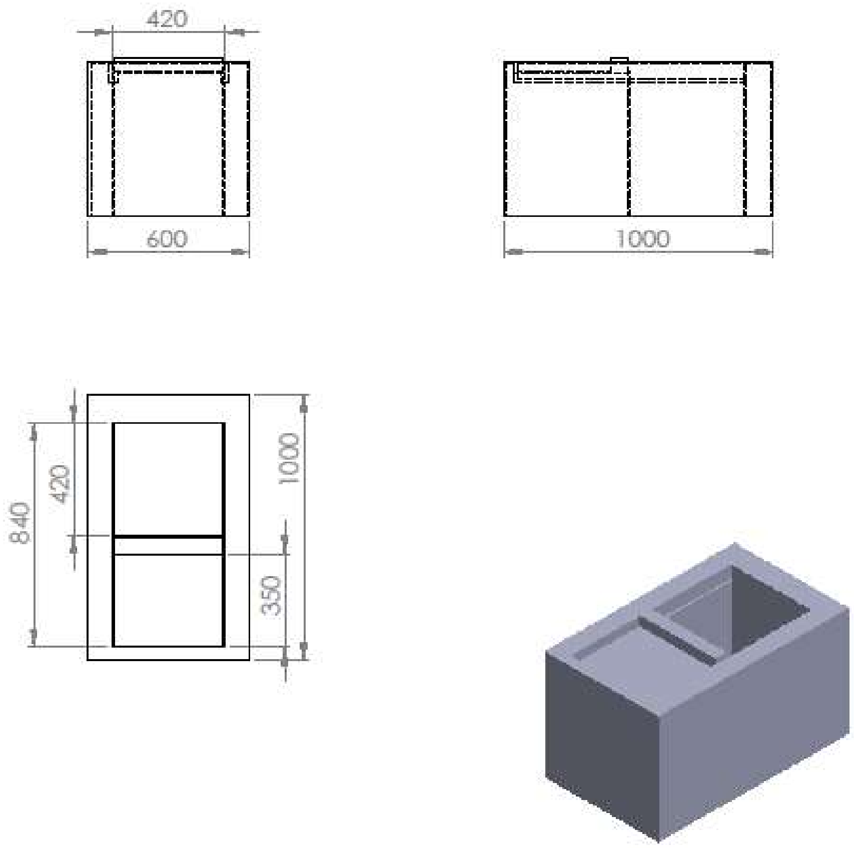
Inspection based system plans



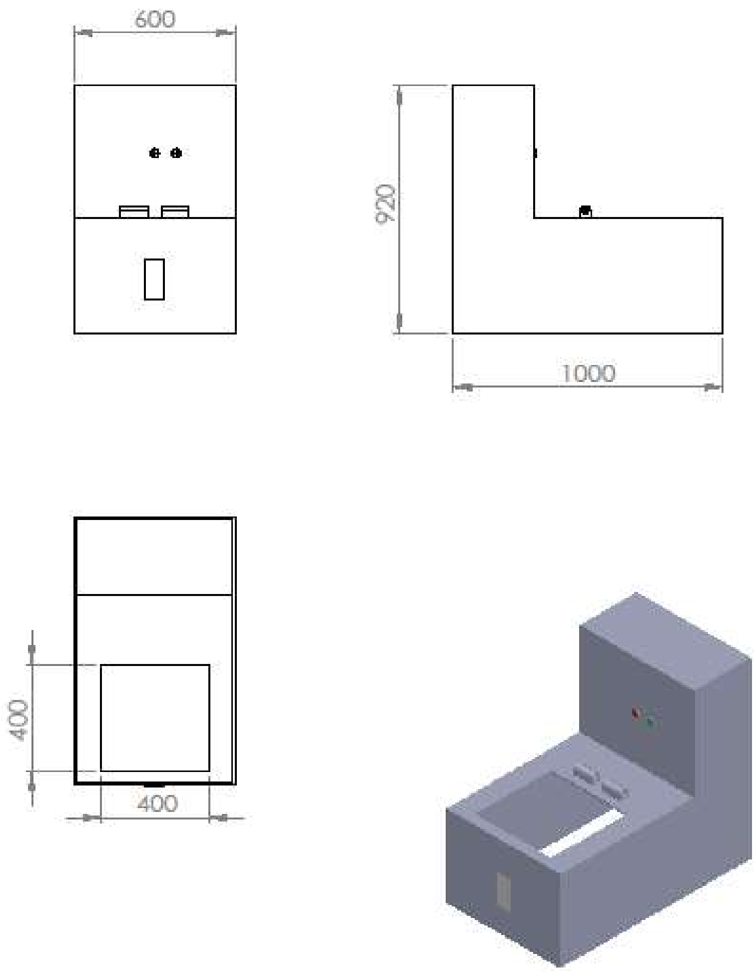
1:20 scale Measures are in mm	**Inspection based system: full system**	Plan 01



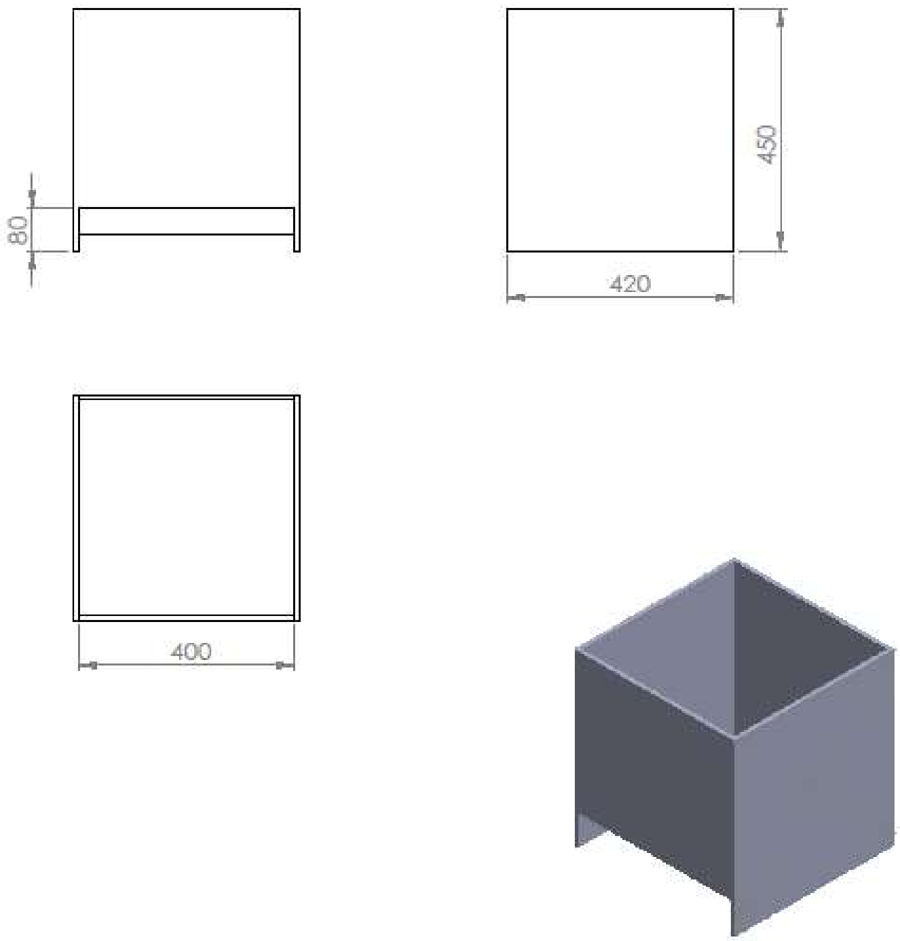
1:10 scale Measures are in mm	**Inspection based system: cover**	Plan 02



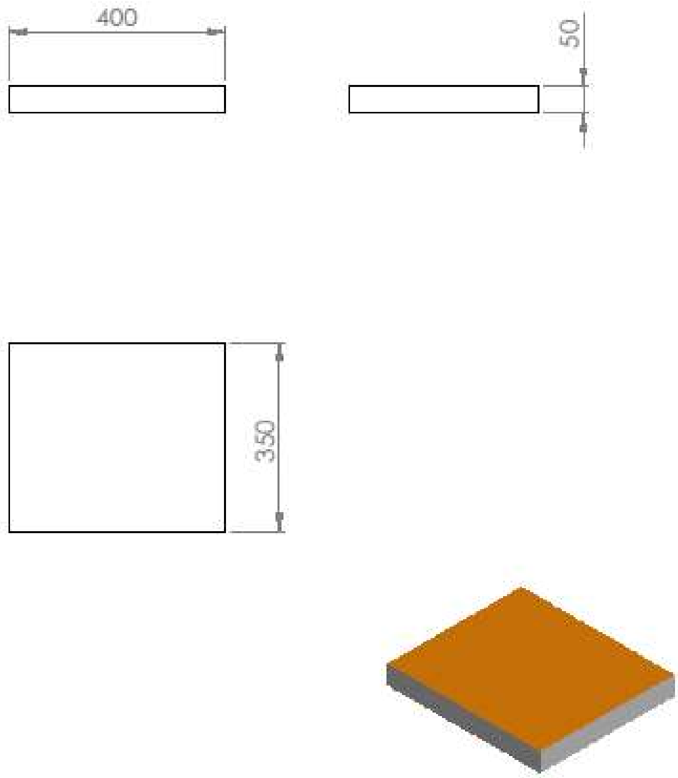
1:20 scale Measures are in mm	**Inspection based system: frame**	Plan 03



1:20 scale Measures are in mm	**Inspection based system: cover**	Plan 04



1:10 scale Measures are in mm	**Inspection based system: bag reception box**	Plan 05



1:10 scale Measures are in mm	**Inspection based system: weighing system**	Plan 06

Annex 4

Calculations

Calculation of the costs of plastic and lead materials.

To calculate the price of lead materials (lead envelope and the small cover) a 3D design software has been used. Using this software it was calculated that approximately 3 m^2 (2.60 m^2 for the frame and 0.18 m^2 for the cover) are needed. The price of 1 m^2 of 1 cm thick lead sheet is 46.15 € [24].

$$\frac{46.15\ €}{m^2} * 3\ m^2 = 138.45\ €$$

The same method has been used to calculate the plastic materials. Thanks to the 3D design software the volume of the plastic elements of both systems is known. On the other hand, knowing that the density of HDPE (High Density Polyethylene) is 0.00097 g/mm^3 and that the material price is 0.377 €/kg [29] costs for both systems can be calculated.

For the X-ray based system:

$$\text{Xray}\ system\ HDPE\ mass\ \approx 75\ kg$$

$$75\ kg * 0.377\ \frac{€}{kg} = 28\ €$$

For the inspection based system:

$$inspection\ based\ system\ HDPE\ mass\ \approx 64\ kg$$

$$64\ kg * 0.377\ \frac{€}{kg} = 24\ €$$

Taking into account the assembly costs structures are estimated to cost approximately 100 € each.

Calculation of the number of houses per container.

According to studies, the capacities of OFMSW containers are usually quite variable, but small containers of 240 litres of capacity serve approximately 80 users (about 25 homes) [18].

Using these data and knowing that underground containers reach capacities of almost 1200 litres [25], the number of homes that each container will serve is calculated:

$$users\ per\ container = 1200 * \frac{80}{240} = 400\ \frac{users}{container}$$

We can also calculate the number of houses per container:

$$users\ per\ home = \frac{80}{25} = 3.2\ \frac{users}{home}$$

$$homes\ per\ container = \frac{400}{3.2} = 125\ \frac{homes}{container}$$

Calculation of tons of organic matter collected per container.

As calculated in the previous section, the number of users per container is approximately 400. Knowing that each of them generates an average of about 450 grams [3] of OFMSW, the amount of organic matter that can be reached per container can be calculated:

$$400\ users * 0.45\ \frac{kg\ OFMSW}{user * day} * 365\ \frac{days}{year} * \frac{tn}{1000\ kg} = 65.7\ tn\ OFMSW/year$$

Calculation of savings in landfill fees and payments for collection and treatment of organic matter.

It is known that the organic fraction of municipal waste represents around 35% of the total [10]. Currently in Catalonia it is collecting over 10% [33]. Therefore, if the systems proposed in this project are capable of increasing this percentage up to 25% (approximately), more organic fraction would be collected, while less of it would be deposited in the rejected fraction. This means saving rejection management costs (landfill disposal costs) and obtaining benefits from the Generalitat by increasing the amount of organic matter collected.

- Annual saving of landfill costs for each container.

If the collected OFMSW accounts for 25% of the fractions and is known that a flow of 65.70 t/container*year is collected the total amount of waste can be calculated.

$$65.70 \frac{t\ of\ OFMSW}{year * container} * \frac{100}{25} = 262.80 \frac{t\ of\ waste}{year * container}$$

OFMSW currently represents 10% of the total.

$$\frac{10}{100} * 262.80 \frac{t\ of\ waste}{year * container} = 26.28 \frac{t\ of\ OFMSW}{year * container}$$

Knowing how much is collected and how much is expected to be collected, it can be approximated how much OFMSW stops being sent to the landfill.

$$65.70 \frac{t\ of\ OFMSW}{year * container} - 26.28 \frac{t\ of\ OFMSW}{year * container} = 39.42 \frac{t\ of\ OFMSW}{year * container}$$

Lastly, the annual savings for each container are calculated, knowing that the rate of waste entering the landfill is 41.30 €/t [34].

$$39.42 \frac{t\ of\ OFMSW}{year * container} * 41.30 \frac{€}{t\ of\ waste} = 1628.05 \frac{€}{year * container}$$

- Payment of the Generalitat for the generation and treatment of OFMSW [35].

$$39.42\ \frac{t\ of\ OFMSW\ treated}{year * container} * 34.00\ \frac{€}{t\ of\ OFMSW\ treated}$$

$$+\ 39.42\ \frac{t\ of\ OFMSW\ collected}{year * container} * 10.00\ \frac{€}{t\ of\ OFMSW\ collected}$$

$$= 1734.48\ \frac{€}{year * container}$$

- Taking into account the savings and payments of the two previous points, a positive balance of 3362.53 €/year*container is obtained respect to the current system.

Systems maintenance cost calculation.

The maintenance cost of the current underground container system is 57 €/year [9]. For the inspection based system is considered the same amount. On the other hand, the X-ray based system has more delicate components, so it is considered to multiply the usual price by 10 to stay within a safety margin. This yields a maintenance cost of 570 €/year.

In addition, the cost of cleaning must be taken into account. The cleaning cost is 36 € per year for the current system [9] and the same amount is applied to the other systems.

Adding all the previous costs, it is obtained that the current system needs a maintenance cost of approximately 93 €/year. The X-ray based system needs maintenance of 606 €/year and the inspection based system of 93 €/year. Therefore, compared to the current system, the cost of maintaining the X-ray system increases by 513 €/year.

Economic comparison calculations.

The following costs are compared to the current system. In this way, it is possible to know how much money over the current it is necessary to contribute and when that investment will provide benefits.

Table 10. Savings of the new systems compared to the current one.

	X-ray based system	Inspection based system
Pre-treatment	1117 €/year	591 €/year

Table 11. Initial investment costs of new systems.

	X-ray based system	Inspection based system
System	21 314 €	4462 €
Installation	2000 €	1000 €

Table 12. Annual costs of the designed systems against the actual one.

	Actual	X-ray based system	Inspection based system
Maintenance	93 €/year	606 €/year	93 €/year
Difference with the current system	-	513 €/year	0 €/year

Table 13. Annual balances of the X-ray based system compared to the current system.

	Costs(€)	*Savings(€)*	*Balance (€)*
year 1	23 827	1117	-22 711
year 2	513	1117	-22 107
year 3	513	1117	-21 503
year 4	513	1117	-20 899
year 5	513	1117	-20 295
year 6	513	1117	-19 691
year 7	513	1117	-19 087
year 8	513	1117	-18 483
year 9	513	1117	-17 879
year 10	513	1117	-17 275
year 11	513	1117	-16 672
year 12	513	1117	-16 068
year 13	513	1117	-15 464

	Costs(€)	*Savings(€)*	*Balance (€)*
year 14	513	1117	-14 860
year 15	513	1117	-14 256
year 16	513	1117	-13 652
year 17	513	1117	-13 048
year 18	513	1117	-12 444
year 19	513	1117	-11 840
year 20	513	1117	-11 236
year 21	513	1117	-10 633
year 22	513	1117	-10 029
year 23	513	1117	-9425
year 24	513	1117	-8821
year 25	513	1117	-8217
year 26	513	1117	-7613
year 27	513	1117	-7009
year 28	513	1117	-6405
year 29	513	1117	-5801
year 30	513	1117	-5197
year 31	513	1117	-4594
year 32	513	1117	-3990
year 33	513	1117	-3386
year 34	513	1117	-2782
year 35	513	1117	-2178
year 36	513	1117	-1574
year 37	513	1117	-970
year 38	513	1117	-366
year 39	513	1117	238
year 40	513	1117	842

Table 14. Annual balances of the inspection based system compared to the current system.

	Costs(€)	*Savings(€)*	*Balance (€)*
year 1	5462	591	-4871
year 2	0	591	-4279
year 3	0	591	-3688
year 4	0	591	-3097
year 5	0	591	-2505
year 6	0	591	-1914
year 7	0	591	-1323
year 8	0	591	-732
year 9	0	591	- 140
year 10	0	591	451
year 11	0	591	1042
year 12	0	591	1634
year 13	0	591	2225
year 14	0	591	2816
year 15	0	591	3408
year 16	0	591	3999
year 17	0	591	4590
year 18	0	591	5181
year 19	0	591	5773
year 20	0	591	6364