Universitat de Lleida

Millora dels sistemes de recollida pneumàtica de residus sòlids urbans

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TESI DOCTORAL

Millora dels sistemes de recollida pneumàtica de residus sòlids urbans

Josep Antoni Farré Cabanillas

Memòria presentada per optar al grau de Doctor per la Universitat de Lleida
Programa de Doctorat en Tecnologies de la informació

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2024

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Universitat de Lleida

Departament d'Enginyeria Industrial i de l'Edificació

Escola Politècnica Superior

Universitat de Lleida

Millora dels sistemes de recollida pneumàtica de residus sòlids urbans

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CERTIFICA:

Que la memòria "Millora dels sistemes de recollida pneumàtica de residus sòlids urbans" presentada per Josep Antoni Farré Cabanillas per optar al grau de Doctor s'ha realitzat sota la seva supervisió.

Lleida, maig de 2024

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Summary

The globalized world, as well as each one of their countries, faces the challenge of mitigating the climatic impact that humanity has on planet earth. The emissions reduction, reduction of waste generation, circular economy, improvement of recycling rates to mitigate the consumption of raw materials, etc., are relevant challenges for a planet with limited resources. All of them described as an objective in the UN SDG (Sustainable Development Goals). Each part of the challenge requires concrete tools and processes that must be analysed individually and together.

In waste sector there are different lines of work focused on the elimination and reduction of generation, but very little emphasis has been placed on the analysis of the management, basically focused of the collection of municipal waste generated.

We are fully aware that there are different technologies for waste collection, both traditionally and more advanced systems such as pneumatic waste collection, among others. Pneumatic collection is an already consolidated system with some implementations in the most sustainable and smart cities of the planet (such as Paris, Singapore, Barcelona, Tel-Aviv), and we just need to see how countries like Israel or Singapore have made it mandatory in those cases where the population density is medium-high. Even so, the technology still has room for improvement since it is a system that evolves continuously with new technologies (such as artificial intelligence - AI).

For this reason, the thesis carries out an analysis of the different approaches to improve the AWCS for municipal waste. These possible improvements of the pneumatic system have been analysed from all possible points of view. Circular economy with the aim of increasing the useful life of the technology, basically in the buried pipe network. Analysis of the environmental impact of the system with respect to other existing management systems on the market (regardless of the collection modality). Analysis of different options for the implementation of the pneumatic system, in all its possible variants and options. And finally at the level of improvements at the level of energy efficiency based above all on the incorporation of AI in the selection process of inlets to be collected (reduction of energy consumption).

Resum

El món globalitzat, així com cadascun dels països, s'enfronten al desafiament de mitigar l'impacte climàtic que té la humanitat al planeta terra. La reducció d'emissions, la reducció de la generació de residus, l'economia circular, la millora dels índexs de reciclatge per mitigar el consum de matèries primeres, etc, són desafiaments rellevants per a un planeta amb recursos limitats. Tots ells descrits com a Objectius de Desenvolupament Sostenible (ODS). Cada part del desafiament necessita eines i processos concrets que cal analitzar individualment i en conjunt. Al sector dels residus hi ha diferents línies de treball enfocades a l'eliminació i reducció de la generació, però s'ha fet molt poc èmfasi en l'anàlisi de la gestió de la recollida dels residus municipals generats.

Coneixem perfectament les diferents tecnologies que hi ha per a la recol·lecció dels residus tant a nivell tradicional, com de sistemes més avançats com són la recollida pneumàtica de residus, entre d'altres. La recollida pneumàtica és un sistema ja consolidat i amb certa implantació a les ciutats més sostenibles del planeta com són París, Singapur, Barcelona, Tel-Aviv, etc. Tan sols cal veure com països com Israel o Singapur han implantat la seva obligatorietat en aquests casos on la densitat de població és mitjana-alta. Tot i així, la tecnologia té encara marge de millora ja que és un sistema que evoluciona de forma contínua amb les noves tecnologies.

Per aquest motiu la tesi duu a terme una anàlisi dels diferents enfocaments per la millora del sistema de recollida pneumàtica de residus municipals. Aquestes possibles millores del sistema pneumàtic han estat analitzades des de tots els punts de vista possible. Economia circular amb l'objectiu d'incrementar la vida útil de la tecnologia, bàsicament a la xarxa de canonades soterrades. Anàlisi de l'impacte ambiental del sistema respecte a altres sistemes de gestió existents al mercat (sigui quina sigui la modalitat de recollida). Anàlisi de diferents opcions d'implantació del sistema pneumàtica, en totes les seves variants i opcions possibles. I finalment a nivell de millores a nivell deficiència energètica basada sobretot en la incorporació d'Intel·ligència Artificial en el procés de selecció de bústies a recollir (reducció consum energètic).

Resumen

El mundo globalizado, así como cada uno de los países se enfrentan al desafío de mitigar el impacto climático que tiene la humanidad en el planeta tierra. La reducción de emisiones, reducción de la generación de residuos, economía circular, mejora de los índices de reciclaje para mitigar el consumo de materias primas, etc, son desafíos relevantes para un planeta con recursos limitados. Todos ellos detallados como los Objetivos de Desarrollo Sostenible (ODS). Cada parte del desafío precisa de herramientas y procesos concretos que deben analizarse individualmente y en conjunto. En el sector de los residuos existen diferentes líneas de trabajo enfocadas a la eliminación y reducción de la generación, pero se ha realizado muy poco énfasis en el análisis de la gestión de la recogida de los residuos municipales generados.

Conocemos perfectamente que existen diferentes tecnologías para la recolección de los residuos tanto a nivel tradicional, como de sistemas más avanzados como son la recogida neumática de residuos, entre otros. La recogida neumática es un sistema ya consolidado y con cierta implantación en las ciudades más sostenibles del planeta como son París, Singapur, Barcelona, Tel-Aviv, etc. Y tan solo hace falta ver como países como Israel o Singapur han implantado su obligatoriedad en esos casos donde la densidad de población es media-alta. Aun así, la tecnología tiene aún margen de mejora ya que es un sistema que evoluciona de forma continua con las nuevas tecnologías.

Por este motivo la tesis lleva a cabo un análisis de los diferentes enfoques para la mejora del sistema de recogida neumática de residuos municipales. Estás posibles mejoras del sistema neumático han sido analizadas desde todos puntos de vista posible. Economía circular con el objetivo de incrementar la vida útil de la tecnología, básicamente en la red de tuberías enterradas. Análisis del impacto ambiental del sistema respecto a otros sistemas de gestión existentes en el mercado (sea cual sea la modalidad de recogida). Análisis de diferentes opciones de implantación del sistema neumática, en todas sus variantes y opciones posible. Y finalmente a nivel de mejoras a nivel de eficiencia energética basada sobre todo en la incorporación de Inteligencia Artificial en el proceso de selección de buzones a recoger (reducción consumo energético).

Nomenclature

AWCS	Automatic Waste Collection System
PWCS	Pneumatic Waste Collection System
MSW	Municipal Solid Waste
LCA	Life Cycle Assessment
USW	Urban Solid Waste
SDG	Sustainable Development Goals
PAYT	Pay As You Throw
KAYT	Know As You Throw
CAGR	Compound Annual Growth Rate
KPI	Key Performance Indicators

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Chapter 1. Introduction and PhD Objectives

1.1. Introduction

1.1.1. Global progress of the waste generation

Between 2010 and 2020, total per capita waste generation decreased by 4.2% in the EU. The EU aims to significantly decrease its total waste generation by 2030 and the observed decrease could indicate some progress towards this. However, the decrease is recent (2018-2020) and coincides with the slow-down of the EU economy due to the COVID-19 pandemic. Waste generation has followed trends in economic growth relatively closely. It therefore does not seem likely that waste generation will significantly decrease by 2030 in context of the current return to economic growth. Substantial additional effort would be required to sustain the decrease in waste generation.

In 2020, the amount of municipal waste generated per person in the EU amounted to 505 kg, 4 kg more municipal waste than in 2019 and 38 kg more than in 1995. In total, the EU generated 225.7 million tonnes of municipal waste in 2020 (Figure 1).

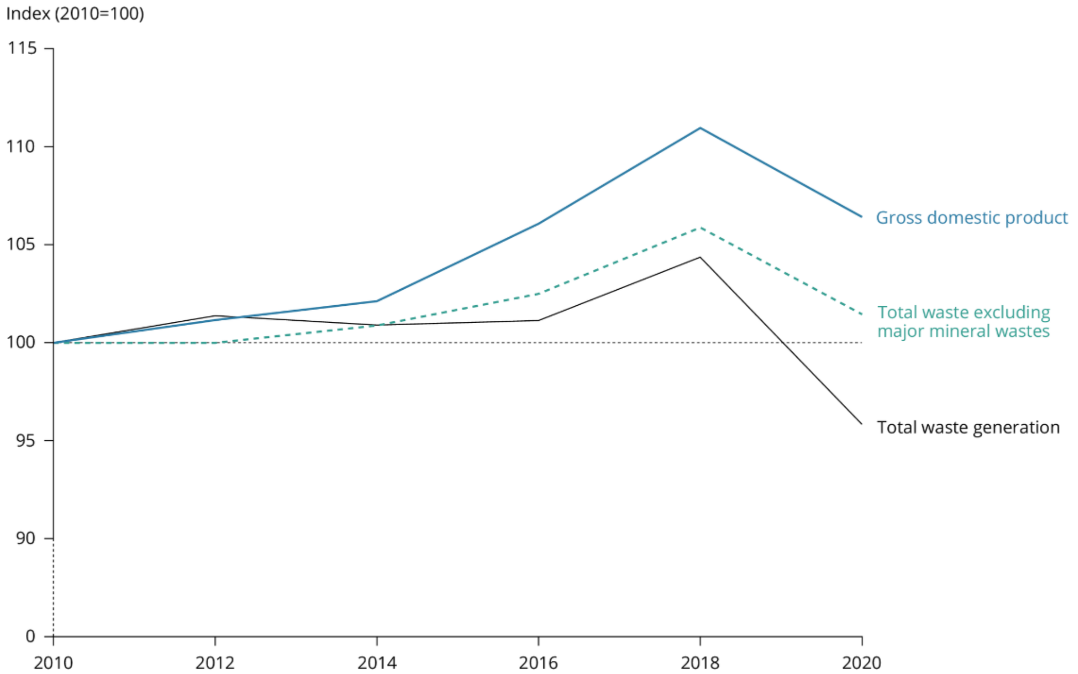

Figure 1. Waste generation and decoupling per capita in the EU-27 (European Environmental Agency, 2023)

Municipal waste generation varied considerably among the EU Member States (Figure 2). In 2020, Denmark and Luxembourg were the highest generators of municipal waste, with 845 kg and 790 kg per capita, respectively, followed by Malta (643 kg) and Germany (632 kg). Romania (287 kg), Poland (346 kg), and Hungary (364 kg) led in terms of registering the fewest municipal waste generation per person this year.

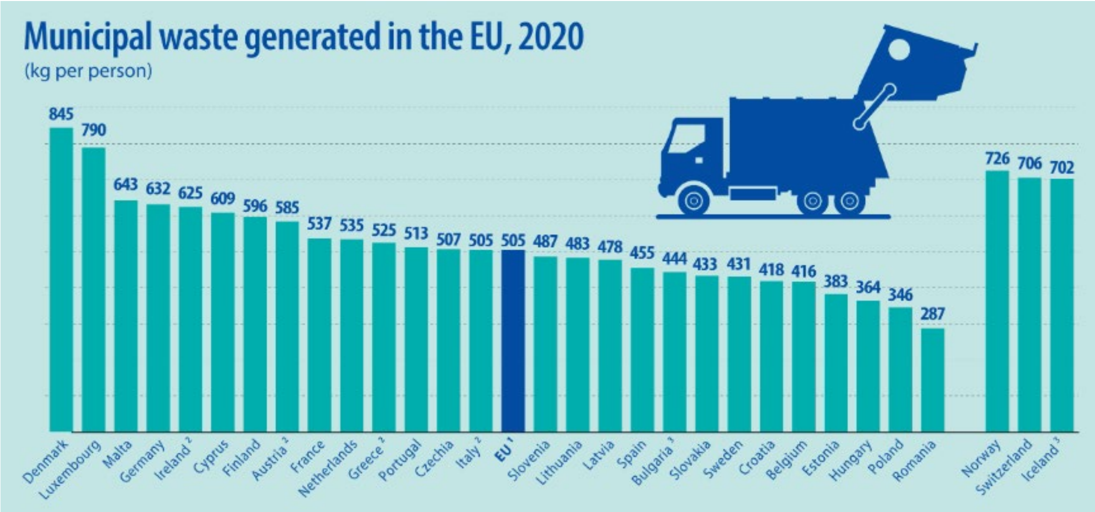

Figure 2. Municipal waste generated in the EU in 2020 (World Economic Forum, 2022)

Compared to 1995, only seven Member States generated less municipal waste per person in 2020: Bulgaria (-36%), Hungary (-21%), Slovenia (-18%), Romania (-16%), Spain (-10%), Belgium (-9%), and the Netherlands (-1%). The variations across countries reflect differences in consumption patterns and economic wealth and also differences in the collection and management of municipal waste. Countries differ regarding how much waste from commerce, trade and administration is collected and managed together with the waste from households. 67 million tonnes of municipal waste recycled in 2020. The amount of recycled waste remained stable in 2020. Recycling of materials fell to 67 million tonnes from 68 million tonnes in 2019, corresponding to 151 kg per person (same as in 2019). Compared to 1995, it means people in the EU recycled 44 million tonnes (97 kg per capita) more than in 1995.

In spite of the EU generating more waste, the total amount of municipal waste landfilled diminished. In 2020, the total municipal waste landfilled fell from 121 million tonnes in 1995 to 52 million tonnes (-58%). This corresponds to an average annualized decline of 4%. There is a very distinct trend towards less landfilling as countries move steadily towards alternative ways of treating waste.

Municipal waste accounts for only about 10 % of total waste generated when compared with the data reported according to the Waste Statistics Regulation (Figure 3). However, it has a very high political profile because of its complex character, due to its composition, its distribution among many sources of waste and its link to consumption patterns.

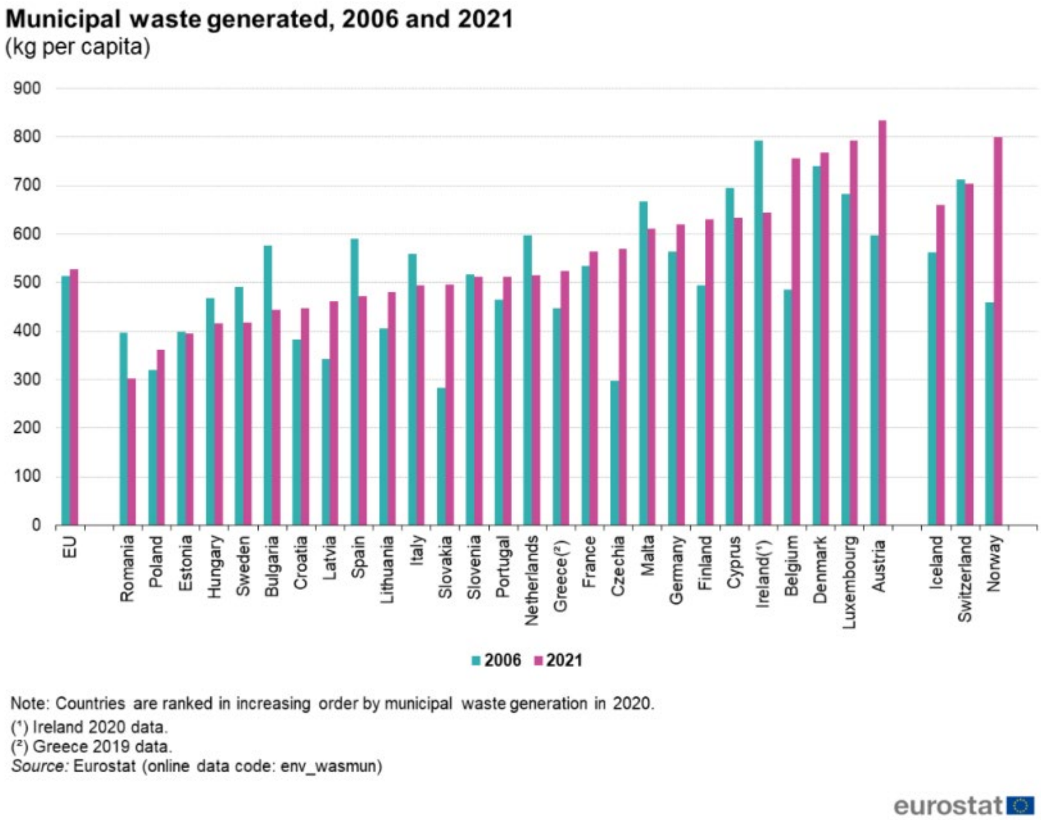

Figure 3. Municipal waste generated in Europe between 2006 and 2021, in kg per capita (Ciuła et al., 2023)

Increase in waste generation globally

Every year, the world produces 2.01 billion tonnes of municipal solid garbage, with at least 33% of that not being handled in an environmentally responsible way. The average amount of garbage produced per person each day in the world is 0.74 kilograms; however, the variation is wide, from 0.11 to 4.54 kilograms. High-income nations produce around 34%, or 683 million tonnes, of the world's waste despite having just 16% of the global population. By 2050, it is anticipated that there may be 3.40 billion tonnes of trash generated globally, more than doubling the population during that time. The generation of garbage and income level are generally positively correlated.

Compared to low- and middle-income countries, where it is anticipated to rise by roughly 40% or more, daily per capita trash creation in high-income countries is projected to rise by 19% by 2050. When income levels fluctuate incrementally, waste creation initially declines at the lowest income levels and subsequently rises more quickly than at higher income levels. By 2050, it is anticipated that the overall amount of waste produced in low-income nations may have increased by more than three times. The Middle East & North African region produces the least amount of waste globally, at 6.0%, whereas East Asia and the Pacific account for 23% of global waste production.

The fastest increasing regions, however, are Sub-Saharan Africa, South Asia, and the Middle East & North Africa, whereby 2050, it is anticipated that the total amount of garbage generated may more than quadruple, double, and double, respectively (Figure 4). More than half of the waste in these areas is currently disposed of openly, and the trajectory of waste increase may have significant negative effects on the environment, human health, and economic growth, necessitating immediate action. Key factors that are driving the market are the increasing demand for smart city solutions, government initiatives, and regulations to promote sustainable development.

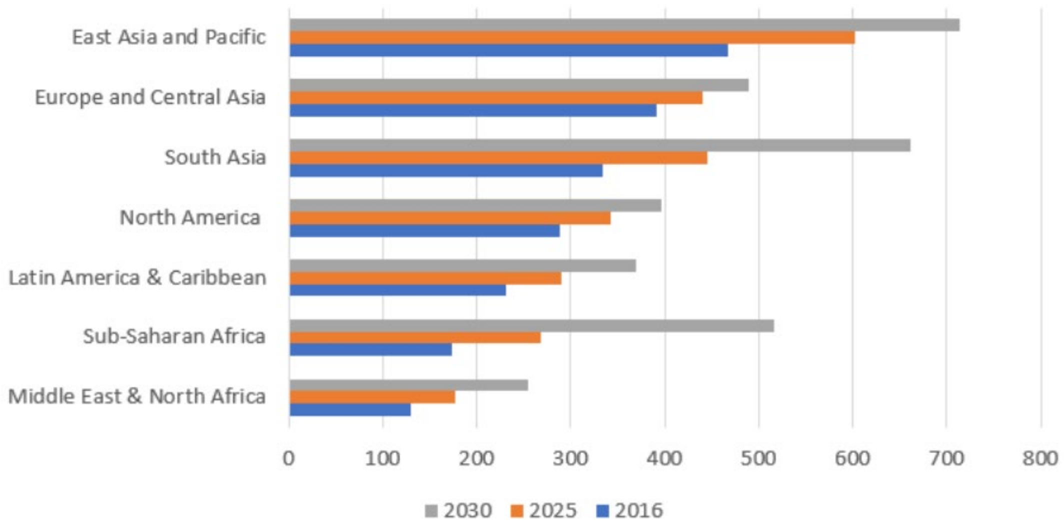

Figure 4. Projected waste generation by region, in millions of tonnes per year (Mordor Intelligence, 2023)

Increasing demand for smart city solutions

Globally, governments are spending billions to build smart cities. In 2050, or 30 years from today, 6.5 million people will live in smart cities, according to the Sustainable development objectives of the United Nations. There is an increasing need for creative ways to handle urban difficulties like garbage management as more and more communities attempt to become "smart cities" around the world.

With a growing emphasis on sustainability, energy distribution, mobility, health, and security, smart city projects are being created. Investment in a contemporary garbage collection and management system becomes crucial for these cities of the future with the greatest technical improvement and sophisticated methods to care for people requirements.

One such technology that is gaining popularity in the sector is pneumatic garbage collection systems. The market for pneumatic waste management systems is being driven by the rising demand for smart city solutions since they provide an eco-friendly and effective waste management solution that can be integrated with other smart city technologies to optimize waste collection and reduce costs while improving the quality of life for city residents.

1.1.2. Global progress of the pneumatic waste collection system

Sustainable waste management promotes less waste generation, reuse and recycling as well as waste recovery. This includes more intelligent methods and systems using for waste managing and processing.

Such technology has the power to completely displace conventional methods for the collection and transportation of household waste. However, a more detailed study the advantages and disadvantages of such systems is need. Although the transition to such innovative systems is not technically and financially easy, should not be forgotten that a social initiative and cooperation of the inhabitants is needed, so that such projects can be implemented, not only in a new neighbourhood, but also in already established residential areas. At first glance, such a transition seems difficult and lengthy, but it can be a significant step towards sustainable urban development, because it takes into account the environment and habitat of society. In addition, this paper discusses aspects of the Automatic Waste Collection Systems and their effects on the environment and human health. Clarifying the above, supposes facilitating all stakeholders, when making decisions, related to urban changes, and better informed about the Automates Waste Collections System.

The automated waste collection system market has witnessed significant growth in the past decade. Local authorities and governments of developing countries are focusing and investing on waste management system to reduce waste traffic in streets of urban areas and preserve human health. A number of players in the automated waste collection system industry are expanding their business to strengthen their foothold in the global market. By type, the pneumatic or vacuum system dominated the automated waste collection system market in 2020, in terms of revenue. This is attributed to rapid rise in urbanization and infrastructure projects where pneumatic waste collection systems are installed.

In the age of Industry 4.0, technology and data analytics are transforming industries, and the waste management sector is not exception. One of the most prominent advancements in this field is the Automated Waste Collections System (AWCS), a cutting-edge solution that holds immense potential for industrial waste reduction. Global automated waste collection system market is set to grow with a 10.19% CAGR (Compound Annual Growth Rate) by 2032, generation 750.77 million in revenue during the forecast period 2023-2032.

One of the key features of AWCS is its ability to provide real-time analytics. Another key feature its possibility to add systems to improve the recyclability ratio and also improve the user's control focused as PAYT system (Pay as You Throw), KAYT (Know As You Throw), weight control, user's identification, etc. All of that features with the goal to achieve better recycling rate than track waste collection and also to improve environmental and human health. On that way AWCS can monitor waste generation patterns, identify waste-intensive processes, and implement targeted waste reduction strategies.

1.2. PhD Objectives

According to the global objectives, there are many variables that can affect to the improvement of the waste management current systems. One of these it could be the AWCS and their improvement in different ways. According to available literature in 2030 more than 70% of the global population will be in big cities, so the objective to improve waste management systems It becomes much more relevant.

The introduction section identified the state of the art of AWCS to evaluate the Technology Readiness Level (TRL). System maturity is one of the most important things to evaluate the system improvement possibilities. On that way the most common defects of the system can be also a important point of the improvement.

The second part of the thesis is focused on the analysis of the environmental impact of the system. The first part concentrated on the analysis of the life cycle assessment (LCA), from the cradle to grave of the whole items of the system, and the second part pointing on the effects of artificial intelligence (AI) in the energy consumption of the system. It's important to remark that the most important impact of the system on the environment is due to the energy consumption.

The research studies carried out in this thesis range from simulations, and laboratory tests, to experimental set-up analyses on-site to evaluate all the improvements.

The main objectives of the PhD are listed below:

- To verify the state of the art of the AWCS and analyse the current state of scientific literature.
- To identify and analyse the main common defects of the AWCS and how it can affect to the life span.
- To characterise and study the environmental impact of different cases of AWCS, checking different solutions of the market.
- To analyse how (AI) can be implemented to the AWCS and how it affects to the energy consumption of the system.

Chapter 2. PhD Thesis Structure and Methodology

This chapter describes the structure development of the thesis and the methodology used to define the framework and experimental studies of the PhD.

2.1. PhD Thesis Structure

The present doctoral thesis is based on three papers and one patent (IP). Papers are already published in SCI journals and the patent is submitted in EPO.

This PhD thesis is divided into five chapters, as shown in the scheme of the structure of the PhD presented in Figure 5. Chapter 1 analyses the waste generation and recycling rate in different Europe countries and the tendency of them, focusing on the way to collect the waste from the latest years. This chapter also presents the main objectives of this PhD thesis. Chapter two describes the structure of the PhD thesis and the methodology followed throughout the thesis. Chapter three details the papers that make up this PhD, providing for all of them the overview of the study, their contribution to the state of the art and the contributions of the candidate. In the fourth chapter, the overall discussion of the results is presented, connecting the results obtained in the papers, and highlighting the contribution of the AWCS to reduce the environmental impact on the waste management sector. Finally, chapter five highlights the main conclusions drawn from this PhD and recommendations for future work.

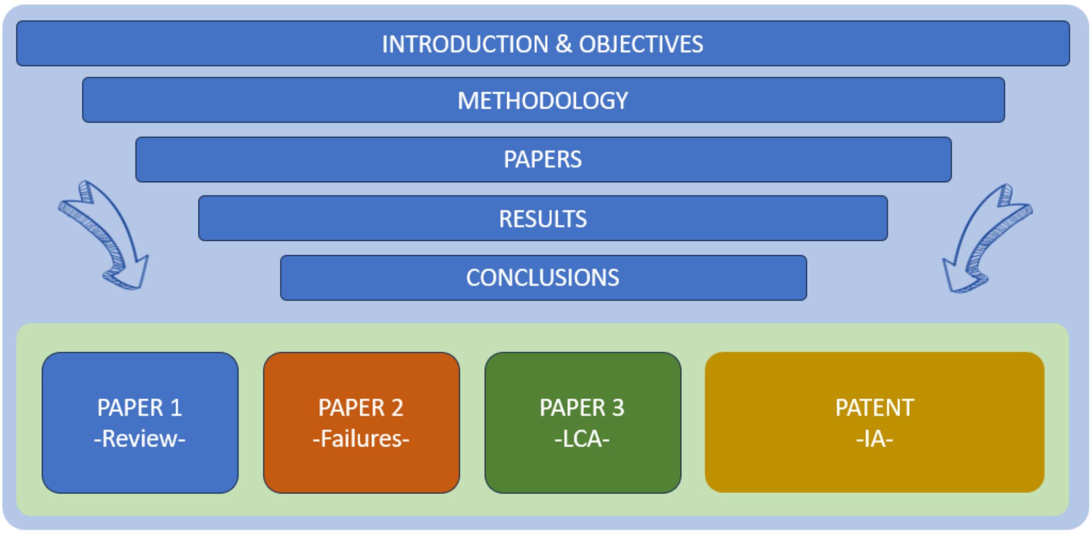

Figure 5. Scheme of the PhD Thesis structure by chapters

2.2. Thesis methodology

This section presents the methodology used to achieve the objectives of the thesis and the materials used for the experimental tests. To have an overview of the path followed during its development, this thesis can be divided into two main parts. The first one focused on the real situation of AWCS, focused on the state of the art of the system (bibliometric analysis) and reviewed the situation of the possible defects on the system, and their possible improvements.

The second part is focused on the impact to the environment of the system, taking in consideration different options of this kind of systems, and also, how IA impacts to the system (energy efficiency).

A diagram of this PhD distribution can be seen in Figure 6, where the relation between the research approaches and the papers that were prepared within each of them is presented.

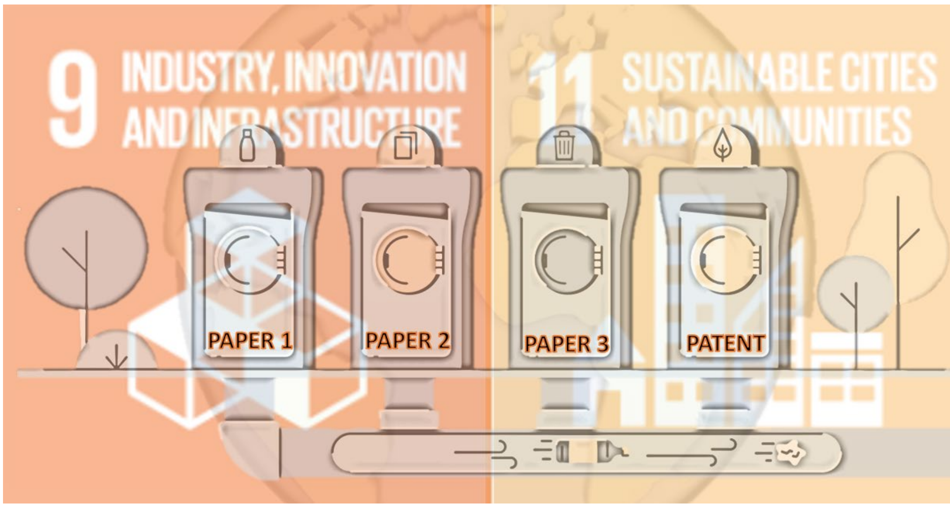

Figure 6. Scheme of the PhD thesis methodology

The first part is focused on bibliometric techniques as a source of analysis of the factors and requirements that can influence to the implementation of the system on the new and old developments. AWCS has many benefits in comparison to the traditional collections system, even with gas or electric powered vehicles. However, many cases the system is not implemented for some reasons.

AWCS has been able to emerge as a promising technology, with the ongoing research together with innovation like to shape their role in the future urban waste management platforms. On that way, how its live span as an urban facility can be implemented in the new smart cities, is one important point of the study. All the urban facilities perform a long period of operation, so AWCS cannot be less than others. The study remarks this possibility and how the user behaviour can affect on that period.

The second part is focused on the how is the environmental impact of the system in a new smart city or new development. There are different possibilities on the AWCS market to achieve a good result, so depending on the development characteristics, we can implement different AWC solutions with better performance. On that way the study s focused on two main parts. The first one is focused on the energy consumption of the system, and how AI can help optimize the consumption. AI gives to the system great opportunities to learn about the users behaviour and better performance on the energy consumption by waste collected.

The other part is focused on the different AWCS options that exist in the market to achieve a better performance of the system (from an environmental point of view). Depending on the urban characteristics AutoWaste can feet better depending on the required demands. So, the study shows how the AWCS has different possible solutions and how the energy mix supply affects directly on the environmental impact.

Chapter 3. Results

3.1. Paper 1: Pneumatic Urban Waste Collection System: A review

3.1.1. Overview

Automatic Waste Collection Systems (AWCS) has a potential as a more sustainable method to various forms of traditional waste collection methods, with a major focus on different issues associated with urban environment that are targeting to mitigate the traffic congestion and even scale down pollution.

On the other hand, through a more advanced form of biometric analysis, the entire research sheds lighter that is known to be surrounding Automated Waste Collection Systems and also goes an extra mile to uncover quite a number of significant insights that are majorly associated with this form of innovative waste management approach.

In relation to examining the existing scientific literature on AWCSs, the entire study perfectly reveals a notable scarcity of research when compared to the other forms of waste collection methods which entails things like the truck-based systems. Furthermore, this entire scarcity is majorly juxtaposed against a specific parallel interest in the entire industry, perfectly evident in the total number of patents that are filed on the subject.

The analysis also employs different keywords that are known to be related to the use of energy, emission of gasses, together with cost benefit analysis, perfectly revealing some of the major central themes that are found within the existing literature.

These keywords, notably "life cycle assessment," "greenhouse gases," and "waste collection," create a solid foundation of the entire discourse that revolves around AWCSs, perfectly illustrating the whole multifaceted nature of all the challenges together with considerations that are existing in this field. Further insights are majorly derived from a word cloud analysis where the entire frequency of specific terms is perfectly visualized, putting much emphasis on the overall significance of “life cycle assessment," "greenhouse gases," and "waste collection" in the whole discourse. Thematic mapping perfectly reveals quite a number of emerging topics with "costs" and "greenhouse gases" at the forefront, thereby underlining their increased importance in all the ongoing discussions that are existing around AWCSs.

3.1.2. Contribution to the state-of-the-art

Throughout the study, the advantages of AWCS are clearly highlighted since they are discussed widely and in depth in a number of articles, with all the possible effects on all interested parties (Figure 7). Different types of users stand to benefit from the continuous availability of different types of services, ergonomic together with accessible waste deposition inlets, together with improved levels of public hygiene situations. On the other hand, different cities are capable of benefitting from a selective collection at the source, an environmentally friendly image that is cleaner together with reduced levels of noise and air pollution. Some of the major economic advantages include decreased levels of operational costs, reduced levels of personnel requirements and also savings in urban cleaning costs. However, all these existing advantages normally come with caveat—the high energy demand associated with AWCSs. The overall ecological impact that is known to be linked to AWCS, most so their energy consumption emerges as one of the most critical concerns. As a result, the paper perfectly highlights energy to be on one of the major contributors to the ecological footprint that is linked to AWCS, perfectly necessitating a closer examination of various types of methods that are meant for optimizing the use of energy.

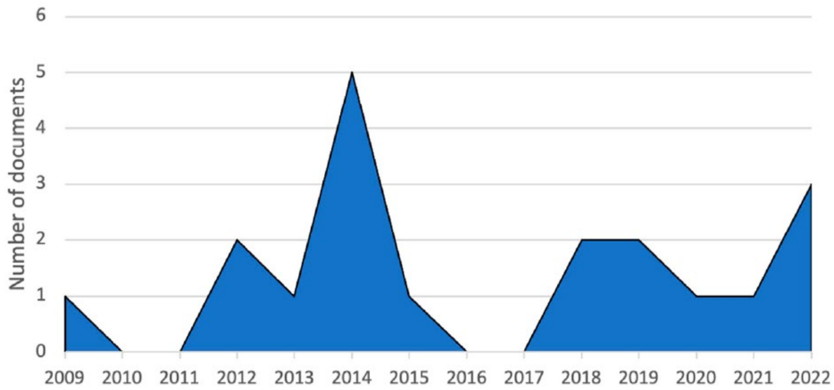

Figure 7. Annual scientific production between 2009-2022 (R-studio)

Unlike what exists in the hardware aspect, where there exists a limited room for improvement, the study perfectly suggests that the whole operational schedule, that dictates when what type of waste is collected, presents one of the perfect opportunities for the implementation of optimization. Surprisingly, this entire aspect did not receive higher levels of attention in the literature when compared to the other aspects like truck routing for the purposes of surface waste collection. Different types of environmental aspects are also scrutinized further through the whole lens of life cycle assessment (LCA) studies, doing a comparison of AWCSs with different types of traditional waste collection methods. All these assessments, conducted in various locations like in the densely populated regions Helsinki, and Zaragoza, Spain, yield mixed results. Moreover, the mobile pneumatic system that is modelled on densely populated urban areas perfectly exhibits one of the greatest environmental impacts together with energy demand when compared with multi-container and door-to-door systems. As the article comes to conclusion, it perfectly reflects the wider implications that are related to AWCS within the boundaries of sustainability together with waste management (Figure 8).

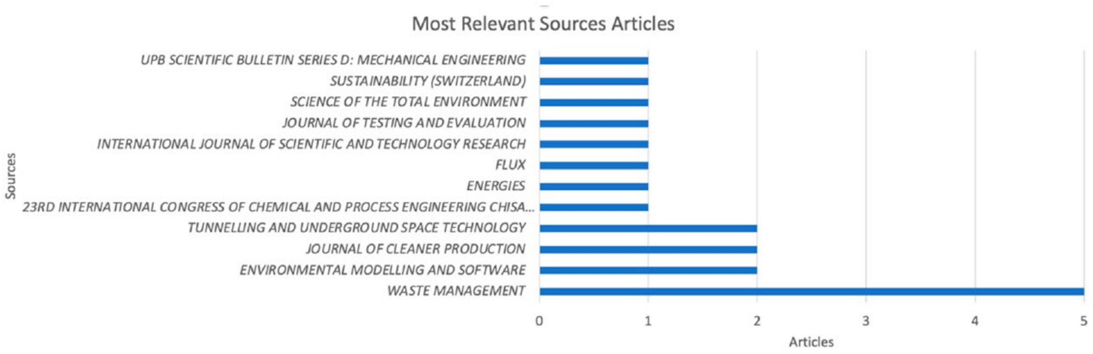

Figure 8. More relevant sources using R-Studio software and bibliometric library of AWCS

It fully acknowledges the niche position linked to AWCS across the entire waste management market while at the same time stressing on the need for more research that is geared towards addressing their advantages, most so the high energy consumption (Figure 9). Again, the article also alludes to various potential solution that exists in patents, perfectly signalling industry interest together with innovation that could contribute towards resolving different challenges that are associated with AWCSs.

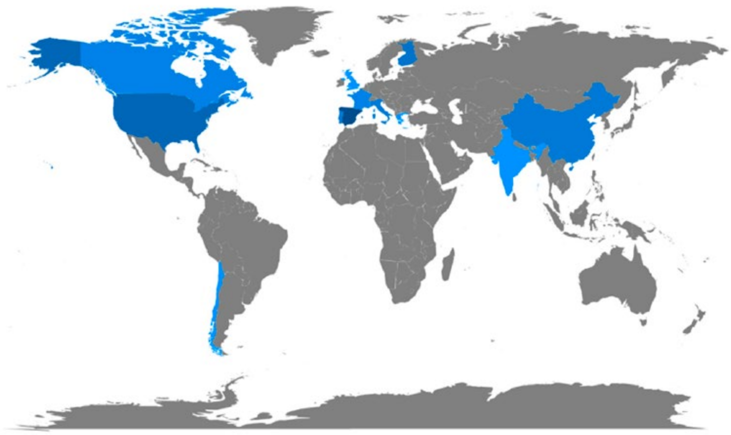

Figure 9. World scientific production using R-Studio software

In summary, the article offers a more comprehensive overview of Pneumatic Urban Waste Collection Systems, clearly examining their respective advantages, market dynamics together with various forms of environmental implications. Again, the in-depth analysis of scientific literature, different types of market players, and various forms of business models together with environmental assessments offers some of the most valuable insights for researchers, various industry professionals together with policy makers who are involved in the entire process of waste management. As the global focus on matters pertaining sustainable practices continues to intensify, AWCSs has been able to emerge as a promising technology, with the ongoing research together with innovation like to shape their role in the future urban waste management platforms.

3.1.3. Contribution of the candidate

Josep Anton Farré and Luisa F. Cabeza conceived and designed the study. After that, Josep Anton Farré performed the analysis of the bibliometric data and both co-authors wrote the paper.

3.1.4. Journal paper

The scientific contribution from this research work was published in Applied Sciences in January 2023.

Reference: J.A. Farré, L.F. Cabeza, C. Mateu, M. Teixidó. Pneumatic Urban Waste Collection Systems: A Review. Applied Sciences 2023 (13) 877.

applied sciences

MDPI

Review

Pneumatic Urban Waste Collection Systems: A Review

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Featured Application: Pneumatic urban waste collection systems for sustainable cities.

Abstract: Due to the increasing need for a more sustainable environment, the study of waste management strategies is increasing worldwide. Pneumatic urban waste collection is an alternative to conventional truck collection, especially in urban areas where there is a need for reducing traffic and pollution. In this study, the scientific literature on such automated waste collection systems (AWCSs) (also known as automated vacuum waste collection (AVWC) systems) is evaluated through a bibliometric analysis. The available scientific literature is found to be scarce, while there are several patents on the topic. The keywords used in the literature are mainly related to energy use, gas emissions, and the cost–benefit analysis. Moreover, the market status is presented and a summary of the environmental studies is provided. The active companies in the field are identified and a complete list of AWCSs is provided. Most of the scientific literature related to the environmental aspects of AWCSs uses the life cycle assessment (LCA) methodology to evaluate the performance of different case studies.

Keywords: pneumatic urban waste collection; automated waste collection; automated vacuum waste collection; sustainability; cities

3.2. Paper 2: Case study of pipeline failure analysis from two automated vacuum collection system

3.2.1. Overview

The study of waste management strategies in smart cities is increasing worldwide due to the necessity of a more sustainable environment. In this framework, the different ways to collect the waste has an important impact.

In AWCS case there are different impacts like the carbon food print (using LCA) of the system due the energy consumption, and also the life span of the system. On that way it's so important to understand that the life span of the system is directly related to the waste managed of the system. Therefore, it depends on the kind of waste that the users through to the system. This life span is related to the life span of the buried network (the pipe through the household waste goes through).

The study shows how different aspects related to the system directly affect the life of the system. Aspects such as corrosion, assembly defects, the geometry of the elbows, size of the particles to be transported, waste characteristics (content), etc. However, the study reveals that there are two main important effects on the pipe network attrition. One of these is the glass content in the transported waste, and the second one, is the high transportation rate 8–10 m/s.

Both factors are in user hands. The allowed content of the AWCS bags is very well defined, so the high glass content in residual stream is due to the bad habits of the users. And in case of the exponential attrition increase due to high speed, it is conditioned by the density of the waste to be transported. The AWCS is a fully automatic system that does not require direct speed modulation. The system itself is set to the established regime depending on the fraction to be transported. Otherwise, the bags would get stuck inside the pipe and several blockages would occur continuously.

3.2.2. Contribution to the state-of-the-art

AWCS pipe network can be manufactured in carbon steel, stainless stell and some specific companies manufacture with special reinforced plastic (composite). However, worldwide leaders of this systems manufacture the pipe in carbon steel, and in some points of the network with special reinforced steel or some kind of steel with greater hardness.

Focusing on the pipeline network of the system it's so important to detect how the pipe failures affects to the life span of the system and directly to the performance of the system (Figure 10). On that way the research majorly aims to elucidate some of the major causes of failures together with their distribution across different types of components, implementing both the imperial failure analysis together with the numerical simulations. One main important thing of the research has been the analysis and understanding of different types of attrition-related issues in AWCS for system optimization.

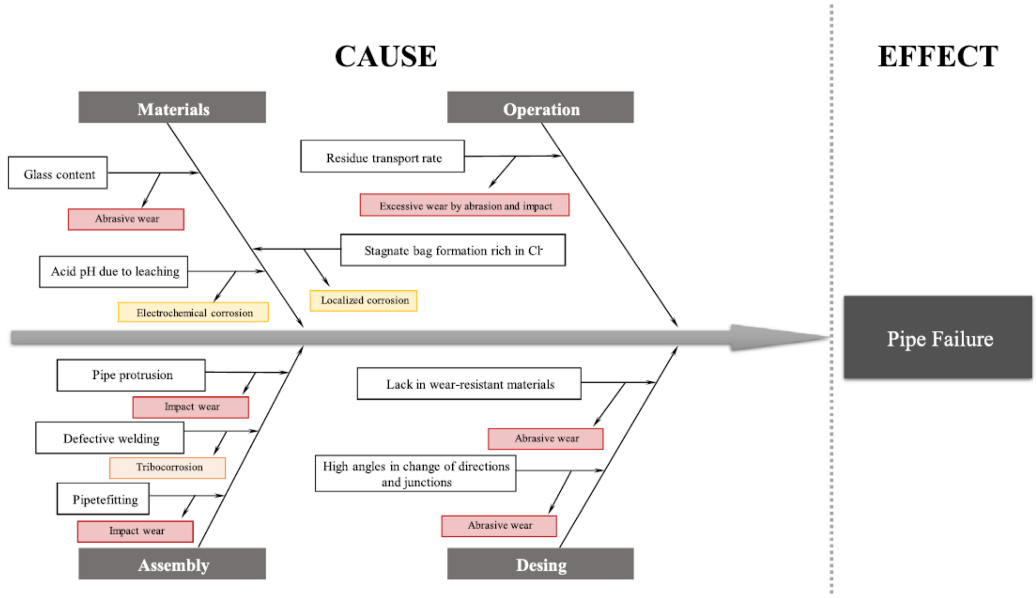

Figure 10. Ishikawa diagram of potential causes and effects of pipes in AWCS

Traditional systems that are linked to municipal waste management is fully dependent on the collection of waste alongside dumper storage until they are collected and transported by the waste management team. In as much as these systems have proved to be flexible, they are linked to quite a number of essential drawbacks together with environmental impacts which entails things like odours and plagues as a result of accumulation of wastes in the dumpsters, different problems that are linked to hygiene, noise, traffic congestions and also the emission of greenhouse gases originating from the garbage trucks. On the other hand, the research also channels its entire focus on the evaluation of different types of geometries, with a specific attention to elbows, connections together with straight stretches.

The research carried out clearly states that waste transported rate is one of the most essential parameters in relation to attrition due to the fact that this parameter is also linked to the attrition grade. The more the transported waste, the more there is attrition which is experienced in an exponential manner. Again, research finally concludes with different types of practical recommendations that are majorly based on the findings. Scaling down glass content in waste, embracing the optimization of transport rates alongside reinforcing attrition resistant materials in different types of critical components are perfectly suggested to be some of the major measures that are reliable when it comes to mitigating the attrition-induced failures.

The research offers quite a number of valuable insights that are associated with a vast range of factors capable of contributing to attrition, providing a perfect foundation for designing and scaling up AWCS in order to scale up their durability levels together with performance. Overall, the entire article significantly contributes to the overall understanding of different types of attrition related challenges in pneumatic waste collection systems, creating a clear path for more effective and sustainable forms of waste management practices. The article therefore contains quite a number of critical information from the insights that it offers thereby making it much easier to develop a clear understanding of the study topic. Such articles are very critical when it comes to environmental protection matters in relation to handling waste within the surrounding environment.

3.2.3. Contribution of the candidate

Luisa F. Cabeza and Josep Anton Farré conceived and designed the study. After that, Marc Martín, Jaume Gasia and Josep Anton Farré performed the analysis of all information and cases. After that all of them perform the conclusions and wrote the paper.

3.2.4. Journal paper

The scientific contribution from this research work was published in Waste Management (Elsevier) in 2021.

Reference: J.A. Farré, L.F. Cabeza, R. Salgado-Pizarro, M. Martín, G. Zsembinszki, J. Gasia, C. Barreneche, A.I. Fernández, C. Mateu, M. Teixidó. Case study of pipeline failure analysis from two automated vacuum collection system. Waste Management 126 (2021) 643-651.

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Case study of pipeline failure analysis from two automated vacuum collection system

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ABSTRACT

Conventional municipal waste management systems based on collecting and storing waste for future management are cost-effective and flexible. These systems present significant problems such as odours, plagues and hygiene problems caused by their storage and greenhouse gas emissions from garbage trucks used for the transport of waste. The Automated Waste Collection System (AWCS) and Automated Vacuum Waste Collection (AVWC) systems, in which waste is transported directly underground to the processing plants, are efficient collection systems and respectful of the environment as alternatives to traditional systems. The pneumatic system reduces the value of the per capita generation of general waste. The present study explains the origin of pipe failure in two different AWCS factories, as well as the identification of the failure phenomena. To carry out the study, a classification of 90 failure cases by primary cause was performed, followed by recommendations to avoid these failures in the future. Moreover, a computational fluid dynamics (CFD) simulation was performed in order to help in the failure determination and the key recommendations to avoid the most common and frequent failures.

3.3. Paper 3: Life Cycle Assessment (LCA) of Two Pneumatic Urban Waste Collection Systems Compared to Traditional Truck Collection in an Airport

3.3.1. Overview

The AWCS landscape is experimenting rapid metamorphosis, with leading industry players pursuing innovative market developments activities to outshine competitors and fortify their market standing. A case in point is the AutoWaste Compact System developed by one specific company in the market (Figure 11). Large systems provide incredible performance in terms of capacity and collection distance. Even so, many times these benefits are not 100% necessaries. Cases such as airports, large shopping centres, etc., where the system gives great advantages to traditional collection, do not require these characteristics.

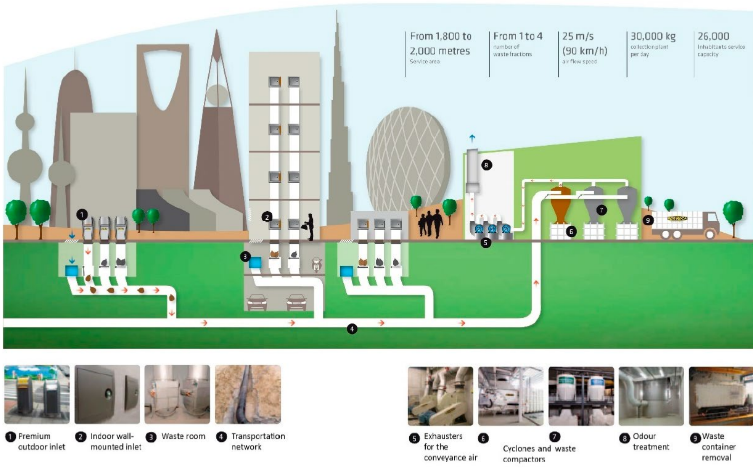

Figure 11. AWCS scheme (URD General Brochure, 2020)

To achieve this goal, the new compact system (AWCS) considerably reduces the performance of a normal automatic collection system but maintains the main advantages of the pneumatic system (Figure 12). Locations where these advantages are even greater (waste management, noise, odours, etc).

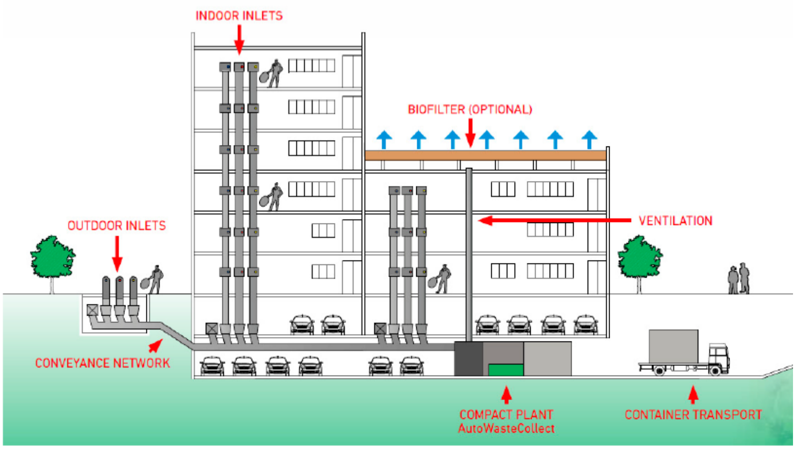

Figure 12. AutoWaste Compact Collect system (URD AutoWaste Brochure, 2021)

Secondly as showed during the research the AWCS has different impacts, but one of the most important is the carbon food print of the system. On that way it's important to analyse the Life Cycle Assessment of the compact system, compared to the truck collection in this special places. On that way, whatever the system chosen, the LCA study shows that the energy mix used is decisive in the results obtained. The high impact of the AWCS energy consumption shown that depending on the energy mix characteristics, it affects directly on the impact. On the other hand, the study shows that AutoWaste has a better efficiency in terms of emitted gases in comparison to the traditional AWC system. Obviously within the framework of their capabilities.

3.3.2. Contribution to the state-of-the-art

The life cycle assessment (LCA) study is focused on various environmental impacts. In this case are linked to traditional truck waste collection systems with two different pneumatic waste collection systems. Furthermore, the assessment also employs the use of two different indicators which includes ReCiPe and IPCC2013, where it also goes ahead to consider various types of energy scenarios. Again, the research highlights the significant role of the energy mix when it comes to influencing the whole environmental performance of various waste collection systems. In the whole analysis that uses the 2014 energy mix, the implementation of the traditional truck collection system emerges to be the one with the lowest level of environmental impact. However, taking into consideration different types of renewable energy sources into the mix, the AutoWaste Compact System is in a position of showing a superior environmental performance, emitting fewer levels of greenhouse gasses when compared to both the traditional and conventional forms of pneumatic systems.

The data perfectly indicates that the AutoWaste Compact System is in a position of scaling down the annual flow of different types of greenhouse gasses by about 25% when compared to all the conventional forms of pneumatic systems hence making it to be more environmentally friendly with a lifespan of more than 30 years. All these findings perfectly underscore the overall importance of taking into consideration different types of renewable energy sources in the waste management decisions with an intention of attaining an optimal level of various forms of environmental outcomes. The research also digs deep into the breakdown of a vast range of environmental impacts during various phases that are linked to the life cycle, including manufacturing and operational stages. As a result, the analysis perfectly reveals that the construction phase is capable of significantly contributing towards environmental impact across all the three systems. As far as the pneumatic systems are concerned, the research asserts that the construction phase contribution appears to be much higher than different impacts that are capable of being generated during the whole operational phase. This whole insight is very fundamental for the decision makers to develop a clear understanding of the major stages that influence the overall environmental footprint of the waste collection systems. The comparison that is done between the systems perfectly demonstrates that pneumatic waste collection systems, most so the AutoWaste Compact System, is able to contribute to a 45% reduction rate in the environmental impact when compared to the traditional truck collection systems.

The findings of this study emphasize the importance of considering the time perspective when evaluating the environmental impact of waste collection systems.

The research also carries an exploration of the environmental impact through the use of the IPCC 2013 20a method, taking into consideration quite a number of energy scenarios. The results indicate that the whole central wastewater station system is associated with the lowest level of impact where the AutoWaste Compact System emits 613 kg CO_2 equivalent per ton, this is followed closely by the conventional pneumatic system with 620 kg CO_2 equivalent per ton. In contrast, the entire traditional truck system is reported to the emitting one of the highest with 1174 kg CO_2 equivalent per ton.

The overall results also underscore all the environmental benefits of implementing pneumatic waste collection systems, specifically the AutoWaste Compact System, especially across various scenarios where renewable energy sources are fully prioritized.

All the insights obtained from the research also capable of contributing towards informed decision-making within the boundaries of urban waste management, thereby guiding the whole selection of different systems that perfectly align with different sustainability goals together with environmental conservation.

3.3.3. Contribution of the candidate

Josep Anton Farré and Luisa F. Cabeza conceived and designed the study. After that, Noelia Llantoy, Marta Chafer and Josep Anton Farré performed the analysis of all energy mix and comparisons, and all authors wrote the paper.

3.3.4. Journal paper

The scientific contribution from this research work was published in Sustainability (MDPI) in 2022.

Reference: J.A. Farré, L.F. Cabeza, N. Llantoy, G. Gomez, M. Chafer. Life cycle assessment (LCA) of two pneumatic urban waste collection systems compared to traditional truck collection in an airport. Sustainability 2022 (14) 1109.

Universitat de Lleida

sustainability

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Article

Life Cycle Assessment (LCA) of Two Pneumatic Urban Waste Collection Systems Compared to Traditional Truck Collection in an Airport

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Abstract: Due to the increasing need for a more sustainable environment, the study of waste management strategies is increasing worldwide. Pneumatic urban waste collection is an alternative to the conventional truck collection, especially in urban areas, where there is a need of reducing traffic and its pollution. LCA is a methodology that can help in the evaluation of the environmental impact of any process or product; therefore, this study, based on the methodologies ISO 14040 and from the cradle to the grave, compares different waste collection systems in an airport. The results show that the pneumatic collection system with the innovative AutoWaste compact central unit can reduce the annual flow of greenhouse gases into the atmosphere (kilograms of carbon dioxide equivalent for 30 years and per ton) up to 25% compared to a pneumatic collection system with a conventional central.

3.4. Patent: Method for the intelligent control of waste collection in an automated waste collection plant

3.4.1. Overview

The main objective of the patent is to optimize the energy usage on an AWCS. To contextualize it is important to note that energy consumption is the highest single cost in the system Operation & Maintenace costs. Energy usage costs can be around 45-55% of the overall cost.

The patent covers a method to organize and schedule the waste collection in a AWCS plant so as to use the minimum possible energy, while keeping service quality and main KPI (Key Performance Indicators). The method, based on AI (Artificial Intelligence), uses sensor data from the plant integrated sensoring, historic data from previous plant operation, and an intelligent control mechanism to operate the plant for a higher efficiency, lower carbon footprint, and enhanced sustainability.

Key aspects of the method include real-time data acquisition and analysis, dynamic route planning, adaptive scheduling, robust communication infrastructure, and continuous feedback mechanisms. These components work in tandem to optimize waste collection routes, adjust schedules in response to changing conditions, facilitate communication and control of collection activities, and enable continuous improvement of system performance.

Overall, the method outlined in the patent represents a significant advancement in waste management technology, leveraging cutting-edge technology and data-driven insights to improve operational efficiency and environmental sustainability within automated waste collection plants. By streamlining waste collection processes and reducing resource consumption, the method contributes to the advancement of sustainable waste management practices.

3.4.2. Contribution to the state-of-the-art

The patent is based on neuronal networks process for IA. Neural networks are a fundamental component of artificial intelligence (AI) processes, particularly in machine learning.

The neuronal network’s structure process is the following:

- Basic Structure: Neural networks are computational models inspired by the structure and function of biological neural networks in the human brain.
- Learning Process: Neural networks learn from data through a process called training (phase 1 of the patent).
- Forward Propagation: In the forward propagation phase, input data is fed into the input layer of the neural network. The input signals are multiplied by the corresponding weights and passed through an activation function.

- Backpropagation: After forward propagation the predicted output is compared to the actual target output. The error between the predicted and actual outputs is calculated, and this error is propagated backward through the network using a process called backpropagation.
- Training and Optimization: this process involves iteratively presenting the training data to the neural network, adjusting the weights and biases through forward and backward propagation, and updating the parameters to minimize the error.
- Prediction and Inference: Once the neural network is trained, it can be used for prediction and inference tasks. New input data is fed into the input layer, and the network computes the corresponding output through forward propagation.

The patent involves an integration of a neural network within the intelligent control of waste collection described in the patent would involve using sensor data as input to the network, training the network to learn patterns and relationships in the data, and deploying the trained network for real-time decision-making and control.

Taking on the consideration all the previous process and characteristics the patent runs by different phases of the IA methodology. These phases collectively form a systematic approach to intelligent waste collection management within an automated waste collection plant, aimed at streamlining operations, reducing costs, and promoting sustainability.

The first one is based on the way to implement a first energy use model, or first prediction model based on previous data collected from other systems (first prediction model – Phase 0). This way is possible thanks to the previous information from different waste collection systems or from fictitious waste collection plant programmed/configured for acquiring operating information of a series of real collection plants.

The second one is based on training the system in order to optimize the energy consumption calculation (first prediction mode -Phase 1l). Training a virtual agent by means of the second artificial intelligent algorithm. This second algorithm particularly comprises a neuronal network based on reinforced learning or deep reinforcement learning based neural network that is trained during a specified number of repetitions or until a cost reaches a specified threshold.

One we have the trained virtual agent; this one receives all the inputs of the real data from the inlets (data acquisition and sensor integration the collection plant). The virtual agent received real information of the inlets status and it can evaluate the energy consumption of the different future actions of the system and stablish emptying control decision-making policies (phase 2).

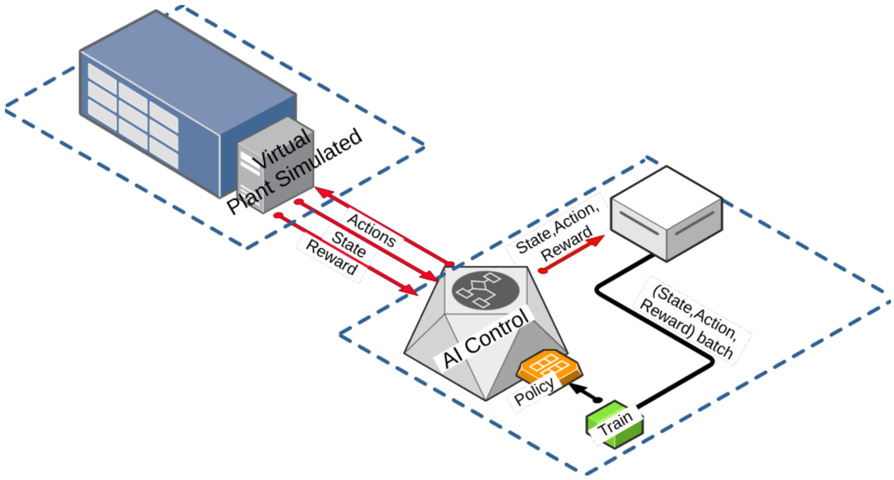

Figure 13. AI Scheme detail

Finally, fourth step, phase 3, is the moment where the virtual agent stablishes a real collection policies. the method comprises operating the actual collection plant according to said one or more emptying control decision policies established by the virtual agent. This last stage of operation, particularly, is also carried out by the controller device.

Particularly, all of this is performed after a sufficient time interval has elapsed in which the virtual agent has not established any incorrect control decision policy.

The controller device and the virtual agent can operate in parallel. That is, while the controller device operates the real collection plant, simultaneously, the virtual agent receives information on the status of the inlets and makes the relevant decisions. In this way, the virtual agent continually improves throughout the operation time of the real collection plant.

In an exemplary embodiment, these decisions are not directly taken into consideration by the controlling device but are previously sent to a monitoring and telemetry system, for validation. In other words, the controller device receives decisions directly from the virtual agent. In any case, the virtual agent can act as a supervisor to avoid erroneous operational actions in the real collection plant.

In some embodiments, the calculation of the simulated model also comprises implementing a third artificial intelligence algorithm on at least part of the operation information stored in the memory or database to calculate a second prediction model of the time that each cycle takes. emptying. In this way, additional variables are taken into account, such as the price of energy (depending on the time), temporal data (day of the week, etc.), time prediction if solar energy is used in the collection plant, etc which allow the simulated model to be further optimized.

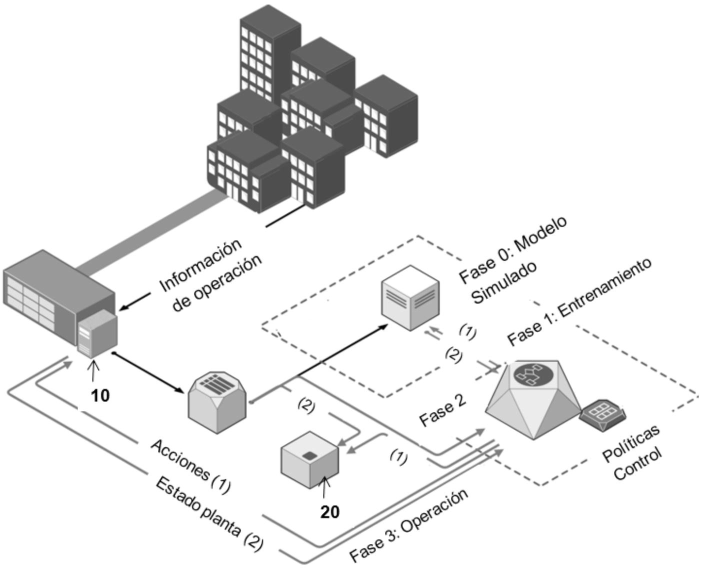

Figure 14. AI Global scheme of the patent

3.4.3. Contribution of the candidate

Carles Mateu, Cesar Fernández and Josep Anton Farré conceived and designed the patent. After that, Josep Anton Farré performed the analysis of the patent structure, and the three authors wrote the patent.

3.4.4. Patent

The scientific contribution from this research work was submitted in EPO in 2022.

Reference: J.A. Farré, C. Mateu, C. Fernandez. Method for the intelligent control of waste collection in an automated waste collection plant. EP 4 060 574 A1, 2022.

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(54) **METHOD FOR THE INTELLIGENT CONTROL OF WASTE COLLECTION IN AN AUTOMATED WASTE COLLECTION PLANT**

Chapter 4. Global discussion and results

Currently, the world situation demands an urgent need to improve all aspects of municipal waste collection. Globalization has brought the planet to a limit situation as if resources were infinite, and thus the rethinking must be progressive but complete and real. In this sense, the world of municipal waste has an important task as we have seen throughout the thesis. Issues such as fractions to be collected, their recycling, etc, are important decisions to improve the recycling of municipal waste.

In this sense, as detailed throughout the thesis, the AWCS system has a great possibility to definitely explode as one of the best municipal waste collection systems worldwide. From a human development perspective, the system brings considerable improvements at a global level. Improved recycling ratios, lower carbon footprint, etc; a system fully aligned with the SDGs.

It is true that the implementation costs of such a system are much higher than the implementation costs of a traditional collection system, but even so, its amortization is feasible with a useful life of more than 30 years. These implementation costs are directly affected by the type of development where the system is to be implemented. In a new development its implementation cost is much lower than if it is required to be implemented in a historic centre. A point to reflect considerably against the thesis is why it is not questioned to have an infrastructure of water, gas. Is it because the system generates much fewer jobs than other types of collection? Is it because there are other interests? In the end, nobody considers not having infrastructures such as gas, sewage, etc., and nobody questions the environmental impact of them. On the other hand, the AWC system is much better than other systems in these respects, and it is continually questioned.

We must bear in mind that many studies detail that in 2030, 70% of the world's population will live in cities. This implies a significant concentration of people in a small area, as well as a very considerable waste generation in a relatively small area. Therefore, the efficiency of the different systems will have an important impact on the decision of the system to be implemented, since points such as urban land occupation, performance, pollution, vehicles, etc., will have a great relevance. The vast majority of traditional collection systems are sized to have surface collection capacity and thus have storage capacity for a whole day (minimum). This means a large occupation of public roads, as well as mini landfills throughout the city. In this sense, the AWC system represents a considerable improvement in terms of road occupation, efficiency, and sanitation. We must bear in mind that the higher the density of waste generation per square meter, the better the collection ratios obtained with the system.

In this sense, the thesis also analyses the useful life of the system in terms of the material and use of the pipes. We must consider that being a buried infrastructure (implementation cost is important) and its maintenance becomes much more difficult. The deterioration of the installation comes basically from the own use of the installation, since the affectation of external factors like humidity, corrosion, etc, can be mitigated and controlled. The problem lies in the uncontrollable part of the system, the user, the contents of the user's bag. The system can be adapted to the number of fractions to be collected with the exception of the glass fraction. This is due to the abrasion involved in transporting glass inside the steel pipes. Its hardness is much higher than the hardness of any material that you can use in the pipes (normally steel), so its presence in the waste bags generates a premature wear for the life of the installation.

Completely linked to the behaviour of users and the content of each bag (fraction), it is very important to highlight the different collection modalities in terms of the type of fraction to be collected. There are modalities of how to collect, but there is also a great worldwide debate on what type and number of fractions to collect. In some European countries there are 3 (wet, dry and glass), 4 fractions (separating cardboard) or even 5 like Spain. On the other hand, many places in the world do not have the concept of fraction. The so-called "all-in-one". Countries like Iraq, Afghanistan, India, etc, do not have the concept of segregation (separating, recycling, etc). This is due to many factors (political, economic, etc.), but the reality is that the type of segregation in developed countries, where there is some type of segregation, is directly linked to the type of treatment plant that exists downstream. In this sense, all systems, including the AWC system, have the possibility of adaptation to each situation.

The collection systems must be adapted to the needs of the users and thus must be "modeled" to be as efficient as possible to meet the demand. The AWC system can therefore be adapted both modularly (product model) and in terms of performance (product scalability). As a result, its performance is much better than any other collection system.

In addition, the thesis clearly details the impact of the energy source supplying the system. As an industrial system, energy consumption is a very important part of the impact on the environment, so its impact depends directly on the source of energy consumed, the type of generation chosen. In the case of using 100% renewable energy, the impact values are much lower compared to other collection systems. Even so, it is important to note that whatever the origin of the energy, the pneumatic collection system is always the one with the lowest impact in terms of carbon footprint.

On the other hand, the thesis also makes important mention of the impact that the continuous development that currently exists at both the IoT and artificial intelligence level can have on this type of system. The AWC system requires control systems, sensors, etc., that help to control the overall operation. Sounding of inlets, user identification, etc., make the system itself improve day by day and continuously. Technology is advancing very fast and, being a technological system, its differential against other systems will soon be even greater than it is today. In the same sense, but more focused on costs, this continuous improvement of the IoT will make the costs of all this sensorization, control, etc., more and more economical and thus the system will improve in terms of implementation costs.

Chapter 5. Conclusions and future work

5.01. Conclusions

As has been developed throughout the thesis, as well as during the study, management of Municipal Solid Waste (MSW) is one of the major challenges worldwide in terms of improving recycling and collection efficiency. Inadequate collection, recycling, or treatment and uncontrolled disposal of waste in dumps lead to severe hazards, such as health risks and environmental pollution. This situation is especially serious in low- and mid--income countries. It is true that many of these challenges are thwarted by a lack of political involvement at both the local and state levels, as well as a lack of investment. Even so, factors such as the SDGs considerably help its continued evolution.

Cities, which are hubs of rapid economic development and population growth, generate thousands of tons of MSW that must be man-aged daily. Low collection coverage, unavailable transport services, and a lack of suitable treatment and disposal facilities are responsible for unsatisfactory solid waste management, leading to water, land and air pollution, and for putting people and the environment at risk. The amount of waste generated is often linked directly to income level and lifestyle.

Newly industrialised countries like China and India are confronted with enormous solid waste management problems that will severely strain municipal financial resources and the handling of the ever in-creasing waste volumes. An ecologically compatible management of natural resources, environmental education, as well as a sustain-able and integrated waste management must be pursued together with cleaner production processes and a change in consumer be-haviour and habits.

The socio-economic, cultural and institutional context in the developing world requires special consideration of appropriately adapted technologies, capacity building, including improvement of skills and know-how at local government level. Innovative and integrated collection, recycling, and disposal systems of MSW, involving community participation, public-private partnerships, etc, are steps in the right direction. Obviously, AWC system is working in the correct way.

During the thesis we have been able to analyse how AWC system has important intrinsic characteristics that make it a system with a great capacity for improvement in the face of the challenges that lie ahead. Globality requires continuous improvement, continuous adaptation, which in traditional systems is very difficult to advance. On the other hand, the AWC system alone has a great capacity for adaptation, both as a system and its intrinsic characteristics, but even more so as another infrastructure of the municipal complex.

Therefore, the main objectives of the thesis have been to provide tools, information, and analysis to improve the selection of collection systems, considering the great potential of the pneumatic collection system for urban solid waste.

As a general conclusion, we could highlight that the AWC system is one of the best options for managing of Municipal Solid Waste. Therefore, this PhD focuses on the potential of the system and what could be the ways of improvement.

5.02. Future work

The research presented in this PhD thesis increased the knowledge about the AWC system improvement. However, being a smart system, it has a long way to go in terms of continuous improvement, which will allow it to reduce implementation and operation costs and also in maintenance revenue. In this way it will be able to further strengthen its position as a leader in municipal collection management systems.

AWCs is directly linked to the technological world, as well as to the global concentration in large cities, so it can trigger a significant growth of the system. In both cases, the necessity to improve the recycling rate is crucial for the planet.

There are global targets in place to focus on these, so for AWCS everything is in their favour, and it can help on that way.

OTHER RESEARCH ACTIVITIES

OTHER JOURNAL PUBLICATIONS

The PhD candidate carried out other scientific research besides the one presented in this thesis during the execution of his PhD. The resulting publications are listed below:

1. Marta Chàfer, Aran Solé, Francina Sole-Mauri, Dieter Boer4, Luisa F. Cabeza

   GREiA Research Group, INSPIRES Research Centre, University of Lleida, Pere de Cabrera s/n, 25001, Lleida, Spain

   Life cycle assessment (LCA) of a pneumatic municipal waste collection system compared to traditional truck collection. Sensitivity study of the influence of the energy source

2. Marta Chàfer, Aran Solé, Francina Sole-Mauri, Dieter Boer4, Luisa F. Cabeza

   GREiA Research Group, INSPIRES Research Centre, University of Lleida, Pere de Cabrera s/n, 25001 Lleida, Spain

   Life cycle assessment (LCA) of a pneumatic municipal waste collection system. Part 1. Comparison with truck collection

3. Marta Chàfer, Francina Sole-Mauri, Aran Solé, Dieter Boer, Luisa F. Cabeza

   GREiA Research Group, INSPIRES Research Centre, University of Lleida, Pere de Cabrera s/n, 25001 Lleida, Spain

   Life cycle assessment (LCA) of a pneumatic municipal waste collection system.

   Part 2. Sensitivity study of the influence of the energy source

4. Carles Mateu, , Luisa F. Cabeza, Josep Anton Farré

   ECO-EICO: 2º Congreso Internacional de Sostenibilidad Urbana

   Pneumatic urban waste collection, a great opportunity for sustainable cities

OTHER CONTRIBUTIONS

The PhD candidate contributed to this other scientific research:

1. ADEME – Agence de l'Environnement et de la Maîtrise de l'Energie - Novembre'17

   Study carried out on behalf of ADEME by Moringa, Philgea and Urban Earth Consulting (Contrat n° 16MAR001608)

   "International benchmark and cost analysis of automated vacuum waste collection projects"

2. INICIATIVES DE REFORÇ DE LA COMPETITIVITAT 2021 - LÍNIA D'AJUTS PER A PROJECTES DE DESENVOLUPAM RECOBRIMENTS AVANÇATS: SOLUCIONS

   ACCIO, CLUSTER MAV (BCN), TM COMAS, CPT (UB) & URD

   "Recobriments avançats: solucions anti-desgast i d'elevada resistència a l'impacte per components metàl·lics industrials"

3. INNOTEC 2021: Ajuts a projectes de recerca industrial i desenvolupament experimental

   UPC & CCP & URBAN REFUSE DEVELOPMENT

   "Millora de la vida útil de les canonades dels sistemes de recollida pneumàtica de residus sòlids urbans a través de l'ús de nous materials"

4. Cupó d'innovació i estratègia 2021

   EURECAT & URD

   "Desenvolupament noves solucions metàl·liques i/o composites per a canonades per a la recollida pneumàtica"

5. Cupó 4.0 2021

   EURECAT & URD

   "Prova de Concepte d'un robot pel manteniment de cannonades"

Universitat de Lleida

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