Analysis of the potential use of smart packaging to improve the management of industrial hazardous waste.

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Diplôme : Master en sciences de gestion, à finalité spécialisée en global supply chain management
Année académique : 2024-2025
URI/URL : http://hdl.handle.net/2268.2/22904

ANALYSIS OF THE POTENTIAL USE OF SMART PACKAGING TO IMPROVE THE MANAGEMENT OF INDUSTRIAL HAZARDOUS WASTE

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Master thesis presented by
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To obtain the degree of
MASTER IN MANAGEMENT
with a specialization in
Global Supply Chain
Management
Academic year 2024/2025

Ecole de Gestion de l'Université de Liège

Acknowledgements

I would like to express my deepest gratitude to everyone who contributed, either directly or indirectly, to the completion of my research thesis.

First of all, I would like to thank my supervisor, Ms Célia Paquay, for her constant support and availability throughout the year. Her expertise and invaluable advice have greatly enhanced the quality of this thesis.

I would also like to thank the professionals who agreed to take part in the interviews, particularly given their busy schedules. Their contribution was invaluable, providing the benefit of their expertise in their field. Their experience and insights have enriched this work.

I would like to thank my family and friends for their constant support throughout my academic journey, especially during the writing of this master thesis. Their patience and encouragement were instrumental in the successful completion of this work.

Finally, I would like to express my sincere gratitude to all the teachers and lecturers I have encountered during my academic journey. Each of them has inspired my curiosity and helped me to develop my skills in some way.

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List of abbreviations

ADR:	European Agreement concerning the International Carriage of Dangerous Goods by Road
ARNE:	Agriculture, Ressources naturelles et environnement – Agriculture, National Resources and Environment
DSD:	Département du Sol et des Déchets – Department of Soil and Waste
HSE:	Health, Safety and Environment
IATA:	International Air Transport Association
LCA:	Life Cycle Assessment
NACE:	Nomenclature statistiques des Activités économiques dans la Communauté Européenne – Nomenclature of economic activities
ONU:	Organisation des Nations Unies – United Nations Organisation
SPW:	Service Public de Wallonie – Walloon Public Service
RFID:	Radio Frequency Identification

Introduction

Hazardous waste such as aerosols, solvents and batteries presents significant risks to human health and environment if not properly managed. This type of waste requires specialised handling like physico-chemical treatments or high temperature incineration to minimise its impact. In 2022, the European Union produced approximately 119 million tonnes of hazardous waste, representing 5.3% of all waste generated (Statistics Explained, n.d.). The large majority – 96% - is coming from industrial sectors such as manufacturing, water treatment and waste management, construction and demolition, and extractive industries, while only 4% originated from households (European Court of Auditors, 2023).

Hazardous waste is generated throughout the lifecycle of products, from raw materials extraction to its final consumption, including manufacturing, storage and distribution processes. Several stages are involved in the effective management of this waste: identification and classification, collection and storage, transport, pre-treatment, treatment and final disposal. However, important challenges remain. These include the risk of accidents during transport, regulatory complexity due to stricter rules in managing hazardous waste, traceability issues such as discrepancies between the quantities of hazardous waste declared and those actually treated which may indicate mismanagement or illegal practices, and high cost of management. For example, the average cost of managing hazardous waste in Europe is €238 per tonne, which is well over the €63 per tonne for non-hazardous waste (European Court of Auditors, 2023). Therefore, innovative solutions are needed to address such issues in handling hazardous waste.

Smart packaging is packaging that uses innovative technologies such as sensors, indicators and tracers to monitor and communicate information including temperature, humidity, product origin and freshness in real time to improve the management and safety of goods during transport and storage. These packaging are developing quite rapidly in recent years in response to consumer's growing expectations, in terms of both product quality and safety, whether in terms of health or impact on the environment (Osmólska et al., 2022).

Smart packaging technologies are already widely used in sectors such as food and pharmaceuticals. In the food sector, this packaging has been introduce mainly for two reasons. The first is to reduce food waste, which is a significant problem as around a third of all food produced globally each year is wasted (Kalpana et al, 2019). Smart packaging helps to address this by maintaining and extending the shelf life of products, thereby minimising spoilage and the need for disposal. The second reason is to improve food quality and safety by monitoring and detecting exposure to unfavourable storage or transport conditions. Smart packaging can alert consumers and actors involved in the chain when food is no longer safe to consume, protecting them from contamination or poisoning. In the pharmaceuticals sector, smart packaging is used to ensure the security, traceability and quality of medicines throughout the supply chain (Michaelis, 2024). In air transport, for example, IATA (International Air Transport Association) estimates a total annual loss of $35 million due to conservation problems with thermolabile[1] medicines (Mecalux, n.d.). Smart packaging help to prevent tampering, counterfeiting and medication errors, while ensuring greater compliance with the sector's relatively strict regulations (SupplyChainInfo, n.d.).

The aim of this thesis is to explore whether smart packaging could address the challenges mentioned above in the management of hazardous waste and thus improve the management of this waste. Some

[1] "Easily decomposed or subject to a loss of characteristic properties by the action of heat". https://www.collinsdictionary.com/dictionary/english/thermolabile

innovative solutions such as smart waste bins, robots and AI or automated vacuum collection systems have already been studied or even implemented for municipal waste management. These systems often rely on technologies similar to those integrated in smart packaging, such as RFID tags, sensors and alarms (Czekała et al., 2023). This study aims to investigate whether these technologies, when embedded in smart packaging, could also be adapted and applied to the specific challenges of hazardous industrial waste management.

The first part of this work will be a literature review on hazardous waste, namely “what it is”, “how it is managed”, “what are the regulations”, “which are the limits encountered”, and “what are the needs of the sector”. It will then focus on smart packaging technologies, exploring their current applications and potential benefits. In the second part of this thesis, the analysis section presents the findings from expert interviews, considering them in relation to the existing literature. The collected insights are presented and discuss directly to gain a better understanding of the results. Then, a section on limitations and areas for improvement will be developed, in which the study’s limitations will be discussed. Finally, a conclusion will summarise the main results obtained, assess how they relate to the initial research goals, and provide future perspectives.

Theoretical framework

In this section, we will present the theoretical basis for understanding the subject. It is structured around two main axes: hazardous waste and smart packaging. We will begin by defining what hazardous waste is, looking at its origins, how it is currently managed, the main regulatory aspects surrounding it and the problems encountered in this field. We will then look at smart packaging, detailing the various forms of packaging technology, their areas of application and the benefits and barriers to their use. The aim is to highlight the points of convergence between these two topics in order to better understand the relevance of introducing smart packaging solutions in hazardous waste management.

1. Hazardous waste

1.1. Definition

Hazardous waste is defined in Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 as "*any waste which displays one or more of the hazardous properties listed in Annex III*". More broadly, waste is described as "*any substance or object which the holder discards or intends or is required to discard*"".

The term "*waste*" should not be confused with "*by-products*", which are substances or objects produced during a production process that were not the process's primary purpose. Unlike waste, they are certain to be used in their current form, meaning they do not need to be reprocessed before use (Union européenne, 2008). One example is the metal chips generated during machining operations, such as milling or turning. Provided they are not contaminated by another substance, they can be considered as a by-product because they can be reused directly, without the need for prior treatment. In contrast, waste products, such as metal chips that have been soiled or contaminated by substances like oil, must undergo one or more treatments before they can be used again. Waste is no longer considered as such, once it has undergone a recovery or recycling process. This applies provided specific criteria: the waste is commonly used for specific purposes; there is a market or demand for these substances or objects; it meets the relevant technical requirements, legislation and standards applicable to products; and its use does not have harmful effects on the environment or human health (Union européenne, 2008).

Waste can be generated at every stage of a product's life cycle (European Court of Auditors, 2023), making it crucial to understand when and how this occurs. Life Cycle Assessment (LCA) is a valuable tool for assessing the environmental impact of a product, both in terms of resource consumption and pollution generated, from design to end-of-life. This analysis is standardised by ISO standards 14040 and 14044, which set out the guidelines and requirements to be met (Osset, 2012). By carrying out this analysis, companies can better understand the environmental impact of their activities and adapt their practices accordingly. The life cycle of a product can be divided into four main stages: production, distribution, consumption and end-of-life. Each of these stages generates pollution or waste. For example, the extraction/production of raw materials can damage soil or biodiversity. Manufacturing can use a lot of water and energy, which can lead to air and water pollution. The transport and distribution phase produces a lot of C02 and therefore pollutes the air, while packaging produced to wrap the products during these journeys also pollutes (Les Cahiers du Développement durable, n. d.). When a product is consumed or used, it continues to have an impact on the environment. If we take the example of a car, it will use fuel and oil during its lifetime (Heggie, 2023). In addition, there is the generation of waste due to the unpacking of the used products by the consumer during the consumption phase (Les Cahiers du Développement durable, n. d.). The product itself, once used, whether once or over time, will eventually become waste. Finally, in the best case scenario, the

product is reused, repaired or recycled, although this may still pollute, consume energy or generate some waste. If it is incinerated or buried, it emits toxic pollutants, leachate[2] and greenhouse gases (Kumar et al., 2023).

1.2. Characteristics

Annex III of the Directive 2008/98/CE describes 15 hazardous properties that enable waste to be considered hazardous. The presence of a single property is sufficient for the waste to be considered hazardous. These hazardous properties include:

- "*H1-Explosive: Materials that may burst under the effect of flame, impact or friction with greater sensitivity than dinitrobenzene".* For example, a dynamite cartridge may explode violently upon impact or when exposed to flames.
- *"H2-Oxidising: Materials capable of causing an intense, high-energy reaction when in contact with flammable substances".* Javel water can cause a fire if it comes into contact with flammable products.
- *"H3-A-Highly flammable: Substances which are liable to catch fire, whether liquids with a flash point below 21°C, substances which ignite spontaneously at room temperature, flammable solids in contact with a source of ignition, flammable gases at normal pressure or substances which emit dangerous flammable gases in the presence of water or moisture".* Ether ignites spontaneously at room temperature.
- *"H3-B-Flammable: Liquids that ignite at moderate temperatures, with a flash point between 21°C and 55°C".* Gasoline ignites easily when exposed to a flame.
- *"H4-Irritant: Substances that cause redness, pain or inflammation when in prolonged contact with the skin or mucous membranes".* Ammonia can cause tingling or redness of the skin.
- *"H5-Harmful: Materials that present a risk to human health, such as mild or moderate disorders following ingestion, inhalation or skin contact".* Inhaling pesticides can cause headaches.
- *"H6-Toxic: Dangerous products that can cause serious, irreversible or fatal effects if swallowed, inhaled or absorbed through the skin".* Even in small quantities, cyanide is lethal.
- *"H7-Carcinogenic: Substances which may cause cancer or increase the likelihood of cancer after repeated exposure".* Years of exposure to asbestos can cause lung cancer.
- *"H8-Corrosive: Materials that attack living tissue and cause serious damage if they come into contact with the skin or eyes".* Hydrochloric acid can burn the skin when it comes into contact with it.
- *"H9-Infectious: Materials that contain germs or toxins that can cause serious illness in humans or other living creatures".* Using a syringe that has been used before can transmit virus.
- *"H10-Toxic for reproduction: Substances that may affect prenatal development or increase the incidence of congenital anomalies".* Lead exposure can result in birth defects.
- *"H11-Mutagenic: Materials capable of causing heritable genetic changes that alter the genetic material of exposed individuals".* Exposure to benzene can cause mutations in blood cells.
- *"H12-Release of toxic gases in contact with water, air or acid: wastes which, on contact with water, air or acids, emit harmful or very harmful gases".* An old industrial waste drum can release a noxious gas if opened.
- *"H13-Sensitising: Substances that may cause serious allergic or hypersensitivity reactions after initial or repeated exposure".* Paints containing isocyanates can trigger severe respiratory allergies.
- *"H14-Ecotoxic: waste that could seriously disturb the ecological balance or affect fauna, flora or ecosystems".* Spilt coolant in a river can kill fish.

[2] "*liquid that takes in substances from the material through which it passes, often making the liquid harmful or poisonous"* https://dictionary.cambridge.org/fr/dictionnaire/anglais/leachate

- *"H15-Waste likely to generate a hazardous substance after disposal: Wastes which, after treatment or disposal, may release by-products presenting hazards comparable to those listed above".* Ash produced by waste incineration can contain toxic heavy metals.

1.3. Origin

According to the European Court of Auditors (2023), hazardous waste generated in the European Union originates from both households and economic operators. However, scientific articles more commonly use the terms "*municipal waste*" and "*industrial waste*". This is why these two categories are therefore used below.

- **Municipal waste**

According to the Federal Planning Bureau (2024), municipal waste is waste from households or other sources such as retail trade, public administration, offices and other services and activities, which is similar in nature and composition to waste from households such as paper, food, garden plants.

In Belgium, municipalities are responsible for collecting household waste. They can either take charge or delegate the responsibility to an inter-municipal company or a private company. There are three types of collection: door-to-door collection, voluntary collection and store collection. Door-to-door collection is carried out according to a schedule drawn up by the municipality, taking into account the frequency and type of waste to be collected. The types of waste that can be collected using this method include PMC, residual waste, organic waste, paper and cardboard and bulky waste. Voluntary collection and drop-off points are containers parks, bottle banks or other collection points where people can drop off certain types of waste free of charge. In the case of store collection, these are mainly small electronic devices, used batteries and light bulbs (Collignon & Gathon, 2010; Union des Villes et Communes de Wallonie, 2024).

Part of the cost of these services is covered by households through a municipal tax, which includes both a flat-rate component and a variable component based on the amount of waste produced (Collignon & Gathon, 2010).

Of the 2.2 billion tonnes of waste generated each year in the European Union, 27% is municipal waste (Parlement européen, 2018). In 2023, a person living in Belgium generates 694 kg of municipal waste, of which 34% is recycled and 45% incinerated (STATBEL, 2024). There are no clear figures on the share of hazardous waste in this category. However, we do know that in 2018, 4% of the hazardous waste generated came from households. This includes solvents, paints and pesticides (European Court of Auditors, 2023).

The challenges faced by municipal waste are mainly sorting and managing the volume produced. In response to these challenges and within the context of "smart" cities[3], a number of innovative technologies have been developed to enhance municipal waste management. These technologies include smart bins equipped with sensors to detect gas, temperature, weight and ultrasonic sensors to detect how full the bins are. These sensors can be used to monitor the fill level and any abnormal events inside the bin. These smart bins are connected via IoT (Internet of Things) systems and can automatically send notifications to local authorities and transmit data via RFID (Radio Frequency Identification) tags. This makes it easier to plan collections and process data for more efficient management. At the same time, artificial intelligence and robotics can be used to sort waste based on its shape, colour, or materials (Czekała et al., 2023)

[3] "*An urban area that uses information technology to improve its services and optimise operational efficiency and costs".* https://www.veolia.com/fr/ressources/smart-city

- **Industrial waste**

Economic activities generate most of the waste produced in the European Union.
There are four main economic activities:

- The primary sector, which includes everything related to the extraction of raw materials.
- The secondary sector, which includes the transformation of raw materials into goods.
- The tertiary sector includes all services related to the distribution and consumption of goods.
- The quaternary sector includes all knowledge-based services, i.e. everything to do with research and development, IT, etc. (Inglezakis & Zorpas, 2011).

In addition to the sectoral breakdown, economic activities in Europe are classified according to a specific nomenclature, the NACE codes (Nomenclature statistique des Activités économiques dans la Communauté Européenne - *Nomenclature of Economic Activities*). These codes are made up of several levels, starting with a letter (the headings), which are then broken down by two, three and then four digits to form divisions, groups and finally classes (STATBEL, 2008). For example, C 28.11 is the NACE code for:

Table 1: Example of NACE code

C	Manufacturing industry
28	Manufacture of machinery and equipment N.E.C.
28.1	Manufacture of general-purpose machinery
28.11	Manufacture of engines and turbines, except aircraft engines, motor vehicles and motorbikes

Source: STATBEL. (2008). *NACE-BEL 2008: Nomenclature des activités économiques avec notes explicatives.* https://statbel.fgov.be/sites/default/files/Over_Statbel_FR/Nomenclaturen/NACE-BEL%202008_FR.pdf

This sectorial breakdown makes it easier to structure economic and statistical data to facilitate comparisons between countries and sectors within the European Union (STATBEL, 2008). However, there is no clear definition of the term "*industry*" in the legislation. As a result, several definitions are intertwined. For some, industry is synonymous with the secondary sector, i.e. any activity that involves the production of goods. For others, industry refers to all economic activities (Inglezakis & Zorpas, 2011). In this work, we agree with this second proposition, the term "industrial" refers to all economic activities. However, given the scope and scale of hazardous waste production, the analysis will focus on the four main sectors that are responsible for the majority of hazardous waste generation in the European Union. These economic activities are manufacturing, water and waste management, construction and extractive industries and they represent 75% of total hazardous waste generated in the European Union. These sectors refer to the following NACE codes: B – Extractives industries, C – Manufacturing industry, E - Water production and distribution; wastewater treatment; waste management; and pollution control, and F – Construction. The two main hazardous waste streams generated in Europe, considering the figures of 2018, are mineral and solidified waste, which refers to waste from mineral origin such as from construction or extraction, and hazardous waste that has been chemically treated and solidified to limit the release of harmful substances. This category only, accounts for 57.3 million tonnes, followed by chemical and medical waste at 26.5 million tonnes. This waste often contains toxic heavy metals (European Court of Auditors, 2023).

Table 2: Comparison between municipal and industrial waste management

Municipal	**Industrial**
Collection: - Collected service from the local authority - Kerbside collection at intervals - Voluntary or in-store collection	Collection: - Private companies - Companies are responsible for managing their waste - Depending on the needs of the company

Cost: - Local or national taxes Types of waste: - PMC, residual waste, organic waste, paper and cardboard, bulky items Problems: - High volume and poor sorting	Cost: - Charged for as commercial service Types of waste: - Hazardous and non-hazardous waste - Inert waste Problems: - Diversity, hazardousness, regulatory complexity

Sources: Awuchi, C. G., Awuchi, C. G., Amagwula, O. I., & Igwe, V. S. (2020). Industrial and community waste management: Global perspective. *American Journal of Physical Sciences*, *1*(1), 1–16. https://doi.org/10.47604/ajps.1043.
Service Public de Wallonie. (2018). *Plan Wallon des Déchets-Ressources*.
https://environnement.wallonie.be/files/Images/Gestion%20environnementale/D%c3%a9chets/PWDR_3.pdf

1.4. Legislation

Waste is regulated at different levels of government. At European level, waste is regulated by Directive 2008/98/EC. This Directive aims to reduce the harmful effects of waste production and management in order to protect the environment and human health. It excludes certain types of waste from its scope, in particular radioactive waste and gaseous effluents emitted into the atmosphere. One of the basic principles of this Directive is the prioritisation of waste. Until recently, the life cycle of waste was extremely short. The main aim was to get rid of it quickly: hide it, bury it or dispose of it and never see it again (D'Arras, 2008). This approach has changed, driven by environmental concerns and regulations. Figure 1 shows the different stages of this prioritisation, namely prevention, preparation for re-use, recycling, recovery and finally disposal. The principle is therefore based on the three Rs: reduce, reuse and recycle. Producers are encouraged to rethink the way they produce in order to use fewer resources, minimise waste and produce more responsible products with a lower environmental impact. This approach is known as eco-design. The easiest way to manage waste is to not create it in the first place. This prioritisation is fully in line with a circular economy approach, as opposed to the traditional linear economy model. Whereas the linear economy consists of extracting, producing, consuming and then discarding, the circular economy aims to optimise the use of products at each stage of their life cycle while limiting negative impacts on the environment (Héry et al., 2014).

Figure 1: Prioritisation of waste

Source: European Commission. (n.d.). *Waste Framework Directive.* https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en

Another point supported by the Directive is the extended polluter pays principle. This is an extension of the basic 'polluter pays' principle, which ensures that those responsible for generating waste take responsibility by making them pay for the costs of that pollution. The extended 'polluter pays' principle goes further by making producers responsible for the entire life cycle of their products. They need to build waste management into the design of their products right from the start. This principle encourages companies to design products that are more sustainable, easier to recycle, reuse or at least easier to manage at the end of their life because they are responsible for them (Pesqueux, 2021).
Hazardous waste is subject to a more stringent set of rules. These rules are as follows:

- Any company involved in the management of hazardous waste must have a special permit.
- Hazardous waste must be tracked from production to disposal using electronic records.
- Hazardous waste must be specially labelled and packaged during collection, storage and transport.
- Hazardous waste must be segregated; it must not be mixed with non-hazardous waste or other hazardous waste (Union européenne, 2008).

The Waste Framework Directive requires each Member State to draw up a waste management plan. In Belgium, this is the responsibility of the regions (Collignon & Gathon, 2010). As a result, each region had to draw up its own management plan. In Wallonia, the plan is called "*Plan Wallon des déchets-ressources*" (Walloon Waste Resources Plan) and its aim is to combat environmental crimes, incivilities in general, as well as littering and illegal dumping. According to figures from 2013, Wallonia produces 15.2 million tonnes of waste, divided between households and industry. Hazardous industrial waste accounts for 763,079 tonnes. Holders of hazardous waste are obliged to declare it annually to SPW ARNE (Agriculture, Ressources Naturelles et Environnement – *Agriculture, Natural Resources and Environement*) (Service Public de Wallonie, 2018). The Walloon Waste Resources Plan highlights a number of objectives in relation to hazardous waste, including reducing its production while maintaining economic activity, and improving and diversifying the treatment facilities located in Wallonia. (Dejemeppe, 2022).

This section demonstrates that waste is governed by Directive 2008/98/EC at the European level. This directive highlights the importance of prioritising waste and encourages eco-design as part of a circular economy. The directive also introduces the extended 'polluter pays' principle, making producers responsible for their products throughout their lifecycle. Hazardous waste is subject to stricter rules, particularly with regard to traceability, labelling, packaging, segregation and authorisation. In Belgium, the regions are responsible for waste management, including setting up a plan that complies with the European directive's requirements.

1.5. Waste management

This section is fundamental as it provides a comprehensive overview of the waste management chain from identification to final disposal. Understanding each stage enables critical analysis of where inefficiencies, environmental risks or regulatory gaps may exist. It also provides the basis for assessing how innovative solutions, such as smart packaging, could be integrated or used to improve certain stages of the process.

The management of waste involves several stages: identification and classification, collection and storage, transport, pre-treatment, treatment and, finally, disposal. These stages are detailed below.

- **Identification and classification**

The identification and classification of waste is based on the list set out in Directive 2000/532/EC of 3 May 2000, in which each type of waste is coded using six digits. The first two digits indicate the source

of the waste, from 01 - Waste from mining and mineral processing - to 20 - Municipal waste from households, businesses, industries and administrations. The next two indicate the sector of activity, process or operation from which it originates. And the last two identify the waste. Here is an example of a code for waste that is considered to be hazardous:

Table 3: Example of a code for hazardous waste

07	Waste from organic chemical processes
07 01	Waste from the manufacture, formulation, supply and use (MFSU) of basic organic chemicals
07 01 04*	other organic solvents, washing liquids and mother liquors

Source: Commission européenne. (2000). Décision 2000/532/CE de la Commission du 3 mai 2000 remplaçant la décision 94/3/CE établissant une liste de déchets. Retrieved October 20, 2024, from https://eur-lex.europa.eu/legal-content/FR/ALL/?uri=celex:32000D0532.)

There are three ways of classifying hazardous waste:

1. Waste marked with an asterisk is considered hazardous in absolute terms.
2. Waste without an asterisk is considered non-hazardous in absolute terms.
3. Waste with both hazardous and non-hazardous characteristics is a "*mirror entry*". To determine the nature of this "*mirror entry",* it is necessary to examine the composition of the waste and identify whether it possesses any of the properties listed in Annex III of Directive 2008/98/EC (see section 1.2., page 4).

- **Collection and storage**

Once hazardous waste has been identified and classified, it is initially stored at the production site. The best practice for this storage is to store the different types of waste separately and segregate it according to the type of hazardous waste. This facilitates the subsequent stages of waste management and reduces the risk of accidents. This storage differs from pre-treatment storage, which takes place in reception centres or interim facilities pending transfer to treatment or final disposal facilities. These reception centres allow waste to be grouped together and avoid long journeys with hazardous waste when treatment and/or disposal facilities are located far from the production site (Organisation Mondiale de la Santé, 1984). Waste must be stored under specific conditions, i.e. in a cool, dry, well-ventilated place. Waste containers must be clearly labelled to indicate the precautions to be taken when handling it (Institut National de Recherche et de Sécurité, 2022).

Waste may be collected regularly or on request. Regular collection takes place at pre-determined intervals, in consultation with the producer, and reduces the risks associated with collection. This type of collection is ideal for regular waste production. On the other hand, on-demand collection is used for more fluctuating waste production (Organisation Mondiale de la Santé, 1984). Collection is carried out when the producer deems it necessary.

- **Transport**

In Belgium, in order to transport or collect hazardous waste, the company must hold a permit issued by the SPW ARNE and more specifically by the DSD (Département du Sol et des Déchets - Department of Soil and Waste) for a renewable period of 5 years (SPW, 2025).

The transport of dangerous goods is subject to the ADR Regulation (European Agreement concerning the International Carriage of Dangerous Goods by Road), which aims to prevent accidents during transport, loading and unloading. The term goods covers anything that is a mixture, object, material

or even waste that represent a danger. This is why hazardous waste must be transported in accordance with the ADR regulations. These ADR regulations define 9 classes of dangerous goods:

- Class 1: Explosive substances and articles
- Class 2: Gases
- Class 3: Flammable liquids (including liquids and articles containing such liquids with a flash point below 60°C, as well as desensitised explosive liquids).
- Class 4.1: Flammable solids, self-reactive substances, and solid desensitised explosives
- Class 4.2: Substances liable to spontaneous combustion
- Class 4.3: Substances which, in contact with water, emit flammable gases
- Class 5.1: Oxidising substances
- Class 5.2: Organic peroxides
- Class 6.1: Toxic substances
- Class 6.2: Infectious substances
- Class 7: Radioactive substances
- Class 8: Corrosive substances
- Class 9: Miscellaneous substances and objects (INRS, 2020).

The classes most commonly used for transporting hazardous waste are: Class 3 – Flammable liquids, Class 4.1 – Flammable solids, Class 5.1 – Oxidising substances, Class 6.1 – Toxic substances, Class 8 – Corrosive substances, Class 9 – Miscellaneous substances and objects (SARPI Veolia, 2023).

Hazardous waste can be transported in packages, in bulk, or in tanks. Here, we are going to focus on the package option. There are three types of packaging: there are simple packages, such as cans and barrels, or combined packages such as crates containing bottles. The other two types are IBCs (Intermediate Bulk Containers) such as big bags and 1000L containers, and LP (Large Packaging), which are similar to combined packages, but have a capacity of between 450 and 3000L. All these packages must be of good quality and strong enough to withstand normal impacts during handling and transportation. Additionally, the part that comes into direct contact with the hazardous substance must not be altered or weakened by contact with its contents, nor must the two be capable of reacting with each other. These packages must also be approved by a recognised body. To achieve this, a series of tests must be carried out on prototypes filled with a similar substance in terms of weight and nature to that which will be carried in the final version. These tests include drop tests, stacking tests, internal pressure tests and leak tests. Once approved, plastic packaging remains valid for two to five years, whereas metal packaging has no expiry date, provided it remains visually intact (FNADE & MAIAGE, 2025).

There are three groups of packaging, depending on the hazard of the product. Group I corresponds to very dangerous goods, group II to moderately dangerous goods and group III to slightly dangerous goods. Regardless of the class, the goods being transported may belong to one of these three groups. Packaging approval includes a code (X, Y or Z) that indicates the level of danger for which the package has been certified: X for groups I, II and III, Y for groups I and II and Z for groups III (FNADE & MAIAGE, 2025).

Each approved package must carry a UN (United Nations) identification number, beginning with the letters UN and followed by a series of numbers and letters that represent the identity card of the dangerous goods (its class, its packing group, the type of packaging, and so on). Pictograms should be used to indicate stacking instructions and maximum loads and, where appropriate, labels should be used to indicate the orientation of the packaging as well as the types of hazard present (SPW, 2025).

A dangerous goods declaration must be completed for the transportation, including mandatory qualitative and quantitative information such as the total quantity of each dangerous good and the

name and address of the consignee. There are also rules on how to load goods on the truck, particularly in terms of compatibility: some goods cannot be transported with others. Drivers must have undergone special training to be able to transport, load and unload this type of goods (SPW, 2025).

Therefore, hazardous waste must be transported by an SPW ARNE-approved carrier in accordance with the ADR rules. It must be classified according to its nature and packaged according to its level of hazard. This packaging must be assigned a UN code to identify the waste being transported. Other markings, such as pictograms and labels, must also be affixed to provide as much information as possible about the contents. The government can requires carriers to provide information on waste movements through registers, forms or tracking document (Union des Villes et des Communes de Wallonie, & SPW, 2024).

- **Pre-treatment and treatment**

The aim of hazardous waste treatment is to reduce its hazardousness and volume so that it can be disposed of properly. There are four types of treatment:

- Physical treatment: the aim is to separate the components of the waste using their physical properties, such as density, particle size or adsorption.
- Chemical treatment: this involves changing the chemical composition of the waste through chemical reactions to reduce its toxicity or reactivity, or to make it more stable.
- Biological treatment: involves the use of living organisms to break down or convert waste into acceptable products.
- Thermal treatment: the aim is to destroy organic contaminants at very high temperatures to make the waste more stable and viable, and to reduce the amount of waste to be disposed of (Polprasert & Liyanage, 1996 ; Varshney et al., 2021).

Depending on the type of waste, these treatments can also be considered as 'pre-treatment', i.e. the stage prior to subsequent treatment. This makes it easier to handle, transport and therefore treat.

- **Disposal**

There are several ways to dispose of waste. These are listed from D1 to D15 in Annex I of Directive 2008/98/CE, titled “Disposal operations”. Only the most common and widely used methods are described here.

The two most common methods of treating hazardous waste are incineration and landfill, each of which has specific advantages and disadvantages. Incineration is often used when the waste cannot be reused or recycle and cannot be discarded safely in landfills due to excessive toxicity or risk of contagious spreading. The aim of incineration is to destroy toxic organic substances and reduce the volume of hazardous waste. The main advantages of incineration include limiting the risk of groundwater pollution, saving space and recovering energy. However, this method produces toxic pollutants emissions such as dioxins and heavy metals, and requires expensive facilities with high-performance filtration systems in order to comply with strict environmental standards (Kumar et al. 2023).

Meanwhile, landfilling remains the most widespread strategy in developed countries. This involves isolating waste in specialised sites after prior sorting in order to minimise the environmental impact of waste. This solution is inexpensive, simple to implement and requires little manpower. However, this method generates large volume of toxic leachate and greenhouse gas emissions, posing long-term environmental challenges (Kumar et al. 2023).

Where possible, hazardous waste should be reused, recycled or recovered. Valorisation operations, like disposal operations, are listed in the annexes of Directive 2008/98/CE. These operation can be found it in Annex II using the codes R1 to R13.

If we take the example of recycling, it involves various techniques that add value to industrial waste by transforming it into useful products, recovering resources or extracting valuable materials. However, this method is a cleaner approach, recycling is relatively underdeveloped because it often requires high investment costs (Kumar et al. 2023).

In conclusion, the management of hazardous waste is based on a rigorous chain of processes that adhere to strict regulations, particularly with regard to identification using the 6-digit codes and transport in accordance with ADR regulations. This section outlines the various stages involved in the proper management of waste.

1.6. Problems and limitations

Several problems and limitations are associated with the management of hazardous waste.

Hazardous waste management is considered to be a long and dangerous process, involving heavy metals and organic chemicals that can have very serious negative effects on human health and the environment. This waste therefore has to undergo several treatment processes to reduce its hazardousness. These treatments are costly compared to non-hazardous waste: 238€ per tonne compared to 63€ per tonne for non-hazardous waste (European Court of Auditors, 2023). This can lead to illegal practices such as illegal dumping and waste trafficking. Illegal dumping refers to the disposal of waste in places not intended for this purpose and is punishable by a fine. Waste trafficking is the act of selling, buying, transporting, exporting or importing waste for financial gain in a manner that does not comply with the regulation in force in the country. Whether it's illegal dumping or trafficking, it leads to pollution and health risks for people living near or exposed to it (Kumar et al. 2023).

Regulations can vary from one country to another, leading to difficulties in import/export despite efforts to reach agreement, such as regulations at European level. Some wastes may be considered hazardous in one country but not in another, and vice versa. Sometimes the definitions of certain terms are not the same, leading to problems of understanding and management (White & Heckenberg, 2011).

Another problem is identification and classification. Indeed, it can sometimes be difficult to identify the type of waste we are dealing with, even more so when it is a mixture. If the waste is not correctly identified and classified, this can cause problems throughout the management chain. For instance, one can cite the inappropriate packaging, or the waste not being treated and disposed of in the best possible way.

- **Environmental and health impacts of hazardous waste**

Hazardous waste can have negative environmental and health impacts if it is not properly treated and managed. These effects vary according to the type, quantity and concentration of the hazardous element present in the waste and may be direct or indirect, i.e. immediate or delayed, the effects being felt over a period of time (Exposto & Sujaya, 2021).

In terms of human health, hazardous substances can enter the body in a number of ways, including inhalation, through the skin, orally or by injection. Once inside, they are distributed throughout the body via the bloodstream. These substances can therefore reach different organs and cause certain acute and chronic diseases, including cancer. This can affect any part of the body, including the

digestive system, the nervous system, the respiratory system, the cardiovascular system, skin problems and, worse still, death (Exposto & Sujaya, 2021).

In terms of the environment, it is not just the soil, water or air that is polluted, but the whole ecosystem. A number of environmental and health disasters have been caused by hazardous waste. The Minamata Bay disaster in Japan in the 1950s is a case in point. A chemical plant from the Chisso Corporation[4] discharged its effluent directly into the bay. The effluent contained methylmercury, a highly toxic compound. This substance first contaminated the fish in the bay and then affected people who ate some of the fish. The main effect was on the nervous system. Thousands of people were affected and many died (Collaborative for Health & Environment, n. d.). There is also the case of Love Canal, an area of Niagara Falls in the state of New York. This unfinished canal was bought by a chemical company, which used it as a waste dump for several decades before selling the land to the city. The city then built housing and public infrastructure on the site. Years later, residents complained of strong chemical odours, with some chemicals coming to the surface during heavy rainfall. In terms of health effects, many cases of cancer have been reported, as well as congenital malformations, miscarriages, respiratory and neurological problems. In terms of the environment, the soil and groundwater were contaminated, making the whole area dangerous (Beck, 1979). These two examples highlight the fact that proper management of hazardous waste is essential for everyone's safety. As a result of these cases, many stricter measures have been taken at government level to manage hazardous waste, leading to a global awareness of the potential impact of industrial production.

- **Transboundary movements of waste**

Waste may be exported or imported, a phenomenon known as transboundary movements. These movements occur for a number of reasons, whether economic, technical or environmental. The management of waste, especially hazardous waste, is extremely costly and requires specialised facilities that are often lacking in some countries. This situation has led some countries to export their waste rather than deal with it locally (OMS, 1984).

However, these movements have led to an increase in uncontrolled dumping, particularly in developing countries. These uncontrolled exports have caused serious environmental problems, polluting soil, water and air. They have also had a major impact on the health of local populations, who have been exposed to toxic substances (Secrétariat de la Convention de Bâle, 2010).

To remedy this situation, the Basel Convention was negotiated and adopted in 1989 and entered into force in 1992. This treaty now has 170 member countries and aims to regulate the transboundary movement of hazardous wastes and their disposal. The main objective is to protect human health and the environment from the risks associated with poor waste management.

The Convention is based on the principle of 'prior informed consent'. This means that each country involved in the shipment of waste - the exporting country, the importing country and even transit countries - must be informed in advance and give its explicit consent before the shipment is authorised. In the absence of such prior consent, the shipment is considered to be illegal and subject to criminal sanctions (OMS, 1984).

By increasing the transparency and traceability of waste flows, the Basel Convention plays an essential role in the fight against illegal waste trafficking.

[4] It is a Japanese chemical company. https://www.chemeurope.com/en/encyclopedia/Chisso.html

2. Smart packaging

2.1. General overview of packaging

Whenever we mention packaging, we tend to refer to the packaging that contains the product we want to use. In reality, there are three types of packaging: primary, secondary and tertiary. Each has a very specific role. The first is the packaging that contains the product itself. This is the last packaging that the consumer throws away. The second is the packaging that surrounds the primary packaging, which groups the primary packaging together and provides visual communication such as hazard pictograms, recycling symbols or brand logos. The third is the packaging used for handling, whether in warehouses for storage or for transport. Packaging is at the heart of four key areas for the company that produces the product: marketing, production, logistics and the environment (Regattieri & Santarelli, 2013).

Packaging for any type of product is often seen as a marketing tool, but beyond the image it conveys, it has other very important functions. There are four functions: containment, protection, communication and convenience. The primary purpose of packaging is to contain the product, it is the basic function. The second function is to protect the product inside by creating a barrier. The packaging must protect the product from impacts, weather changes, pressure, and theft. The barrier protects the product from oxygen, water, mould and dust. The third function is convenience, meaning the packaging is designed to be easy to handle during loading and unloading. It also helps with stock control, especially for bulk products such as milk or sugar. The presence of packaging makes it easier to keep track of stock. And finally, the last function is communication. As well as communicating from a marketing point of view, packaging provides information on how to handle the product such as weight or the way it should be stored (e.g. opening upwards), how to use the product, how to recycle it after use and where it comes from (Limbourg, 2023). Some information is sometimes required by the authorities, particularly for food, pharmaceutical/medical or chemical products.

2.2. Introduction to smart packaging

Smart packaging is an overall term that encompasses two different types of packaging technologies: active packaging and intelligent packaging. While the terms “smart packaging” and “intelligent packaging” are often used interchangeably, they refer to different concepts. Active packaging incorporates components such as additives or materials that interact with the product or its environment to maintain or extend the shelf life and preserve product quality. This goes beyond conventional or passive packaging, which simply serves as a package without affecting the product. Intelligent packaging, on the other hand, does not interact directly with the product, but incorporates sensors and indicators that can detect, record and communicate changes in the product or its environment. This makes it particularly useful for ensuring quality and safety. Intelligent packaging can thus be seen as an extension of the communication function, while active packaging extends the protection function (Yam, Takhistov & Miltz, 2005). Intelligent packaging first appeared on the Japanese market around fifty years ago, before developing in the 1990s, mostly in European and American markets (Osmólska et al., 2022).

As a concept, smart packaging combines both approaches: it monitors (intelligent packaging) and reacts (active packaging) to its environment (Schaefer & Cheung, 2018).

2.2.1. Intelligent packaging

Intelligent packaging can also be divided into two groups: data carriers and recorders.

- **Data carriers**

Data carriers allow products to be tracked throughout the chain, from production to distribution. This improves product safety and allows consumers to track the entire history of a product. This traceability can be achieved using barcodes, which store data and information and can be read using a reader that scans the lines and has access to the data relating to the product to which the barcode refers. There are two types of barcodes: 1D and 2D, or QR codes. These barcodes are also used for inventory management.

RFID tags are also widely used. These are attached to products, pallets or packaging and are also used to store information and data about the product. The RFID tag consists of a chip which contains a unique serial number, an antenna and a substrate (Kalpana et al., 2019b). The tag is operated by a reader which emits a radio signal that activates the RFID tag. The two will then identify each other and the tag transmits its information to the reader. We can distinguish two types of RFID tags: passive tags and active tags. The difference is in the power source: active tags have a battery, while passive tags are powered by signals from the reader. RFID tags have several advantages over barcodes: they do not need to be on the surface to transmit their information, they can be read much faster than barcodes and from much further away (<100m), they can be reprogrammed if necessary and have a large memory capacity if required. The obstacles with this tag are that there are several frequencies that can be used depending on the country, certain liquids or metals can deflect the waves, and there can also be interference with walkie-talkies, for example (Limbourg, 2023).

- **Recorders**

In terms of recorders, there are indicators and sensors. The most common sensors used in food industry are gas sensors such as oxygen and carbon dioxide, pH sensor, humidity sensor, and time and temperature sensors. All of these sensors measure data that, depending on the amount, can have a positive or negative impact on the food product. On the indicators side, the three main categories of indicators are time-temperature indicator, freshness indicator and gas indicators (Ozcan, 2020).

Indicators provide only qualitative or semi-quantitative data on observable physical changes. For example, a colour-changing label that indicates if a product has been exposed to high temperatures or a time-temperature indicator that darkens over time. These tools do not give precise values, only a visual indication. Sensors, on the other hand, provide precise quantitative measurements of the information detected by converting it into a signal. For example, a digital temperature sensor that records and displays the exact temperature, or a gas sensor that measures the concentration of oxygen. This is a more sophisticated and complex device than an indicator.

A sensor can be define as "*[…] an instrument that detects, locates, or determines events or changes in the surrounding environment and then transmits signals to measure physical or chemical parameters*" (Osmólska et al., 2022b). Sensor consists of two main components: a receptor, which transforms chemical or physical information into signal and a transmitter, which converts this energy into a chemical, optical, electrical or thermal signal (Osmólska et al., 2022b). To be an ideal sensor, a sensor should have these five characteristics: specificity, meaning it should be able to focus on what it has to detect without being distracted by other information, be sensitive to changes in concentration, have a quick reaction time, last over time, at least a few months and be small in size.

On the indicators side, they indicate the absence or presence of certain substances, as well as differences in the concentration of chemicals present and changes in colour (Ozcan, 2020). These can be found both on the outside and inside of the packaging.

2.2.2. Active packaging

Active packaging is accurately defined as "*packaging in which subsidiary constituents have been deliberately included in or on either the packaging material or the package headspace to enhance the performance of the package system*" (Huff, 2008). This is a packaging where the product and its environment interact to actively change the conditions within the packaging to extend the shelf life of a product, improve internal safety and maintain product quality. (Wyrwa & Barska, 2017). Active packaging combine physical, biological and chemical effects to achieve these interactions.

The conditions inside the packaging can be modified in two ways: either by absorbing unwanted substances or by diffusing substances that will have a positive effect on the preservation of the product. These two types of substances are called "scavengers" and "emitters" respectively. Scavengers are mainly used to absorb oxygen, moisture, ethylene and odour. The most commonly used emitters are carbon dioxide, ethanol, antioxidants and antimicrobial emitters. These emitters and scavengers are often in the form of small sachets or films. (Yam, Takhistov & Miltz, 2005)

2.2.3. Application areas

Nowadays, smart packaging are mainly used in the food industry for two reasons: to avoid food waste and contamination caused by poor storage or transport conditions. The two main functions of smart packaging in this sector are to maintain the quality of the product and to extend its shelf life. This type of packaging is also of interest to consumer, especially thanks to the freshness indicators and QR codes that can provide more information about the products, thus offering greater transparency (Kalpana & al, 2019). The food industry is currently the main sector using smart packaging, accounting for 45% of global sales in 2015. (Aliakbarian, 2019).

In the pharmaceutical industry, smart packaging is also used to maintain product quality and safety. They allow product movements to be authenticated and tracked, which is very important in this sector. Again, as with food products, this enables better communication with patients who are the consumers of these products. For example, dosage information, real-time interaction, and reminders (Collazo, 2024). This can help ensure better compliance with regulations, which, like those for food, are quite strict. The healthcare sector accounted for 15% of smart packaging use in 2015 (Aliakbarian, 2019).

2.2.4. Benefits

Once the principles of smart packaging have been discussed, it is time to look at the practical benefits. While these innovative solutions have already proven their worth in the food industry, they also offer interesting potential for the hazardous waste sector. We will therefore examine how the benefits of smart packaging for food products can not only be recognised, but also potentially applied to improve the management and safety of hazardous waste.

According to Young and al., (2020), the perceived benefits to consumers of using smart packaging in the food sector can be divided into 3 categories; functional, epistemic and hedonistic benefits. These three categories will be used to highlight the benefits of smart packaging for the management of hazardous waste. These benefits will be more focused on the actors involved in the chain of such management, rather than on the end consumer, as is the case in the review of Young and al., (2020b). Functional benefits refer to the practical and operational advantages that a product or technology provides to its users. In the case of smart packaging, a functional benefit can be the improvement of product safety. Sensors can be used to monitor the real-time condition of the waste during transport, or indicators can be used to indicate any changes in the packaging environment. This enables a rapid response in the event of an abnormal change with the help of active packaging for example. Another functional benefit is in terms of logistics and product traceability. RFID tags or barcodes make it

possible to locate the package at any time and thus know its status throughout the supply chain, which can be useful in the event of problems. Data carriers can also be used to prove the authenticity and integrity of the waste transported.

The epistemic benefits are those associated with the knowledge and understanding that a product or technology offers. These benefits mainly concern the acquisition, organisation and diffusion of accurate, reliable and useful information. In terms of using smart packaging for hazardous waste, smart packaging could be used to dynamically communicate product details concerning the history and quality of the waste. Here again, sensors and indicators provide useful information as well as data carriers, which give valuable indications about the entire supply chain and enable critique points to be identified. As a result, the various actors in the chain will have better information about the waste and will therefore have better control and quality management over them.

Hedonistic benefits refer to the advantages associated with pleasure, satisfaction and the positive emotional experience that a product or technology provides for users. These benefits are considered to be ancillary. Interaction with the consumer is also a benefit in the food sector, by placing a QR code for example, on the product to direct the consumer to a website or interactive content, thus enriching the user experience. It is imaginable that this could also be used for hazardous waste, either by looking to the manufacturer's information or by providing information on the constituents of the waste or on preventive measures, for example. This benefit could be used for transporter as well as anyone else in the waste management chain.

2.2.5. Barriers

The barriers of the application of smart packaging can also be divided into several categories according to Young and al. (2020b). These categories are namely the usage barrier, the value barrier and the risk barrier.

The usage barriers are the obstacles that prevent users from adopting or using a product or technology effectively. These barriers may be technical, ergonomic or related to the perceived complexity of use. When it comes to smart packaging for hazardous waste management, one potential barrier is the complexity of implementation. This could necessitate changes or updates to certain programmes, which would require time and resources. Incompatibility with existing systems and infrastructure can also be seen as a barrier to uptake, and people's skills or training of people may not be adapted to these technologies. Technically, RFID tags have more difficulties with metals and liquids, especially as the frequency increases. The higher the frequency, the greater the distance and the transmission, but this also leads to more interference. Similarly, oxygen scavengers are also incompatible with liquids ((Fernandez et al., 2022); (Ozcan, 2020)).

Value barriers are obstacles that prevent users from perceiving or recognising the added value or benefits of a product or technology over what they are already using. These barriers are often related to the cost-benefit ratio and the value proposition of the product. If the cost of smart packaging is too expensive and the perceived benefits are not seen as a significant improvement over what is already available, adoption may be limited.

Risk barriers are obstacles linked to the perception of risks or uncertainties associated with the adoption of a new product or technology. These barriers can relate to economic risks, performance risks, physical risks and social risks. Companies may be concerned about an uncertain return on investment, hidden costs associated with maintenance or training, as well as concerns about material safety, the environmental impact of end-of-life smart packaging or customer privacy in the transfer of sensitive and personal information in the pharmaceutical sector.

Table 3: Comparison between problems in hazardous waste management and benefits of smart packaging.

Problems related to the management of hazardous waste	Benefits of smart packaging
- ***Better classification of waste*** - Different regulations in different countries: standardisation of rules. - ***Complex regulations*** - ***Waste trafficking*** - ***Illegal dumping*** - A long and dangerous process - ***Costly*** - ***Negative impact on the environment and human health*** - Sometimes, there is no appropriate treatment available in the country of production. - The producer is responsible for the waste throughout its lifecycle. - Some developing countries accept hazardous waste in order to make money, even though they lack the resources to treat it properly. - ***Involves heavy metals and organic chemicals.*** - Mitigate the hazardous characteristics of the waste. - Reduce the volume. - ***It must not come into contact with other hazardous or non-hazardous waste.***	- ***Ensures quality (in real time or not) and safety during storage and transport*** - Prevents chemical contamination - Facilitates decision-making - ***Alerts you to potential problems*** - Protects against theft and counterfeiting - ***Improves traceability*** - ***Interaction between the contents of the packaging and its environment*** - Records the external conditions of the product - Maintain or extend product shelf life - ***Emit or absorb desirable/undesirable substances into the packaging*** - ***Detect the presence or absence of a substance*** - ***To detect a reaction between two or more substances*** - Exchange information with consumers - Prevents spoilage - Reduces waste and loss (of food) - Meets consumer expectations - ***Provides accurate data*** - ***Better logistical control*** - ***Reduces costs*** - ***Provides additional information (origin, location, storage conditions, destination)***

This comparative table highlights the potential connections between hazardous waste and smart packaging. Five hypothesis have been formulated based on these connections. They are as follows:

- Smart packaging could help/improve the traceability of hazardous waste
- Smart packaging could improve safety in the management of hazardous waste
- Smart packaging could help meet the regulatory requirements
- Smart packaging could reduce the cost of managing hazardous waste
- Smart packaging could lead to better waste identification

The second part of this thesis will attempt to either validate or invalidate these hypotheses. This lead to the central focus of this work, which is "*Analysis of the potential use of smart packaging to improve the management of industrial hazardous waste*".

Methodology

This section describes the methodological approach used in this research.

A qualitative study was chosen to obtain the opinions of experts on the subject of smart packaging in hazardous waste management and opinions about the hypothesis listed before. Interviews via videoconferencing were chosen to collect these opinions. For the sake of completeness, interviewees were chosen among companies matching one of the following selection criteria:

- Companies specialised in hazardous waste management (sorting, collection, transport, treatment)
- Producers of hazardous waste (metallurgy, chemicals, construction, etc.)
- Regulatory bodies
- Companies developing smart packaging solutions

The companies and experts were initially contacted by email, found through their websites. However, this method gave a low response rate, we had to adapt and find another approach. A LinkedIn post was written to reach out a professional network and widened the scope. The contacts received were contacted also by email. Thanks to the University of Liège's alumni network, interesting profiles were also found on LinkedIn by applying search filters and contacted directly via the social network's messaging system. This approach proved to be very successful. Even if people didn't think they met the criteria, they still put us in touch with others who were more suitable. An advertisement was also written for the University of Liège's alumni newsletter to encourage a more spontaneous call for testimonials. This method has not been very effective.

The interviews conducted were semi-structured. This method was chosen in order to have some freedom in the course of the interviews. In fact, the interview guide (see appendix I) which had been drawn up beforehand, gave us the overall structure of the interviews, but also to a certain degree of flexibility in the course of the interviews. This meant that we could bounce ideas off interviewees, change the order of questions, add or subtract questions. Every interview will be different, even if there is a common basis. Most of the interviews were conducted in French and then translated in English for analysis and inclusion in this thesis (see appendix II). An initial translation was performed using DeepL.com, followed by a careful manual review to ensure the final version accurately reflected the participants' statements.

The interviews were conducted via Microsoft Teams, which allowed greater flexibility in terms of the availability of participants, as well as saving time since no travel was needed to reach the place of interview. The fact that the interviews were conducted online allowed them to be recorded (with the consent of the participants), which made them easier to analyse afterwards. The interviews were relatively short, lasting around thirty minutes, so as not to take up too much of the participants' time and to be as efficient as possible. The interviews began with a brief introduction to my subject and the purpose of the meeting. We then moved on to the questions set out in my interview guide, starting with general questions, which varied depending on the interviewee's sector of activity. These initial questions usually involved a brief introduction of the expert and their company to gain a better understanding of their operations and objectives, particularly in relation to hazardous waste. This was followed by a brief introduction to smart packaging, after which the interviewees were asked to share their opinions on its relevance and potential applications in their specific context. Finally, we discussed the hypotheses that I had derived from my literature review.

- **Profiles of the interviewees**

For the sake of confidentiality, the interviewees, as well as companies that did not wish to be disclosed, have been anonymised. The interviewees will therefore be identified as P1 to P6 with "*P* " standing for "*Person*". The same applies to companies, which will be referred to as "*Company A*" and "*Company B*".

P1 is the country manager of *Keep-It Technology*, meaning he is in charge of the company's sales and marketing development in the Nordic countries. *Keep-It Technology* is a Norwegian company that operates in the field of smart food packaging. Their product consists of an indicator that shows how long a product can be consumed, depending on transport and storage conditions. It is intended to replace the « best before » date on food products. Thanks to this indicator, food can be consumed several days after the original expiry date, provided that the temperature chain has been respected. Otherwise, the product may be no longer fit for consumption due to exposure to harmful conditions. They are currently working on another version. They want to move from static expiration dates to something more dynamic.

P2 is an account manager who has been working for the company for three years. He is responsible for managing industrial customers in the Liège and Luxembourg provinces. He works for Company X, a French multinational with a strong reputation in the waste management sector. The company handles all types of waste, including paper, cardboard, residual waste and PMC, and offers a variety of containers such as bins, drums, and canisters.

P3 is an account manager at *Sarpi Veolia*, a subsidiary of *Veolia*, a major international company in waste and water management. *Sarpi Veolia* is specialised in the treatment and recovery of hazardous industrial waste, as well as soil decontamination. P3 is responsible for the Wallonia and Brussels regions and has around ten years of experience in the field of hazardous waste management.

P4 is both a prevention advisor and an HSE (Health, Safety, and Environment) manager, meaning she is responsible for all environmental matters within the company. Company Y is a small company in the fine chemicals industry with fewer than 100 employees, and is part of a large group with multiple sites in Europe, the United States and Canada. The company produces active ingredients for medicines and, this Belgian site specialises in active ingredients for cancer medicines. Before joining company Y, she worked in the metallurgy sector, which has added to her knowledge and experience of managing hazardous waste.

P5 is the account manager for the Walloon region for a small structure based in Milmort, Liège that only manages hazardous waste. This structure is part of *Remondis*, which is a large German group with hundreds of subsidiaries around the world, and acts as a consolidation platform. Most of the waste collected at the Liege site is sent to one of these companies in Cologne. P5 describes her role as acting more as an adviser than a salesperson towards her clients. Before joining this company, she worked for *SITA*[5], which was later acquired by *Veolia*. There, she managed conventional waste and small amounts of hazardous waste.

P6 is a hazardous waste manager at *Revatech*. He is responsible for sales in Wallonia and Luxembourg, as well as for developing the company in France. He has been with the company for 16 years. Trained as a chemist, he sees his role as advising his customers on the best possible solutions to their problems. *Revatech* treats both hazardous and non-hazardous industrial waste. The company has two sites: one in Engis and one in Monsin, both in the province of Liège. These sites manage around 1,500 different types of waste which can be recycled, recovered, or disposed of on site.

[5] *"[…] French company specialising in waste management and recovery, which became a subsidiary of the Suez group in 2015*". https://fr.wikipedia.org/wiki/Suez_Recyclage_&_Revalorisation_France

In order to have a clear presentation of the results, the list of respondents will be in the format given below:

Table 4: Summary of the interviewee profiles

Identification	Function	Company	Sector	Location
Person 1 (P1)	Country manager	Keep-it Technology	Smart food packaging	Norway
Person 2 (P2)	Account manager	Company A	Industrial waste management	Liège and Luxembourg
Person 3 (P3)	Account manager	Sarpi Veolia	Hazardous waste management	Wallonia and Brussels
Person 4 (P4)	Prevention advisor and HSE manager	Company B	Fine chemical industry	Mont-Saint-Guibert
Person 5 (P5)	Account manager	Remondis	Hazardous waste management/consolidation platform	Wallonia
Person 6 (P6)	Hazardous waste manager	Revatech	Treatment of hazardous and non-hazardous industrial waste	Wallonia, Luxembourg and development of France

Analysis

This section presents the results of interviews with experts in the field of hazardous waste and smart packaging. The aim of this section is to highlight the most significant elements in relation to the research question studied, following a clear logic, and structured around the five hypotheses identified. These results will then be discuss in the light of the literature to provide a critical analysis of the findings, highlighting points of convergence, divergence or new insights.

- ***Smart packaging could help/improve the traceability of hazardous waste***

Respondents P3, P5 and P6, felt that traceability was already sufficiently ensured by labelling systems such as barcodes and QR codes, and automated scanning procedures. For example, P5 emphasises that "*everything is now always scanned, everything is always traceable*", whether in consolidation centres or treatment centres. P6 describes an internal system based on QR codes that enables precise tracking of package movements, with information such as arrival date, truck number and internal movements. He highlights the technical robustness of this solution: "*[…] we switched to QR codes because barcodes have to be at least 80% legible to be secure, whereas even 20% printed on an entire QR code is enough. QR codes make all the difference".* As for P3, he believes they are already using a kind of smart packaging for their containers. In fact, the containers have labels that indicate their location.

P2 also confirms the existence of effective computerised systems for tracking waste movements from production to destruction or recovery, with automatic transmission of information to the customer. In his opinion, the use of integrated tracking and tracing systems such as smart packaging could be useful, but he puts the usefulness of such technologies into perspective: [talking about the bins provided by his company to the customers for the disposal of waste] "*In general, you rarely have a customer who says: "yeah, no, that's not mine", that almost never happens".* He considers that the packaging on the market are already "*well equipped*", sometimes with trackers on the larger models.

By contrast, P4 is more critical of the usefulness of smart packaging for waste. She insists that, unlike for the production of pharmaceuticals, waste is already mixed and that detailed traceability is not necessary: "*In terms of waste, it's already a mixture, so I don't see the need for traceability in that respect*". She points out that the producer's liability is covered once the certificate of treatment (destruction or recovery) is issued by the operator: "*With the invoice we get a certificate of either recovery or destruction. If we don't have that, we don't pay the bill because we are responsible for the waste until we have proof that it has been destroyed or recovered. It is very smooth. Once it's destroyed, we have the document and everything goes smoothly*."

P1 did not comment on the subject of traceability.

With this knowledge, we can now properly discuss our hypothesis. As a reminder, European regulations require hazardous waste to be tracked from production to disposal through electronic records. However, literature also highlights problems such as illegal dumping, waste trafficking and illegal waste movements. These problems are related to overly strict regulations on hazardous waste and the high cost of managing it, which leads producers to dispose of their waste illegally (European Court of Auditors, 2023). As previously discussed in the theoretical framework (see section 2.2.1, page 15), smart packaging can contribute to improving traceability by using data carriers. Barcodes, QR codes and RFID tags can be used to store data and track the entire supply chain, improving safety and proving the authenticity and integrity of the products being transported. This is why the hypothesis "*smart packaging could help/improve traceability of hazardous waste*" was formulated.

A clear divergence emerges when these theoretical perspectives are compared with the results of the interviews. Respondents generally express a high level of confidence in their existing traceability systems and see little added value in further innovation. They believe that barcodes and QR codes already provide sufficient traceability and are considered robust and reliable. In fact, we can say that traceability is already being achieved through the use of smart packaging although the name for this has not yet been established. This perception contrasts with the concerns raised in the literature. While the literature emphasises the ongoing risks of fraud and traceability gaps, these issues were not reflected in the field. One possible explanation is that the professionals interviewed work within well-controlled systems with clear procedures. Furthermore, some respondents suggested that issuing official destruction or recovery certificates effectively closes the traceability loop.

Therefore, the results of the interviews do not support the initial hypothesis. While smart packaging may offer theoretical benefits, those currently managing hazardous waste do not perceive it as a necessary improvement. Either because they already use it in some way, or because they don't feel they need it. The perceived adequacy of existing systems, combined with the absence of urgent traceability issues in practice, explains the limited interest in further technological innovation in this area.

- ***Smart packaging could improve safety in the management of hazardous waste***

Overall, respondents recognised that safety is a critical issue in the management of hazardous waste, although existing systems are already well established such as the ADR regulations. The idea of using smart packaging to improve safety was generally viewed positively, although opinions varied depending on the intended use, context and types of waste.

Some respondents such as P4, are clearly in favour of the idea that technology built into packaging such as temperature sensors could provide a warning before an incident occurs. She believes that in certain cases "*If you have something that warns you that the temperature is going up, I think that's great and maybe more expensive, but if there's a risk involved, I think that risk is worth more".* She supported her remarks by saying that for her company, it wasn't interesting because they mainly had inert waste such as gloves and protective clothing, and it didn't pose any real risk. This view in favour of smart packaging is shared by P1, who also sees smart packaging as a potential tool to improve safety, especially in the face of possible risks during collection or transport.

P6 has a more detailed view. Although he stresses that safety is already a priority in his company and that they have few accident: "[…] *it's more incidents than accidents but the job is obviously very dangerous […]",* he admits that there are still some problematic situations. For example, some waste is stored for too long or handle manually in non-ergonomic conditions. He believes that smart packaging could play an important role for the most hazardous waste such as strong acids, reactive metallic dusts, explosive or radioactive waste and end-of-life packaging. If the packaging can signal a risk: *"be careful because this packaging no longer meets the standards and there is obviously a risk of spillage"* or "*it no longer meets the ADR standards"* or again "*it might be useful to be able to detect the gases",* it could be interesting.

P3 expressed moderate interest: the idea only seemed relevant to him if it triggered a concrete action such as an alarm, a visual or audible signal. He acknowledges that this could be useful to prevent a temperature rise, an ignition or a flash point[6] that are too low, but feels that current regulatory requirements such as ADR rules are already well respected by the companies. In his view, it is not

[6] "*The lowest temperature at which a liquid (usually a petroleum product) will form a vapour in the air near its surface that will "flash," or briefly ignite, on exposure to an open flame".* https://www.britannica.com/science/flash-point

necessary but if the basic packaging is smart and they can use the information, he thinks it's nice, otherwise he doesn't have any real problems or requests in this area.

P2 was more reserved. He sees a possible interest in certain specific situations. For example, a large manufacturer with many types of waste on site. He imagines that smart packaging could facilitate compliance checks without having to check everything manually or provide direct access to safety data sheets via a QR code. However, he puts the benefit into perspective in terms of real savings: "*it doesn't save you an hour, it saves you 5 minutes"* and thinks the tool is a bit of a gadget. He insists that accidents are now rare thanks to close monitoring and that customers are already well aware of the risks. He adds that some more sensitive types of waste, such as isocyanates[7], may warrant more advanced technology because of the risk of contamination in the event of a spill.

P6 further agrees that the QR codes they use today are mainly useful for logistics and traceability, but not directly for safety. In his opinion, safety still relies heavily on visible labels, hazard pictograms and protective equipment. He stresses that "*the danger signs should be visible for the firefighters, and so we don't have to scan the QR code in a hurry*". A system that requires scanning would not be suitable in an emergency situation.

P2 and P5 did not comment on the subject.

After presenting the main results, a brief theoretical recap is given to contextualise the analysis, after which the interpretation and implications will be discussed. In terms of safety, the literature review highlighted the fact that poor management of hazardous waste can lead to health problems or serious environmental problems such as contamination of soil or water. Indeed, hazardous waste can contain heavy toxic metals or chemicals substances. Regulations therefore require hazardous waste to be segregated, either between different types of hazardous waste or between hazardous and non-hazardous waste. In terms of smart packaging, safety can be assessed and maintained thanks to sensors and indicators that can detect and indicate the presence of a particular substance, such as oxygen, which can alarm the actors in the chain and allow them to react before an unwanted reaction occurs. In addition, active packaging, such as emitters or absorbers, could be used to act directly within the packaging to remove or inject the required substance.

The interview results generally support the hypothesis that smart packaging could improve safety but only under certain conditions. Respondents P1, P4 and P6 clearly identified scenarios in which such innovations could add value, particularly when dealing with highly hazardous waste such as radioactive, explosive or sensitive waste. Useful improvements were identified as features such as sensors including temperature, gas or leak detectors that could alert users if packaging conditions deviated from safety standards. QR codes were also seen as a useful tool, particularly by larger companies managing significant volumes of hazardous waste. However, these QR codes are not very useful in an immediate security situation. Others such as P2, P3 and P6 pointed out that current safety systems are already robust and that the value of smart packaging will depend on its practical usefulness, ease of use and the type of waste involved.

In summary, the hypothesis receives partial support: smart packaging is considered a promising safety enhancement in specific high-risk situations, but not a mandatory upgrade for all types of hazardous waste. Its perceived value depends on practical integration, reactivity and the nature of the waste involved.

[7] *"[…] They are potent respiratory and skin sensitisers and a common cause of asthma and allergic contact dermatitis. A range of other adverse health effects are also associated with isocyanate exposure including cancer […]".* https://oshwiki.osha.europa.eu/en/themes/isocyanates

- ***Smart packaging could help meet the regulatory requirements***

Several respondents mentioned the complexity, constant changes and relative imprecision of the regulatory requirements for the management of hazardous waste. P1 even identified this aspect as the main obstacle encountered in implementing their smart indicator: "*My biggest problem is the regulatory requirements*". Here, in the context of food industry, administrative constraints seem to slow down innovation rather than encourage it.

P6 agrees, describing the increasingly strict and complex regulations, especially concerning operating permits, reporting obligations, and constraints on certain hazardous waste such as cyanide or ammonia: "*[…] standards change over time and we have to take into account all the new environmental constraints that are imposed on us"*. He also criticises the lack of digital harmonisation between different actors, which makes it difficult to trace and cross-reference regulatory data: "*I don't think everyone is using the same software. We need to standardise, quite simply, it's not the case yet".*
For his part, P5 highlights the contradictions between official regulations and practical application: "*I think there's the law on paper and then there's the practice. And there is a huge amount of waste that nobody agrees on how to transport".* This grey area is perceived as a source of uncertainty and disagreement among actors.

While some respondents recognise its potential, few see smart packaging as an effective means of ensuring regulatory compliance. P3 for example believes that his company already complies with current requirements, so he sees no particular need for it. However, he acknowledges that these tools could be useful for managing storage space: "*We have so many m² available, how we manage this storage space according to the type of waste we have?*".

P4 makes a general reference to the declarations to be made to the Walloon Region, which requires data on the type, quantity, collector and carrier of the waste. However, she does not specify whether smart packaging could facilitate this procedure. Nevertheless, she considers that "*the use of this type of packaging should not be imposed, but strongly encouraged, if it can avoid safety problems, whether in the company or during transport*".

Although P2 does not directly mention smart packaging in this context, it describes a digital traceability system that enables customers to easily produce their annual declaration. "*[…] they* [the customers] *can simply download an Excel file from our platform and then have all the transport orders that they have made during the year and then have that traceability. We work in total transparency with the customer".* Smart packaging could complement these systems, but the connection has yet to be established.

As previously, a theoretical summary will be provided before the results are analysed. In terms of regulatory requirements for waste, there are two main requirements: the prioritisation of waste and the extension of producer responsibility. More stringent rules are imposed on hazardous waste: all those involved in the management of hazardous waste must obtain a special permit; hazardous waste must be tracked from production to final disposal; it must be properly labelled and packaged during storage, collection and transport; and hazardous waste must be segregated and not mixed with non-hazardous waste or other hazardous waste. In theory, smart packaging could help provide more accurate data such as location, origin and destination, enable better control of the chain or provide additional information such as storage and transport conditions. This could be done using temperature, shock or leakage sensors, using RFID tags to store information and access it without direct contact, or using QR codes to access, for example, safety data sheets or handling instructions.

Although regulations are widely regarded as complex, inconsistent and occasionally contradictory, smart packaging is not considered an effective solution to these issues. In theory, embedded

technologies such as QR codes, RFID tags and sensors could streamline compliance by automating documentation and improving traceability. In practice, however, these features are often already integrated into existing systems or considered to offer only marginal improvements.

The main obstacles are structural, including a lack of standardisation between actors, fragmented regulations and limited digital compatibility. Unless it is fully aligned with official platforms and procedures, smart packaging risks becoming yet another isolated tool with limited impact.

Most organisations believe that they already comply with the current rules, particularly if they have digital reporting systems in place. For these organisations, smart packaging would introduce unnecessary complexity. Interest is limited to specific cases, such as managing large volumes or complex storage and it is not considered a viable solution on a broader scale.

Finally, from the perspective of technology manufacturers, regulation is more often a barrier than a driver of innovation. Approval processes are slow and legal frameworks have not yet been adapted to accommodate these tools.

In short, smart packaging has the potential to promote compliance but this is hindered by structural and institutional constraints. Without greater openness from regulators and better integration, its role will likely remain secondary.

- ***Smart packaging could reduce the cost of managing hazardous waste***

Respondents had mixed reactions to the idea that smart packaging could help reduce the cost of managing hazardous waste. While some saw it as a potentially profitable investment, others were more cautious, highlighting that the initial implementation costs remain a barrier particularly if the benefits are not easily quantifiable.

P1 explains that currently, the cost of smart packaging is covered by producers and distributors, as it is difficult to pass this cost on to the end customer. However, he notes that this cost is compensated by increased customer loyalty, thanks to the transparency offered by traceability throughout the supply chain which boosts sales.

P6 provides a specific example of the investment made in his company to modernise waste management using QR codes. He believes that the cost is relatively low compared to the benefits in terms of both efficiency and employee motivation: "*It's just that you have to invest a little"*. He adds: "*We are, that's clear* [profitable] *[…] we'd say that for a total of €10,000, yes, it's really useful, and even for the people who use it, it really does make you feel a bit more in the 21st century. It's given our staff a lot more motivation to see that we're doing things differently and investing in modernising their work*. […] *I'd say it's not much compared to what we earn."*

P4 pointed out that the cost of treating hazardous waste is already very high, primarily due to the necessary transport and treatment precautions. She emphasised that certain methods such as recycling could be cheaper than incineration but that the chosen treatment method directly impacts budgets: "*[…] the cost is much higher, depending on the method you choose, but if it's recycling and so on, it's a bit cheaper because they* [the collectors] *know how to sell the waste than if it's just simple incineration. My biggest budget is waste"*. P6 agrees, explaining that the chemical complexity of certain

types of waste such as cadmium[8] or molybdenum[9] adds considerably to costs due to the large number of treatment stages required: : "*Cadmium and molybdenum are elements that are really very complicated to control and precipitate in the different processes that we have. That's obviously what affects the price, the more complicated it is, the more different steps are required and the more expensive it is".*

P3 is more reserved. He acknowledges that smart packaging could have an added value but only if the additional cost remains moderate compared to traditional packaging.

P2 and P5 did not comment on the subject.

With this knowledge, we can now properly discuss our hypothesis. As a reminder, the cost of managing hazardous waste is significantly higher than for non-hazardous waste, with a median price of 238 euros per tonne compared to 63 euro for non-hazardous waste. This difference can be explained by the higher safety and treatment requirements. Unfortunately, this high cost may encourage some producers to engage in illegal practices, such as illegal transfers within and outside the EU, or not declaring them as hazardous, in order to reduce their costs (European Court of Auditors, 2023).

While respondents generally agreed that hazardous waste management is costly, they were divided on whether smart packaging could reduce these costs. While some recognised the potential for increased efficiency and improved customer loyalty, most remained cautious due to the required initial investment and the difficulty of quantifying direct financial gains.

The perceived value of smart packaging appears to be highly dependent on the context. In cases where it simplifies operations, or motivates staff through modernisation, the cost can be justified. However, in organisations without any particular issues to address, the additional expense is more difficult to justify.

Moreover, although smart packaging may offer indirect benefits such as streamlining processes or building client trust, these do not always result in tangible savings. In contrast, the main driver of high costs remains the complexity of treating certain hazardous waste and this cannot be addressed by packaging alone.

Overall, the hypothesis is not rejected but it remains speculative. Smart packaging could contribute to cost efficiency in favourable conditions but it is not currently considered a key way of reducing the cost of managing hazardous waste.

- ***Smart packaging could lead to better waste identification***

Regarding the hypothesis that smart packaging could improve the identification of hazardous waste, several respondents highlighted specific challenges and situations in which such a system could provide significant benefits.

P3 considers this interesting, particularly as they currently rely heavily on information provided by producers. When in doubt about a mixture or the exact nature of a waste product, P3 believes that

[8] "*A metallic element that occurs naturally in tiny amounts in air, water, soil, and food. It is a by-product of zinc refining and is used to make batteries, pigments, plastics, alloys, and electroplate. […]Exposure to high levels of cadmium may cause certain cancers and other health problems".* https://www.cancer.gov/publications/dictionaries/cancer-terms/def/cadmium

[9] "*A chemical element. Molybdenum is a silver-grey metal that breaks easily and is used in some alloy steels*". https://www.oxfordlearnersdictionaries.com/definition/english/molybdenum

smart packaging could provide as much information as possible about its composition. P5 confirms that they rely on the information received from producers. She describes frequent situations in which customers send waste without providing safety data sheets or provide totally incorrect information: "*Customers who don't care at all, who don't send us the MSDS [Material Safety Data Sheet] sheets and who give us very random or wrong information".* She also gives the example of small independent businesses recovering premises that have been abandoned: "*When a young heating engineer or plumber or whatever takes over a small warehouse, there are often previous owners who have left a lot of waste around, so it's completely unidentifiable. So we call in our chemist, who goes out and identifies it as best he can […]".* P2 reinforces this observation, stating that if a customer cannot identify his waste, the company of P2 cannot identify it either. In this case, as P5, P2 suggests a chemical sorter to go on site and to try to define the waste. If this is not the good identification, this can lead to major complications and even non-compliance. He gives the example of hazardous mixture: "*[…] if you mix cyanate isocyanates with skips and put it all in one box, it can cause dangerous chemical reactions".* He insists on the fact that even if identification is not a structural problem as long as sorting is carried out properly, errors are possible.

P6 refers to the way identification is managed on its site, using references specific to each customer and type of waste. However, he criticises the current regulatory coding system stating that the six-digit codes are "*badly designed*". He illustrates his point by saying: "*you can put 5 people around a table and put a piece of waste in the middle and say: "which code should we use?", we might not have 5 different codes, but we might have 3".* He believes this is a prime example of what needs to be improved.

P1 and P4 did not comment this hypothesis.

We can now compare the results with the theory and discuss their implications. In theory, waste is identified and classified according to a list drawn up by the European Commission. Each type of waste is coded with a six-digit code and hazardous waste is marked with an asterisk. If a waste has both hazardous and non-hazardous characteristics, it is considered to be a mirror entry. To find out which category to put it in, you need to look at its composition and see if it has any of the properties listed in Annex III of Directive 2008/98/EC. This identification is sometimes difficult to carry out, especially when a mixture is involved which can caused problems for the subsequent management of the waste: inadequate packaging, inadequate treatment or inadequate final disposal. Smart packaging could help in this regard, using sensors to determine whether the type of substance that should be present is present or not, or whether another substance is present without necessarily identifying it.

All respondents acknowledged that identifying hazardous waste is a weak point in the current system. Errors, missing data and ambiguous classification codes create operational and safety risks, particularly when dealing with unknown mixtures or abandoned stocks. This problem is exacerbated when actors rely solely on information provided by clients, which is often incomplete or inaccurate.

In this context, smart packaging is seen as a valuable support tool with great potential. By embedding identification data directly on the packaging through QR codes, RFID tags or integrated sensors, critical information can travel with the waste, reducing dependence on manual declarations and improving reliability.

However, the benefits depend heavily on compliance at the upstream stage. If producers fail to input reliable data or refuse to adopt the system, the added value decreases rapidly. Furthermore, the current regulatory coding systems are considered poorly designed, which limits the effectiveness of even the most advanced packaging if the underlying classification frameworks remain inconsistent or unclear.

In summary, the identification issue is real and smart packaging could help to solve it by standardising and securing key data. However, for this to be effective, it must be adopted throughout the supply chain, alongside improvements in regulatory clarity and enforcement.

- ***Additional insights from the interviews***

Although the interviews were designed around five specific hypothesis, several respondents raised other interesting points that are worth mentioning. These points offer a broader perspective on the subject, highlighting issues or concerns in the field that were not necessarily the core elements discussed in this work.

Environmental issues were spontaneously raised by several respondents. P5, for example, is outraged that some of the drums, which are "*all nice and blue and certainly made of good plastic*" are incinerated immediately. She adds that there are not many treatment centres in Europe, meaning there are few solutions and a lot of incineration. P6 also agrees, saying that although there are sometimes recycling or recovery solutions, they are often too far away: "*you have to travel thousands of kilometres by truck to get the waste to that place*". Therefore, transporting waste over long distances to give it a second life is not environmentally friendly either. P4 also confirmed that they do not recycle the bins they use for inert hazardous waste. Instead, the bins are sealed and wrapped on pallets before being incinerated. However, where possible, such as with non-chlorinated solvents, they are sent to cement factories, where they are used to recover energy.

This raises the question of what will happen to smart packaging once it reaches the end of its life. In some cases, packaging is incinerated with waste. But what about smart packaging? Some of its components, such as sensors or RFID tags, could complicated its final disposal. This raises questions about how such packaging should be treated: as reusable, recyclable or requiring separate handling? The environmental impact and end-of-life of smart packaging must therefore be important considerations during the design process.

Another point that respondents did no mention much was active packaging (i.e. packaging that can interact with its contents, for example via transmitters or absorbers). Of all respondents, P3 was the only one to have clearly mentioned that he was interested in active packaging. For him, this was clearly the most interesting smart packaging technology. However, he did not provide any further details.

Limitations and areas of improvement

This section discusses the study's main limitations, including methodological and contextual ones, and suggests improvements and directions for future research.

This study has several limitations that should be acknowledged. Firstly, considering the profiles of the interviewees, the initial aim was to conduct interviews with professionals coming from four different sectors in order to gain a comprehensive understanding of the subject: hazardous waste management professionals, producers of hazardous waste, smart packaging manufacturers and, regulatory bodies. Despite attempts to reach out for participation, not all targeted sectors were represented in the final interviews. Some potential participants did not respond, while others declined to take part. For example, the interviews lack input from regulatory bodies. Therefore, the regulatory aspects of smart packaging in the context of hazardous waste management was only addressed by a limited number of respondents. The perspective of a regulator or legal expert would have enriched the analysis, particularly in relation to compliance issues and potential barriers to implementation. In addition although the sample included waste producers, it was not sufficiently diverse in terms of size and types of sector. Only the chemicals sector was interviewed in this work and it is a large company in size because it is part of a substantial international group. The inclusion of small independent producers or companies from various sectors such as metallurgy, construction, or extractives industries might have revealed different challenges and expectations. As highlighted in the theoretical framework, these sectors are among the largest producers of hazardous waste in Europe. Their opinions could have permitted comparisons to be drawn between sectors. The same limitation also concerns smart packaging manufacturers. In fact, only one smart packaging manufacturer was interviewed, despite several being contacted again. Its technology was specifically focused on an indicator of the shelf life of the food product according to its storage conditions. This reduces the scope of technological knowledge and makes it impossible to compare different types of smart packaging solutions such as sensors or data carriers.

Another limitation is the method used to contact professionals for interviews. They were mainly contacted by email, which is a professional method but emails can easily end up in spam folders and be overlooked. If we don't have a direct contact at the company, we have to email a general enquiries address, which then has to redirect the enquiry to the most suitable person. This can take time and, in many cases, result in no response. One option would have been to call the companies and try to speak to someone directly. While this method could have been seen as audacious, it could also have been an effective solution. Some companies might have appreciated the initiative and proactive approach.

Limitations may also be related to the scope of the study. The research focused on the European Union, and more specifically on Belgium and the Walloon region. The interviewees were therefore all from the same area, with the exception of one person. Given the length of a master's thesis, it seems reasonable to establish a more restricted perimeter for conducting the research. However, this approach has obviously drawbacks. In fact, the results cannot necessarily be applied to the whole of Belgium or other European countries, where the management of hazardous waste, as well as the profiles of industries and the maturity of technologies, may differ, even if there is a common European directive. In fact, the only person interviewed about smart packaging came from a Norwegian company. This highlights the fact that technological maturity can vary from one country to another. The same question can also be asked on a larger scale. As mentioned in the literature review, intelligent packaging first appeared in Japan before developing in Europe, which is the area of study, but also in the United States. It could be interesting to find out what opinion these regions have on the potential use of smart packaging for managing industrial hazardous waste.

Two further limitations of the interview method can be identified. Firstly, the interviews were conducted via Teams. While this method has advantages such as ease of transcription and analysis, as well as flexibility in terms of scheduling, it also has disadvantages. The online format of the interviews makes it more difficult to perceive participants' reactions and observe their body language. Technical problems such as connection issues or poor video/audio quality can sometimes hinder the flow of the conversation. The second limitation regarding the conduct of interviews relates to their time duration. Indeed, in order to convince the professionals to participate to the interviews and to work efficiently, thirty-minute interviews were proposed so as not to overload their schedules. However, this time constraints presented a limitation in terms of time allocation. In retrospect, the contextual questions took up most of the time, whereas the questions relating to smart packaging and their opinions on these technologies and hypothesis were covered more quickly and perhaps less deeply in view of the time remaining. This represents a missed opportunity, given that these questions were at the heart of this work. Even so, the contextualisation questions were essential for understanding the current situation and the sector's difficulties.

The lack of feedback on active packaging is clearly another limitation of this analysis. This may indicate either a lack of interest among professionals in this technology, which was presented in the same way as the others during the interviews, or an error in how the interviews were conducted.

In terms of improvements, the views of scientists such as researchers from the University of Liège on the technical feasibility of smart packaging could strengthen this research. During some interviews, it was observed that a lack of technical information meant that some respondents were unable to provide an informed opinion. Technical questions, such as which types of sensors could be developed, which substances could be detected and whether smart packaging technologies are compatible with hazardous waste components, could have been asked in an earlier interview with a chemist or engineer. This would have provided a more informed perspective and given the respondents better context for answering the questions. However, the aim of this work was not to assess technical feasibility, but rather to explore the potential applications of smart packaging in the hazardous waste sector. Similarly, and still in collaboration with scientists or engineers, a prototype of smart packaging solution for hazardous waste could be designed and developed to provide a clear idea of what is involved. This would enable respondents to engage with a tangible concept rather than a theoretical one, facilitating a more accurate assessment of practical feasibility and perceived benefits.

Conclusions

This master thesis aimed to analyse the potential use of smart packaging to improve the management of industrial hazardous waste. To achieve this, a literature review was first conducted to establish a theoretical framework for the two main topics of the study: hazardous waste and smart packaging. This theory has identified five hypothesis that demonstrate the potential usefulness of smart packaging in the management of hazardous waste. These five hypotheses cover the following areas:

- Smart packaging could help/improve the traceability of hazardous waste
- Smart packaging could improve safety in the management of hazardous waste
- Smart packaging could help meet the regulatory requirements
- Smart packaging could reduce the cost of managing hazardous waste
- Smart packaging could lead to better waste identification

Then, a qualitative study was carried out with experts in the field to better understand the current practices and to gather their opinions on the hypotheses drawn up via interviews. The results showed that two of the hypothesis were more interesting than the others: "*Smart packaging could improve safety in the management of hazardous waste"* and "*Smart packaging could lead to better waste identification"*. However, these results are subject to certain conditions. For instance, smart packaging could enhance the safety of hazardous waste management, especially in high-risk situations involving highly hazardous waste such as radioactive or explosives. The most interesting technologies are temperature, leak and gas sensors. It would also be very interesting if smart packaging could detect when the packaging no longer complies with the standards. In terms of waste identification, it is interesting because most respondents agree that there is a real problem in this area and that they rely heavily on information provided by producers. To be truly effective, this type of packaging must be adopted throughout the chain, supported by greater clarity in the regulations for identifying types of hazardous waste. The other hypothesis are viewed less positively. Respondents are not interested in traceability, regarding the hypothesis "*Smart packaging could help/improve the traceability of hazardous waste*", because they believe they already have all the necessary resources and are not experiencing any issues in this area. Regarding the hypothesis: "*Smart packaging could help meet the regulatory requirements*", some argue that regulations differ in practice from theory. Nevertheless, many already believe that they comply with the rules, and some even contend that the directives themselves could hinder this technological advancement. Finally, with regards to the hypothesis "*Smart packaging could reduce the cost of managing hazardous waste*", rather than reducing management costs, smart packaging could actually increase them. Furthermore, smart packaging cannot influence the main reason why hazardous waste management is expensive: the cost of treating this waste. The interviews also raised environmental issues, such as the fact that many waste are still incinerated due to a lack of solutions or because treatment centres are too far away. This raises questions about what happens to smart packaging at the end of its life. It also important to note that active packaging was rarely covered in the interviews.

The research presented a number of limitations. Firstly, regarding the sample of respondents, it does not correspond to all the target sectors identified in the methodology. In particular, regulatory bodies and various industries that produces hazardous waste, differing in size and sector, were underrepresented. The participation of only one smart packaging manufacturer meant that the range of technological perspectives explored was limited. Secondly, the method of contacting professionals, which was primarily via email, may potentially have contributed to the lower-than-expected response rate. The study focused mainly on Belgium and particularly Wallonia. This restricts the ability to generalise the findings to other regions or countries. Additionally, the use of short remote interviews meant that some discussions were not as in-depth as they could have been, and it was more difficult to observe non-verbal communication.

Future research could expand the geographical scope to include other European countries or regions of the world, enabling comparative analysis. Quantitative studies could also be carried out to measure the real impact of smart packaging technologies on specific indicators, such as the rate of hazardous waste identification errors or the number of incidents avoided. In parallel, pilot projects could be launched to test these technologies across the hazardous waste chain in real conditions. Another perspective would be to explore in more depth the potential impact of smart packaging on highly hazardous waste. This point was raised during the course of this work. Finally, future work could focus on the economic feasibility and environmental impact of implementing such technologies on a large scale. Particularly, on the end-of-life stage of smart packaging, also suggested in the context of hazardous waste.

This research highlights the potential and complexity of the intersection of smart packaging and hazardous waste management. Although smart packaging is not a miracle solution, it offers interesting prospects for addressing some of the sector's ongoing challenges. While this research thesis does not offer definitive solutions, it opens the door to new perspectives and innovations in the specific sector of industrial hazardous waste management.Appendices

- ***Appendix I: Interview guide***

Introduction

"*I'm currently studying Global Supply Chain Management and doing my research thesis on the potential use of smart packaging to improve the management of hazardous industrial waste. The interview will last between 30 minutes and your identity will remain confidential. Can I record this conversation?"*

Experts in waste management

- Could you introduce yourself and briefly explain what your company does?
- Can you describe the typical stages of hazardous waste management in your company?
- How do you identify the type of waste?
- How is waste sorted? What criteria are used?
- What is hazardous waste transported in?
- What are the main challenges involved in handling, storing or disposing of this waste?
- What type of hazardous waste do you deal with most?
- Is there a type of waste with which you have more difficulty?
- How do you currently ensure the traceability of hazardous waste?
- How do you ensure the safety of both staff and the environment?
- Do you lack any information to improve your practices?
- Have you introduced innovative technologies into your work processes?
- Are you familiar with 'smart packaging' technologies?
- Do you think that smart packaging could reduce risks (accidents, non-compliance)?

Manufacturers of smart packaging

- Could you introduce me and briefly explain what your company does?
- What technologies are currently integrated into your smart packaging?
- What types of functions or sensors are most in demand from your customers?
- Have you already worked on waste management applications?
- What technical or material constraints would you face in designing this packaging so that it is suitable for hazardous waste?
- In your opinion, what would be the lifespan or estimated cost of such packaging?

- How do you recycle or reuse such packaging?

Legislators

- Can you introduce yourself and your role in your company?

Present a summary of legislation

- Do you think that devices such as smart packaging could be incorporated into future standards?
- What incentives or public policies could encourage their adoption?
- What support mechanisms (subsidies, public-private partnerships, training) could be put in place to support this type of innovation?

Hazardous waste producers

- Can you introduce yourself and briefly explain what your company does?
- What type of hazardous waste does your company produce and in what quantities?
- How do you currently manage your waste production?
- Are you experiencing any particular difficulties with this management?
- Do you use any tracking systems to manage your waste?
- Are you familiar with 'smart packaging' technologies?
    - If so, which technologies do you know about and/or use?

Perceptions and opportunities of smart packaging for each actors

- In your opinion, what would be the benefits of smart packaging in the management of hazardous waste (improved traceability, process optimisation, regulations)?
- What type of data or functionality would be particularly useful in this area (real-time monitoring, leakage sensors, etc.)?
- What obstacles do you see to the adoption of smart packaging for this type of waste (cost, compatibility, regulations, and operational complexity)?
- What adjustments would be needed to overcome these barriers (technical, organisational, legislative, etc.)?
- In your opinion, what would be the first steps in testing and validating the effectiveness of smart packaging in this context?
- What collaborations (with other sectors or institutions) could facilitate the deployment of these solutions?
- Do you know of any examples of similar successful applications in other sectors?
- Do you have any other recommendations or points you would like to add?

Acknowledgements

"Thank you so much for your time. Your answers to my questions will be very helpful in writing my thesis. May I contact you again at a later date to clarify certain points if necessary?"

- ***Appendix II: Transcripts and notes of the interviews***

    - *Interview of P1:*

Slides with the presentation of the indicators provided by email but confidential.
The price is absorbed by producers, retailers, or both, but not by consumers — maybe later, but not yet. The biggest problem we're facing is the EU regulatory system. They're really into date stamps, but they've only succeeded with chicken in the Netherlands in the last two years. For now, it's just an additional piece of information — if you don't want to look at the K1, you don't have to.

They are added directly to the production line and remain there until the product reaches the consumer.

K1 is liquid → meat, poultry, fish
K2 is printed and disappears over time, future QR code that disappears.
This could be interesting, but it wouldn't be their priority, hazardous waste is not their sector.
Their technology is mainly based on shelf life, so it might not be suitable for hazardous waste.
However, he thinks that an indicator with an alarm could be useful for hazardous waste.
An indicator alone is not enough, because what would you do if it turned red? Is it too late? You need this dual system.
He thinks it could be reusable (the smart packaging). Indicator: throw away.
For them, it's really an indicator, not a sensor.
He thinks smart packaging could be very interesting because problems can arise at any stage, whether during collection or transport. Even with food, things can go wrong.
Dynamic vs static
It allows you to monitor the entire cold chain, which means better sales and loyalty.

- *Interview of P2:*

Can you briefly introduce yourself?
I manage the Liège and Luxembourg region for all [name of the company] industrial customers. I've been working there for 3 years, so I hope I can help you and answer all your questions. On [name of the company]'s web shop site, you'll find all the different types of packaging, which is normally more visual. So, for example, you'll find IBCs, drums, whether plastic or metal, with different capacities. We also have ASPs, boxes 650L plastic and other types of packaging. But I'll give you the basics, the simplest ones, and in fact what happens here is that they're approved, they come from a center, they're ready to go to the customer, so they can be used, I mean, they're totally watertight. And then, once we've encoded a box in our system, for example, the customer wants to have a box for waste soiled materials. We code it in our system as such: a 650L box for soiled materials. The customer then throws waste into it. And then, once it arrives at a processing center, well, it's opened up and they retrieve it in large containers, i.e. the big skips you can see on the road, and once it fills up box after box, well, then you go to a processing center and not to a consolidation center, which allows the waste to be sorted. So that's how I see hazardous waste. Others can explain in length and breadth, but here it is, it's the base. And here, we're going to the consolidation center. Why do we do this? Because it's small quantities in small packages. And that's how we work, because there's always a minimum amount of invoicing at the centers, precisely to try and regulate flows. You see, every time we go to a processing center, we bring back small boxes to be sorted. It's a huge amount of handling, rotation and passage. You need a lot more staff, so the aim is to go to our consolidation center, to group together the waste that customers generate to a lesser extent, and then to go to a final processing center. That's more or less the idea.

Your customers are individuals or companies?
We don't deal with private individuals, only with companies. Private individuals have to go to container park because they don't generate the same types of waste. At home, if you want, you have the PMC, you have your residual waste. In some municipalities, you now have organic waste. And

then for everything else, you've got paper and cardboard collection for all that glass, in general it's done at container parks. And those are the 5 main flows. After that, for the rest, when you have a fridge, when you have a broken cabinet, when you have large quantities of frigolite or aerosols, or what have you, you're supposed to go to a container park and sort, for example, even your green waste or your wood, you put it in large containers in the park, that's kind of the point, there's also a small amount of hazardous waste. There are plastic boxes with a capacity of 650 l, often with a lid, and inside, you can put aerosols, soiled materials, anything that has contained solvents or oil and is soaked, and so you have to put them in. Put them in and treat them in a center. But other than that, it's a conventional container park and that's for private individuals. And that's it. So we deal with the parks. If things are going well. So if there have been contracts, if relations are good, that's how things are going now, but for us, it's more industry, so I'm more interested in Liège- Luxembourg and industry, and here we find classic industrial customers, production companies or companies generating many different types of waste. And indeed, industrial clients often include hazardous waste. Over and above the classic categories I've just mentioned, such as DIB, cardboard and so on, the aim is to try to have a small container park on the customer's premises, so that he can sort it out, because he inevitably has a lot of waste, and then I can arrange for trucks to go and collect it.

What type of hazardous waste do you handle the most?

We can get anything, depending on the type of customer. In terms of quantity, it's highly variable. One year, it can be a flow that stands out from the rest, but in general, it holds up well. We have soiled materials, we can have aerosols, we can have anything acidic. So it's no longer liquid waste, it's anything that's fluid, you've got acidic solvents, chlorinated solvents, non-chlorinated solvents, organic bases, non-organic bases, anything that's mixed oils, fuel oil, diesel.

We have liquids, but you also have solid waste. It depends a little on the packaging. You've also got palletized packaging, i.e. packaging that looks like a customer ordering a paint can from his supplier, for example. When they empty it, we also take from them what we call PECR (paint, ink, glue, resin). This is also taken in ASPs or plastibacks, so either plastic or metal boxes. So there you have it, you can have other types of waste too, but these are really the main types.

What are the main industries?

Basically, all industries that generate waste. If we're talking about hazardous waste, if I have to give an example, it could just as easily be [name of waste producer companies], for example. In the way they create their products, their internal operations, sometimes maintenance and so on, there is hazardous waste that can often be generated on production sites. You've got operators, workers, and people with more a technical background, who maintain machines and so on. Well, all these trades generate hazardous waste linked to the activity or maintenance of the activity. And we don't even realize it. But then, it can come from just about anywhere. You can sometimes have smaller companies that just have aerosols and so on. Well, it depends a bit, but we're talking about industry, it can be small or large.

Do you encounter any problems managing this hazardous waste?

Yes, yes, very much so. Well, I'm exaggerating a little. In fact, what happens is that non-hazardous waste is already something that has to be sorted. So, once you haven't sorted it properly, there can be non-conformities. For example, in your DIB, i.e. at home, you've got 240L, a conventional garbage can. If you put a metal bar in there one day, for example, it will block the incinerator's shredder.

Imagine an industry. They wouldn't have a metal bar, they'd have a column. You see, everything is of different proportions, so it's not even going to block the crusher, it's probably going to break it, so there's really a sorting that has to be done upstream, plus acceptors who monitor everything, who have to take a good look at what fits into which category and how. And finally, to visualize the quality. And then, it can take its course. That's for the non-hazardous, now for hazardous waste, in fact they don't usually have just one category of hazardous waste, there are several, so when you get the wrong category, it can be problematic, so that's why we have to provide the most suitable packaging, try to

find a way of sorting so that the customer has the easiest option. And then, depending on the waste that generates the most, he manages to sort it, but from time to time, there's waste that's a bit between 2 zones, so between 2 categories. From time to time, it can happen that the customer doesn't even know what it's about. And that inevitably creates complications. Another thing I didn't tell you about is that when a truck goes to a site to pick up plastic boxes, it usually exchanges them, so it takes them full and drops them off empty. That's why the packaging, as you've heard here, the plastic bins, are in fact all identical, and don't have any markings on them according to the type of waste, because we work on a rotation basis, so we often don't empty them directly into the truck and drop them off again. We leave it at the customer's premises; it's something we take back full and put back empty. So I think it's also important to take this into account.

Can we still identify these boxes?
No, not that, it's far too complicated logistically. Well, at least in my eyes, in the first instance, I think that the operational side could probably say the same thing, because when a truck goes on a round to pick up the various plastic boxes, it has a huge number in its truck, so it has as many trucks as it does as many customers as it does as many boxes in rotation, it's enormous, so we might as well put nothing on, just have an internal follow-up where we really have the waste. The number of boxes to up from this customer and the moment they are identified, it's rather by the driver when he receives them and then sticks the label he got with the transport order, you see?

So we know which box comes from which customer?
Inevitably, to be able to invoice the tonnage. We have to be sure of that, but they're not, I mean, they're labeled rather, that's the only identification we give them, so that, yes. From memory, that's how it goes. I confess it's been a long time since I've done tours with drivers, but that's how it goes. But you see, for example, everything that's IBC or barrel or whatever, it also has to be intact packaging, i.e. it can't be corroded, it still has to have a validity date that's still in order, it can't have any holes in it. You see, there are ADR regulations to follow.

All the packaging you make available to customers must have been tested, I imagine?
The bins, yeah all the bins we have, they're up to standard, so when they're received at the center, they're checked, cleaned and then sent back to the customer, sometimes with a liner, sometimes with a micro-perforated bin, depending on the type of waste, so everything's well monitored too.

Are there any other problems apart from waste identification/sorting?
So for me, it's not really a problem. In fact, as long as the sorting is done properly, everything's fine. You know what I mean? What can sometimes happen is that customers, like us at home, users can make mistakes, which is normal. Sometimes there's a fine line, and sometimes that creates more problems than just putting cardboard in your residual waste. You see? Cardboard can be burned, so it doesn't bother anyone, but you mix iso cyanates with skips and put everything in one box. It will be refused and there will be non-conformities, and that's normal because it's dangerous, it can cause chemical reactions. And then, it requires even more sorting in the center, because in the end, if we go to a center, we'll be refused too, so we have to be sure that the acceptance conditions of the centers are respected.

What happens if you bring back a box that contains mixtures that shouldn't be there? Do you have to sort it out and send it back to the customer?
We usually report it to the customer when we can, but otherwise it happens very rarely. But sometimes waste has to be returned to the customer because we have no other solution for the moment. Then it's up to us to find a solution, but we need to have more information on the waste's technical data sheet.

Do you have a waste sheet that lists the type of waste, quantity, etc.?

Not always.

And that's not a problem?
If the customer doesn't know what it is and can't tell us, we can't either. So we can't identify it and assign it a category. So in these cases, what we can suggest is a chemist's sort. In fact, a chemical sorting operator can go on site to try and define the waste.

Can there be any problems with storage? When regrouping?
I don't know. Unfortunately, I'm not the one in charge of that.

How is the type of waste disposal or recovery chosen? Does it depend on the type of waste?
Absolutely. It depends on the type of waste, and on the centers, which always dictate the rate. If they're full. Then they'll tell us to go elsewhere. In Belgium, there are some well-known centers, but that's a world apart. There are plenty of centers that can receive oils or soiled materials. And then, what they do with it is try to reuse it, that's all. But I think they use chemical memory processes depending on the PH and so on, to try and use water and sometimes recycle it. Or other products of this kind can be separated according to a chemical operation and therefore be recovered and try to do certain things again with it. In general, what's done now, everything that's solid, has a calorific value, so it can become an energy recovery, that's it, it's possible.

In terms of safety, both for personnel and the environment, have there been any incidents or accidents?
Yes, there are, but it's very low now, because we monitor it very closely. The aim is to achieve at less as possible. There will always be accidents. I just hope we can minimize them, limit them. Lately, I confess, I haven't heard any. At least, since I've been here, I haven't heard many. I don't think I've even heard one. Now there are some, that's for sure. We just don't hear about it. But what happens is, well, you know, the pallet truck hooks up to a drum that's put in the storage area, and the drum has a hole in it and spills all its liquid. That's why it's a good idea to put them under a drip tray, or in a container that's perhaps more appropriate, or in another place, and so on.

Can we say it's human error?
Exactly.

Does it ever happen that the packaging leaks?
In general, no, I must confess that I've never had a case like that. I've never really heard of a case like that. So yes, it can happen but if nobody notices, well nobody notices, but generally customers are careful because they're monitored by the environmental police, so they also know their responsibilities. They also know what to dispose of, and they take care to manage their waste yards. And every day, we've got trucks on the road, so there are evacuations at an industrial customer's site, at least 2-3 times a year, you know? So let's just say that people know what they're doing. And then in the event of a real accident, I know that there are often absorbent kits that you put on, for example, I think it's a kind of powder that you put on the waste that has leaked and that absorbs it. If the surface is dirt that absorbs everything, nobody would know what.

What about waste traceability?
We work with a computer system, so once the waste has been created, we create the order. The driver then receives the order with an assigned code, i.e. the waste code. It goes into the treatment center. They have the weight, so it's encoded in the system. The customer then receives the waste code, the name of the waste, the weight, the destruction or recovery code.
And I think that's all, and from there, he has all the information and he can have it. I mean, he can access it through the platform, and that's possible.

Who weighs the waste? Companies or collectors?
It's not the companies. It's the truck that picks it up and I think it's weighed at the center, from memory. I think they're weighed when the truck arrives at the collection and processing center. That's when they're weighed. You see, since it's a collection, his truck fills up every time, so he accumulates a lot of waste, so we have to be able to divide each weight, each box, according to the cost of processing each category of waste. Once it's out of the truck, it's weighed. One after the other, it's encoded in the system, but I must confess that I'm not an expert on this, so I don't really know how it works.

Is there a certificate for the producer stating what has been done with the waste?
Exactly. When he needs them, he can go and find them. But above all, in his annual waste declaration, he can just download an Excel file from our platform and then have all the transport orders he has made during the year and then have that traceability. We work in total transparency with the customer.

Traceability assumption
I confess that, in fact, I don't know, maybe there's a way, it depends a little on the prism through which we see the problem or the situation. I think it depends on the type of waste we're talking about.
For example, you've got waste that's quite dangerous, more so than others where there isn't always a solution. And maybe, these types of waste should be the focus of your study, for example, by saying: "Well, yes, isocianates, for which there may not be many outlets at the moment, may need to be packaged much more securely at in view of the pollution you could get if there were ever any spills or anything like that. Well, that's true, and it may not be stupid now, but the problem with smart packaging is that it comes at a cost. So there's also that, but I'm not saying that it's a bad or good idea, it's just that we need to see how to defend and make good use of it, both for the customer and the collector, to have some traceability, there again, packaging in itself.

But wouldn't you find it useful?
I wouldn't really know how to answer that. The thing is, with smart packaging, you'd have to be able to exchange them with the customer, you'd have to collect them. In fact, the difference between a label and smart packaging is that in smart packaging, everything is integrated. The label is more “customizable”, either it's adapted to the situation, so you stick it on, or you peel it off.
In my experience, that's how I see it now: I'd have to confirm the label system, but that's generally how we work with pallets. So that's good. I have to admit that I don't have a chemical background at all, but when they do analyses for tests, sometimes yes, they raise the PH. I think that's what happens in swimming pools. You've got a little collar, I think something like that, you dip it in and according to the color indicated, I think you've got a bit of a notion of PH from memory. There may be this type of packaging, you see, depending on the IBC that fills up, eventually, the color will change. Everything to do with safety, whether for packaging, operators or transport, with all the iso aspects. It could be something quite nice. Now we'll just have to see how it works out in practice. For example, for a customer who has a lot of waste on site, in this case, it could be useful so that he doesn't check each packaging one by one, so he really has something more functional. And who really knows whether its packaging is still compliant or not, and if it isn't, we still need to find solutions. Frankly, I'm no expert on the subject, but your hypotheses aren't bad in absolute terms, I even think they're good. Now you have to be able to defend them. In fact, in terms of smart packaging, without necessarily selling [name of his company] or even the other collectors, I find that the packaging on the market, for both small and large packages are already, let's say well-equipped, they're already quite smart I think. As they're on large containers, you've got tracers. So there you have it, it's not bad but in general, you rarely have a customer who says yeah, no, that’s not mine, but you see, it almost never happens. So in terms of traceability, I'm already going to say that everything is more or less good.

And what about during transport?
That's something we generally avoid. In general, when we take back the box, it's compliant. When we take back pallets, they're filmed, there are drums that are also well sealed, so at that level, a lot of

precautions are taken to try and avoid any problems. In general, what happens, for example, if I take the case of other colleagues who manage all hazardous waste, is based on the customers and their experience. In the context of a new contract with a new manufacturer, you look at what they have in the way of hazardous waste, and they tell you the categories. Generally speaking, they're the same for everyone: aerosols stay aerosols, you know you have to put them in a box, but if they're smaller, you can put them in a 140L garbage can, and so on. Now, if there really is waste for which you have no idea of a possible outlet or solution, then you're going to ask internally, here's how it's packaged, here's their process, here's how it's done. Well, they'll say, well, generally speaking, this is the box we're heading for, because it's suitable for almost everything. And we assign a category, so that's the most standard. In fact, it's really the 6 650L plastic box where you can always have a category for everything when it's a little more ADR, you can have the ASP which is metal in general that's how I see it and then the rest is the drum when there are liquids. The ASPs and the boxes, they don't have any holes in them, they don't present any problems. They just drop them in, you see, there's nothing that's going to cause a real problem. The person who's there might have more experience in reporting problems if they really do exist. But of all the things we have, this is very exceptional.
When it comes to geolocation, tracking and all that, I'd like to say yes. Yes, it's useful, but since we're renting them out, we have to charge the customer for them. It's in his interest to keep them. So you see, in general, we rarely have any thefts or containers going missing. Well, I've never heard of that. It's true that he's also talking about any damage to the container. He puts packaging with QR codes giving access to the safety data sheets. Let's imagine you arrive in front of a waste park, you have several bins, so of course we're not talking about a small producer but a large producer. For example, he has a dozen 240L bins. Some of them are full, others empty, so he has to organize himself internally. Either put a label, for example. Say OK, this is where we'll put the soiled materials, and so on. And he can change them as often as he likes, as long as they're not yet full. As soon as they're filled, it's really that waste that's going to be in there. But if at any point he's in doubt about whether to use soiled materials or anything that's still paint or resin. Well, it's a matter of putting a QR code giving access to the collector's acceptance conditions, and going straight to the waste category he wants and seeing the description of where it's put, what's accepted and what's refused. That can be interesting. But in general, well, they're already doing it, they're checking their computers or asking us questions.

So it could be quicker and easier?
Now I'm thinking of really putting it into practice, but I think it's a bit of a gimmick. It's good, but if it doesn't save you 1 hour, it saves you 5 minutes. Now that can be interesting too. But it's all in the use. You see, an operator knows what's going on. He knows a bit about his waste, so he knows when it's full because he's the one who fills it. You see, if there's nothing left in it, well, if there's no more room in it, there's no more room in it. Now, it's true that sometimes you have big sliding containers, it's good to know according to the weight for example or the volume that's occupied to say “OK, there you go”, like on our compactors, I don't know if you've seen you have an indicator, it's a little lamp that lights up once it's 75% full, that means that the waste that's compacted, It starts to fill up all the spaces in the container, and then all of a sudden a little light system goes on, informing the customer that he has to call his collector to come and collect it, since it's a production company, and that's interesting, because in general, those who have a compactor, it means that every day, they throw in. But now, you generate less hazardous waste. Well, it depends on the person. But if you've got a big container, it can be interesting to know when it's full or when to call.

It could be interesting for big companies who have the budget to put into it?
In general, they tend to use tanks, you know, for large flows, double-walled tanks for example, or things like that. No, I'll admit it. In fact, the smart packaging system is brilliant. For me, it's super interesting, it's evolving, but I don't really have a distant vision of it.

- *Interview of P3:*

He would be interested in putting this on dangerous products upstream of their production.
He is more interested in active packaging.
He has no idea about the cost, but if it's not much more expensive than 'classic' packaging, it could be worth considering, as it still provides useful information. However, it's not essential.
It could be interesting from a regulatory storage perspective: how can we manage our available storage space properly depending on the type of waste we have?

- Traceability:

They already have labels on containers, so they know where they are. They already have a smart packaging system with a tracking system, albeit indirectly.

- Regulations:

This is not interesting for them because they are already operating within the rules. However, if it became compulsory, they would have no choice but to comply.

- Security:

It can be interesting, but it's not necessarily necessary. If it's basic packaging and they make use of the information, that's fine. Otherwise, there are no real problems or demands at this level, because companies' own packaging is often already in order (ADR, etc.).
For sensitive waste, avoid ignition and low flash points.
It's good to know when the temperature is rising, but what happens next? You need an alert or a reaction of some kind.

- Classification:

This could be interesting because the producer is responsible, so if they have any doubts about the mixture, they can check with them. This would provide them with as much information as possible about the composition.

There are a lot of questions:

- Often, during incineration, the packaging is incinerated along with the substance, so what about the SP?
- Technically, how is this done?
- How can it be configured?

We get the impression that it lacks the information it needs to make a decision.

- *Interview of P4:*

Could you give me a brief introduction to your company?
We are xxx, a small company based in Mont Saint Guibert with fewer than 100 employees. We operate in the fine chemicals sector at the Louvain-La-Neuve site. We are part of the xxx Group, which has different entities in Europe, the United States and Canada that perform various functions. In Europe and Canada, we have four xxx sites: two in France, one in Canada, and one in Mont-Saint-Guibert. We manufacture active pharmaceutical ingredients. At Louvain-la-Neuve, we specialise in active ingredients for anti-cancer drugs. Our main product is Inca, a plant from which we extract cataranthin and vaneline, both of which are completely natural. We have also developed it to produce certain products called vinca alkaloids, which are used in the composition of cancer drugs. We don't manufacture the drugs themselves; we only produce the active ingredients. Dafalgan, for example, is a drug whose active ingredient is paracetamol. So, we synthesise paracetamol.

So, what is considered hazardous?
Well, the active ingredient is extremely potent — that's why it's called 'high potency' — and is effective in very low concentrations of micrograms. There is less than a microgram of the active ingredient in

the drug. We manufacture a few grams or a few hundred grams of it, but the products are toxic in terms of quantity — they are toxic materials. To produce these extracts, we use large quantities of solvents, such as chlorinated solvents like chloromethane and chloroform. Why don't we change the type of solvent? Because when we formulate an active ingredient or a drug, we have to submit a dossier to the WHO's legal department — i.e. the health department — and we can't just change the formula as we wish. The formula has been filed and tested to minimise side effects, so any changes would require further testing. Before we start manufacturing, we do a lot of R&D work with our customers, who are pharmaceutical companies, so we have to carry out a lot of tests. First, we conduct research and development. Then, once something appears to be working in the laboratory, the customer takes over and conducts clinical tests. We then manufacture small quantities for these tests, which have up to three phases. If we reach phase three, it means that everything is working well and there are no problems. If there is sufficient demand, we can consider industrialising the laboratory process. Sometimes, after the first phase, we find that there are too many side effects or problems, so we stop there, or at phase two or three, depending on how things are going. You can't anticipate things because you have to test them, so unfortunately many projects are abandoned beforehand due to problems in one of the phases. If everything goes well in phase three, we can start the industrialisation process and move on from R&D to production.

Do you produce any hazardous waste during these phases?
Yes, we do. During the laboratory phase, the amount of waste is minimal, of course, because we're only asked for a few grams. We might have a 20-litre drum, for example. I'm exaggerating, but we might have a 20-litre can of solvent, acid, base, etc. But yes, it does generate waste. In the industrialisation phase, we sometimes have to use large quantities of solvent to make 100 g of a product. Why is this? It's because, in our process, we have to mix different products to get to the finished product, and then evaporate and crystallise them. This often requires the use of large quantities of solvent. We often have to use a lot of solvent to dissolve the powder, wash it and regenerate it. For maybe one kilo of product, there can be up to ten tonnes of solvents involved.

Do you have any other types of hazardous waste, or is it mainly solvents?
We mainly have non-chlorinated and chlorinated solvents. Depending on the synthesis and rinsing processes, we end up with water contaminated by solvents. Our synthesis takes place in reactors, so everything is closed. Staff are protected by masks, gloves and protective clothing because, if a reactor breaks down or something happens, they could come into contact with either a solvent or the finished product that we manufacture. As I said, this product is extremely toxic by inhalation. They are always protected by a mask, and when we finalise the process and have powder, we handle it in glove boxes. These are plastic or glass boxes with gloves that fit inside, so our staff never come into contact with the finished product. They are always protected by a hood, a glove box or masks.

I imagine you have a precise safety protocol?
Yes, it's very strict indeed. We also have to be extremely strict about product quality to ensure that nothing pollutes our products. When we manufacture a product, we have to guarantee its quality. Since the extract will be in patients' medicine, we have to work extremely cleanly, precisely and carefully, for the benefit of both our staff and the patients. We manufacture our products in reactors. These are large pots that we sometimes cool down and sometimes heat up. Everything is done by pipe transfer, including the waste. When we rinse, we either use a chlorinated or a non-chlorinated solvent. We pump the solvent from the bottom of the tank into another tank on our site, so that people are not in contact with the waste. Everything goes into a tank, and when it is full, we either pump out the chlorinated or non-chlorinated solvent or the aqueous phases, i.e. the rinsing water. We call in a vehicle to pump out this waste, and we have different channels depending on whether it's a chlorinated solvent, unfortunately, it's destroyed. If we only have chlorine methane, it's regenerated. We don't buy it back because we require a high level of purity, which is impossible to obtain. Instead, it is resold or recycled. Non-chlorinated solvents are sent to cement works for energy recovery, for

example. We're really trying to come up with environmentally friendly solutions for waste that can sometimes give waste a new lease of life. To us, waste is raw material for someone else.

Which company do you use for waste disposal?
There aren't many in Belgium. We mainly work with Veolia.

So far, we've been talking about liquid waste. Do you have any other types of waste? Solid waste?
Yes, those are really our three main types of waste and liquid volumes. Regarding more solid waste, as I was saying, when we come to do a synthesis, we are equipped with gloves, protective clothing, etc. We also consider that, when we come in to do a synthesis, the area could be contaminated. We also consider that a synthesis can be polluted. As long as there's no incident, there's normally nothing to worry about, but even an infinitesimal quantity of extractive can contaminate someone, so we throw everything in bins dedicated to that purpose. These are cytotoxic bins and they are incinerated. I don't produce many different kinds of waste. The waste is placed in sealed bins and sent by truck to an incinerator in Antwerp called Indaver, as it is the only one that can handle cytotoxic waste. I can't use Intradel as they only handle medicinal waste. As for other waste, we have standard laboratory waste. Small reagents because they've expired, because there's still the bottom of a jar, so that's what we have as waste, we have laboratory glassware that's either broken or too worn, but which still contained products. Of course, they're washed and rinsed, so there's always something contaminated in them. We don't have many batteries, but we do have some otherwise, and the rest is just normal rubbish, cardboard, PMC and when we really don't know what to do with it, but that's what we call the famous class 2s. And since last year, we've been separating class 2 from all organic waste. And when we clean the soil of the syntheses, the first wash is still considered to be dangerous and the rest is considered to be non-dangerous, but it's not discharged into the sewer, it's managed as waste, there's a truck that comes to pump it out, only the water from our sanitary facilities is discharged into the sewer and we have what we call a non-pro, so we have city water and we transform it into purified water, so to transform it into purified water. But there's quite a lot of clean water that goes down the drain, it's the only thing that goes down the drain.

Are you responsible for transport?
No, I'm a prevention advisor and HSE manager, so I manage all the environmental aspects and I call on Veolia because in Belgium we are obliged to use not only an approved haulier but also an approved collector, which my French colleagues don't have, so they contact Indaver, for example, and they hire a haulier to collect the waste. In Belgium we can't do that, we have to go through a collector and so the collector either already has his own hauliers or he uses the services of someone else, so all we ask for is a certificate from the haulier and the collector that they are approved hauliers and collectors.
Well, Veolia is well known, so we get their certificate and then it's up to them to contact Indaver, for example, to arrange a date for the transport of our waste.

So the solvents arrive in a sort of tank before being emptied into a vehicle?
Exactly. So we have a 20m³ buffer and when that buffer is full, we call the haulier to come and pump it out and then send it to an approved facility.

For solid waste, do you have to put it in a certain type of packaging?
We have to put it in those famous special bins. So we prepare the bins on a pallet, we film the bins and they come and take them and put them in the truck.

How do you store these bins before they are collected?
We've got a holding area where we store them in a dry place and when they come, they're filmed, they just come and take the pallet. And then they're gone.

Are these bins returned to you?

No, no, no, they're incinerated, so we don't reopen the bin because there might be toxic waste in there, so they're sealed and they're incinerated as they are. No, there's no recycling of bins, no.

By law, you should be able to trace waste. How does this work?
Once it's been incinerated in an Indaver plant, recycled in cement works and so on, we get a certificate with the invoice, either for recycling or destruction. If we don't have this, we don't pay the bill because we are responsible for the waste until we have proof that it has been destroyed or recycled. We also have to make a declaration to the Walloon Region, which asks us a whole bunch of things, including how much waste we have and what kind of waste. We have to prove that this waste was X tonne and I have to have the document to prove that the weight corresponds to where we are supposed to have sent it.

Do you know exactly what happened to each piece of waste? Was it incinerated or recycled?
Yes, absolutely, because we have codes for everything that's R1, R2 and so on, that's for recovery, recycling and so on. And then there are others called D9, D10.

Do you think the traceability system is sophisticated enough?
Yes, it's very fluid. Once it's destroyed, we have the document, it's very simple. What I have a problem with in terms of waste is that there used to be more players than those managing waste. And since the year, well, it's been a year and a half since Veolia bought Suez, so there are a lot fewer players and so they have a monopoly. And so if we're not very big, well, sometimes we're not interested in the waste, and so they don't give us a date for emptying it, so we end up with a full tank, which could prevent me from producing, and they charge very, very expensive prices.

Can you give me an idea of the price? Is there a big difference between hazardous and non-hazardous waste?
Yes, anything that's hazardous is already quite expensive because you have to take precautions for transport and so on. It's also expensive to treat because it can be flammable, so you really have to do a lot of work to treat it. So the cost is much higher, depending on the method you choose, but if it's recycling and so on, it's a bit cheaper because they know how to sell the waste. If it's stupid incineration, it's expensive because you're burning the waste and doing nothing with it. I'll give you an example, so it's not the exact price. I'll give you a range. For example, when we destroy laboratory waste, as I said before, it's between 4 and 5 euros per kilo, and then you have to add the transport, which in this case costs between 5 and 600 euros. That's because they actually come and collect it and send it to their own sorting centre, so they cross-check it. Then it's sent on its way. But a bulk truck, for example, for our water phase. For 20 tonnes or so, we're talking about 10,000 euros, including transport. Waste is a budget, but that's for aqueous phases. And for non-chlorinated solvents, we're also talking about 11-12,000 euros. Because I don't have a subsidiary in Belgium, we have what we call a cross-border subsidiary in France. But already the transport costs are higher because it's in the south of France, it's further away. And so we always have to arrange with the carrier to drop something off in Belgium. They come to us, so the delays are quite long. And then there's, the mixture of chloroform and chloromethane, but it's burned. So, unfortunately, we don't know what to do with it when we have this mixture and so it's actually more expensive. There is also the cost of buying bins, so to buy a bin is already €8, which isn't cheap.

Do you buy the bins from the company that collects them?
Yes, that's right.

Do you have more than one type of bin?
No, I only have one type of bin.

So there's a cost involved?

You have to recommend bins each time, so that adds to the cost, yes. I buy empty bins. I usually buy 250 per vehicle, and then when they're full we call the truck to come and collect them, so I've got not only the weight of my waste in there, but I've got the weight of the bin and the weight of the pallet, because it's all incinerated. So for 5 tonnes of this type of waste I have almost €5,000. My biggest budget is waste.

When it comes to collection, do you contact the company yourself or do you have fixed dates?
No, because it depends on production. As we don't always have continuous production because we work in batches depending on the orders we receive, we check the level of the tank when it is more or less 3/4 full, we ask for an appointment because it actually takes a bit of time.

So it's on demand?
Yes, and I don't have enough flow to say that we can come every 3 weeks on that date and, what's more, because we make batches of different products, I have to take a sample and give it to them to see if we're still within the specifications we've been given, otherwise the truck arrives at the centre and there's something wrong with it. They can send it back to us. Sometimes it's just a small thing, so the price goes up because there's something that doesn't fit. But if the product really doesn't comply with the defined process, they pack the truck.

So what happens then? Do you have to redo the paperwork?
Absolutely everything then, but apart from that we have to redo the paperwork so that they can bring the waste back to us, because they have paperwork to go to the centre, so we have to redo the paperwork so that they can bring it back to us, and we have to store the truck's tanker because if we've already put something back in the tank, we can't always put it back in again. And then, as I said, if I fill the tank, but the production doesn't come out, then it's blocked. So we put the production in storage. It happened once and then we found a solution, but we really try to make sure that everything fits together so that we don't end up with unnecessary costs. And then we end up with waste that we don't know where to send and under what conditions.

Are there any other problems?
No, no, I'd say a few. It's really since the takeover that we've had problems, because we don't know how to compete anymore, because there are fewer and fewer players, and because we're small, but we're not always interesting next to a big producer who's a bit more interesting. So it's difficult for smaller companies.

Explaining smart packaging

Does it make sense to you? Is there any particular technology that would be interesting?
In waste bins, what I'm putting in there is inert, it's actually contaminated but it's inert so its fine, it's not going to be relevant to the waste that's being used. I think it's the type of waste that's interesting. For example, I used to work for Caterpillar, in metallurgy. So if I was still at Caterpillar I would have been really interested, sometimes in that kind of packaging for example, but with us because the bins are potentially toxic, but it's inert, it's a pair of jumpsuits, it's a pair of gloves, it's a bottle, so it's not going to get temperature, it's not going to disintegrate with anything that can be measured. And the rest of the tank has safety valves so it can't go up in pressure or temperature because it's regulated, so it's a bit like your packaging. We've got level detectors, so if there's a problem with pressure or temperature, we've got a computer that tells us there's a problem, so it's a bit smart like that? Same thing, but on a bin level. Unfortunately, I have no rubbish like that. Maybe in the chemical industry, like UCB or GSK. They may have other waste that could be interesting in terms of oxygen measurement or temperature measurement. But not in our business.

As far as traceability is concerned, you told me that you don't have any problems, so you don't see any point in having continuous monitoring?
No, because the bins and what's in them, well, we have a certificate. We have a point of correspondence, but we don't need traceability, unlike what we sell as medicine, where there are labels and so on, so we know which batch it came from. But in terms of waste, it's already a mixture, so I don't see the need for traceability in relation to that.

Do you see any problems or barriers to using this type of packaging?
I don't have any because I like to move with the times and if there are things that can make the job easier. And from a safety point of view, if we have something that warns us that the temperature is going up, I think that's great and maybe more expensive, but if there's a risk behind it, I think that risk is more valuable. It will be more valuable than if we do something preventive by putting in temperature sensors, pressure sensors, whatever? No, I think that's really good, and I tell you, I was at Caterpillar too and you talked to me about it, but I would have immediately thought of this grinding powder, which is self-igniting and we've already had several fires. So if we have something to warn us that it's heating up because it was on the truck when it caught fire, it could have been a much more serious incident. But maybe you should try Nelka in Clabecq or La Louvière. They also make steel, so they could have problems, yes. Not in our case, but there are certainly things that can and do help with this type of packaging.

In terms of legislation, do you think this could help?
I think that in certain areas, legislation should not impose this type of packaging, but strongly encourage it. If it can avoid safety problems, whether in the workplace or during transport. So I think it could be seriously developed, don't you?

Do you carry out inspections or do we come and see how things are going on site?
Yes, every 3 years we have an inspection, yes. We have to show all our analyses, all the measures we've taken, whether it's waste, water, air or soil. In fact, we show everything we've done to prevent pollution of water, air or soil, which includes waste.

- *Interview of P5:*

Can you tell me a little bit about the company and what you do there?
So Remondis in Milmort, we have a very small structure, we only manage hazardous waste and it's a consolidation platform, so we're not a treatment centre. We group all the waste by families of hazardous waste and we have a couple of pits, a couple of halls. It's small, but it's efficient. We're really the only ones in the Liège area. Renewi used to be in Seraing, but now we're really the only ones. We depend on the big Remondis group in Germany, which is very well known. It's really the leader in water management and waste treatment. We have a very small structure, but all the waste, most of it anyway, goes to them, to Cologne. We're not very far away, so that's it in a nutshell. We started about 20 years ago with all the waste from printing companies here in Belgium, and then we expanded. I worked for years for Sita, which is now Veolia. And I did a bit of conventional waste and a bit of hazardous waste. And then I have a colleague who left and a lot of us former Sita people are now at Remondis and that's it. It's all the customers that come to us, except for the big structures, because they're quite confused about hazardous waste, they don't really know what to do. That's more my job, it's more of an advisory role when I go to them, it's not about selling. They really need solutions and we do what we can to guide them. And then, of course, to make sure that the waste is disposed of perfectly, they get treatment certificates, in short, everything from A to Z is managed by us. We're a very small company, with just two sales representatives for Wallonia.

Can you explain the typical management stages?

There are really two scenarios. There are the big structures, the big factories. I have a lot of customers, they already know what's going on, they already know how to manage waste, so there's a lot of price negotiation, a lot of negotiation for larger volumes. We don't teach them much other than to sort properly, to respect the sorting procedures. Anyway, they're aware that we can't mix everything up like we used to, and they're aware that it's in their interest to sort properly. And then there are all the smaller customers, from body shops to small printers and stove manufacturers. Finally, I'm thinking of all the people I've had on the line today, they're quite lost, they don't know anything at all, because years ago they could do just about anything with waste. And so these small customers really have no idea how to deal with it, so my role as an advisor is really very important for them because sometimes we arrive and there's a pile of rubbish and they don't know what to do. Or a newcomer, a heating engineer who's just starting out or a roofer who's just starting out, so we have to identify all the waste. So it's often easy for these small customers. After a few years of experience, I know, but in more specific cases, a small laboratory starting out with very specific and chemically dangerous products, I take photos if I don't know, and I come back to the office and together with the chemist we see what it is, so we always refer to Belgian law, which tells us what we can or cannot do with the products on the road. They can pick up a few drums, for example, and we'll guide them through the waste sorting process. And when everything is sorted into ADR packaging. He then sends the documents with a fairly simple order form, and a few days or a week or two later the truck leaves, and as part of a local round we take all the packaging in accordance with the regulations in force. That's how it works.

So it's you who travels to do the identification, the initial sorting?
Yes, absolutely, and I have to admit that if it's too far away, because we don't have much internal support, so we really do everything. When I work from home for 3 days, I ask the customers for photos or videos and really, most of the time, I don't have to travel, we just take delivery, of course. We also ask them for the MSDS sheets, the product safety data sheets, unless we see that it's mixed soiled waste from the customers I mentioned, garages, stove manufacturers or others, heating engineers, it's almost always mixed soiled waste and so it's not really, it's not liquid, it doesn't run, it's really very soiled with paints or oils, so we provide them with bins with lids to prevent spillage. It's a bin with a holding tank underneath and generally, sometimes they don't call for six months and we come and collect it when it's full, otherwise we use drums for anything that's really toxic, very standard things like that. So there's no need for photos. I just ask them in a few words what kind of waste they have, and then if it gets a bit more technical, a bit about the labs for example. We have 6 main family categories to help them sort: acids, bases, solvents of course, anything flammable, organic and inorganic solids, organic and inorganic liquids and anything that's really dirty. These are the main categories for laboratory waste in the broadest sense, all of which go to incineration. We put them in drums, seal the drums and then come and collect them when they're full. But customers can sort based on our recommendations.

Do you supply the packaging? Have they been tested?
Yes, the packaging, yes. Exactly, yes. There are validity periods for some packaging, not all.
Those that are for ADR type waste, which means they have specific regulations for road transport, are validated and/or replaced every 5 years.

Do you visit the site to collect the packaging?
Yes, or the customer can come and collect it from us because some people have small vans or whatever to avoid the cost of dropping it off. We're so small that it's not like going to the big sites of the very big consolidation centres, customers like that, individuals, can't come, but we're really quite small and very flexible, so for customers, if I see that they're a bit reluctant to pay the €100 drop-off fee, or if they're neighbours in the Liège area. I allow them to come and collect the packaging, of course, so that they have time to prepare the waste properly. And in the emails I send them, it's really the procedure to follow. I tell them again what they shouldn't mix, depending on the waste, and how to pack it properly. And once they've prepared everything in the drums, they send the documents back to our

planning department. It's an order form with all the waste specific to each customer and all the waste codes are on it. It's the driver who comes when my planning colleague knows which day she's in the region, she makes a whole round of all her small customers and the driver has labels so he sticks 2 labels with all the waste codes required and these 2 labels stuck like that per pallet or per container and so in the event of an inspection we're perfectly in order and we can of course give the duplicate labels to the customer because for their usual storage. If they recommend empty barrels so that their storage is always in order, they can also stick the labels on internally to make it easier for their colleagues to sort. And so that everything is clearly identified.

Are there any challenges, anything that might make the process a little more complicated?
Yes, very often, when there's unknown waste at a customer's premises, it happens very often. If it's a young heating engineer or plumber or whatever who takes over a small warehouse, very often the previous owners have left a lot of rubbish around and it's completely unidentifiable. So we call in our chemist who goes out and identifies it as best he can, or at least tries to separate it, even if it's just with his little PH test to check that there are no incompatibilities, and above all the Walloon region is very strict about transporting things, so you can't transport things that are not in good condition, and that's something we find very often, So when the chemist arrives, the truck has to drop off some packaging or over-wrapping to make sure that all these old products are transported safely, and we also do that very often when we see that it's completely impossible to transport in its current state, we come with a pump, so we have a pump like that, a special truck, and then they pump the liquids, We repackage it and then transport it. Empty packaging is easier to transport on the road in terms of regulations than liquid substances, which are dangerous. For example, that requires another vehicle. But what else often gets in the way? Customers who don't send us the MSDS sheets, who give us random or incorrect information, or who don't seem to be concerned at all. Sometimes, the waste arrives at our premises and, as I have trusted the customer's information, all the labels are linked to my price quotation. The truck arrives at our storage centre, is weighed, and the operators scan the labels. Then it's tested and double-checked, and often we realise that it's not organic liquids, but acids, or not liquid at all, but solid. So, from experience, when customers tell us that their products have been on the slab for two or three years, I always add extra lines to the price offer. Obviously, I'm adding what they told me, but to protect us a little, I'm also adding that it can be solid. For example, the tariff for liquids is not at all the same as for solids — they're not treated in the same way. Sometimes there are liquids. The customer thinks it's liquid, but the upper phase is liquid, whereas the residue underneath can't be disposed of at all, and that's extremely common. This kind of problem constitutes dangerous waste, so we are well aware that it can happen on our site, and sometimes the customer is surprised by the bill.

So, do you have to redo all the labels and so on?
Yes, the products have been put aside. We had a similar case not long ago. The customer told us he had a lorry full of IBCs — cubic tankers containing 1,000 litres of liquid — but it turned out that they were actually pastes. The lorry that can pump liquids can't also pump pastes, so the prices are totally different. It just so happened that there were a lot of completely solid drops that couldn't be unloaded. The prices here are double. When it's a full lorry, the invoices are higher, but the customer has accepted the offer. Obviously, the offer includes acceptance conditions for the products, so even if the customer has only signed for liquids, the conditions attached to the price offer still apply. Liquids. We make it clear if the products are incompatible or have a different flash point. Finally, we add a huge number of technical aspects so that the customer can't turn against us, since we've treated the waste as we found it.

Apart from that, can you think of any other potential challenges or problems?
Yes, quite a few. I think there's the law on paper, and then there's how things are done in practice. There's also a lot of waste, and nobody agrees on how it should be transported. Does it have to be ADR? That's the first problem. There's still a bit of a grey area at the moment because, obviously, we

have old friends, acquaintances and networks in the hazardous waste sector, such as Veolia. Everyone is sometimes faced with the same problems. Everyone has a different opinion, so when we put the question to one ADR Council and another, the answers differ. It's not necessarily ADR for everyone and it's not necessarily how it should be transported. There's a real gap between the practical and theoretical sides because the theory is in the documents we receive. We should transport each product separately, but in practice, we can't leave a customer who has a little bit of everything twenty bins for twenty different products in storage. This kind of challenge is something we are very often faced with when a customer has practically no quantity. We drive around thinking that we won't get an extremely heavy fine if we aren't checked. Even so, the packaging is often not designed for customers who have a little bit of everything. So, we have large containers or bins into which customers may only need to put 2 or 3 small bottles or cans. That's why, whenever you talked to me and my colleagues about smart packaging, we said we needed compartmentalised packaging to accommodate all these small quantities. Most of them have a little bit of everything, so we don't have to provide 10 bins, and on top of that, we fill a lorry with them, meaning customers pay for a full lorry when it's only partly full. There's no volume either. There's obviously work to be done here in terms of the practical side compared to the theory, and above all the packaging we have at the moment. It's not really adapted to what the law recommends. I could mention lots of other issues, but I'm trying not to digress. Yes, it's really difficult with customers in any case. We try to keep them well informed, but when it comes to their waste, we can't always help them in an ecological or economic way. We really need to work on this. I'd also mention the third thing: the processing codes. The Walloon region asks us and the customer to make declarations. Until last year, we were allowed to use the R13 code, which is for a consolidation centre. All our customers used this code for their declarations to the Walloon region. We took over. We used the R13 code to declare all our destinations for all the waste we had collected in a year. However, for a few months now, all our customers have been asking us lots of questions because apparently the R13 code is no longer accepted. We now have to provide each customer with the final treatment code that has been decided on. This is almost impossible to do in practice with all our very small customers, as we group waste together from several customers. When the trucks are full, we send them off. There really is a new one; it's not an inconsistency, but customers are a bit lost because the information is vague. We don't have the right information from the Walloon region, where it's taking a long time to arrive. It's very difficult at the moment. Ecology is a hot topic right now, so everyone's interested. Some people are interested because they have to be. Then there are those who are genuinely concerned and interested.

Do you know what will happen to the waste once it has been consolidated?

Yes, yes, yes and yes again. The fourth point is that there aren't enough treatment solutions for hazardous waste in Europe. We've been in a hazardous waste crisis for years now. The centres are completely full, and even our own plants in Germany are refusing our trucks. Sometimes we have to wait months to dispose of certain types of waste because the whole of Europe is sending trucks to our plants. There aren't enough centres or incinerators. Overall, there aren't enough solutions for treating hazardous waste. Very little can be recycled, and many customers resent the fact that it's incinerated. Of course it's incinerated, but public authorities and Europe have done nothing about it for years, creating a terrible snowball effect. A lot of waste is piling up. Customers don't know how to dispose of their waste. Prices are obviously soaring, and this situation is not going to improve. These are the four aspects that are extremely difficult to manage on a day-to-day basis. I have the same customers all the time. Obviously, they're the ones with the same waste that's causing problems. They can't take it any more and they're waiting, waiting, waiting, waiting, waiting. All our competitors are in the same situation. It's always the same waste and it's extremely difficult. The treatment centres have become so saturated that they can only take what they want. The near future is not looking good, because I've been hearing this for years and the situation is only getting worse. Italy, for example, has no solution. It sends all its waste to our factories. England doesn't have many. Thousands of tonnes arrive every day. So facilities have to be built.

What type of waste is involved?

The waste that really poses a problem is the big bags. Big bags look like flexible containers made of fibre and a mixture of plastics, and they often contain powders. Many of our customers buy powders, which are always delivered in big bags. These empty bags are stored in large containers at our customers' premises and are very light, so we're on the road with practically no weight. Almost nobody wants them. The fibres get stuck in old branches and there has been so much damage that they no longer fit. Some centres therefore ask for them to be pre-cut. For other centres, it's the dust that is the problem because anything powdery causes huge problems for treatment centres. Initially, they accepted everything, but they have become increasingly demanding as more and more facilities have encountered problems. We're building new facilities, but we're not taking these products into account. This is causing problems for them, so they don't want them anymore. It's really very complicated. Some people are thinking about it because we need many more people to think like that and try to find solutions upstream — perhaps we could change the process that generates the waste. Some factories are considering an alternative process, but it's an additional cost that not everyone is willing to accept. Some are considering it because they're well aware that we can't continue like this. Others are considering it because the powder is harmful to all the workers and operators. There's an awareness of this, but it can't be done overnight.

Then there's the issue of everything that's very pasty, such as polyurethane and PU foams. Have you seen how much volume these products take up before they dry? They contain isocyanates, which are very reactive. This is a huge problem for many centres, and it's very difficult to find any that will accept small quantities. The prices are also very high. Where is this waste stored while we wait for the centres to accept it? Is it stored with you or with the customer?

We don't have much space, so we only store what we can. At the moment, however, we're overstocked. It's really very complicated. Customers agree to stock, but I'm having a big problem with one customer who can't stock anymore and doesn't have any more space. I've been making phone calls for days and days. I've got a former colleague from my Veolia site who's agreed to help me out. In my opinion, you just have to have a network, because these things happen to everyone. Sometimes Veolia doesn't turn up, and as we're all colleagues, we can help each other out. Overall, though, it's the customer who stocks up, and fortunately it doesn't last six months — often it's just two months of waiting. We sell off the stock, then wait for new dates — maybe in three or four months' time — but there shouldn't be any more production. That would be really complicated.

How do you manage the legal obligation of traceability?

Essentially, I submit my price offer via the programme. Then it goes to the planning department. The programme prints the labels and the driver has the same information in his documents. Even if several weeks or months have passed by the time we arrive, the labels are still there — they're very solid. When it arrives at our centre or a consolidation centre, or sometimes directly at a treatment centre, it is always scanned. So, whether it's the treatment centre here in Belgium or Germany, everything is scanned and traceable, and we always know where the waste is going. We always know how it was disposed of. Obviously, when we send a lorry full of mixed waste from several small customers or producers, we can no longer say that a very small bin was really there. We take a bulk container, so we know that the small packaging was in the bulk lorry. Ultimately, nothing goes to waste: the packaging is recycled and the small packaging is kept and recycled in large containers. This applies to everything that's mixed.

There's no problem there. Is everything going well?

Yes, it is. I've never heard of any problems. I think it's going to get better and better because we're looking forward to achieving perfect traceability over the next few years. In all the years I've been here, I've never heard of anything going wrong.

In terms of safety, for example, are there any concerns about the staff, collectors, etc. who handle this waste?

Fortunately, I haven't heard of any accidents since I've been here. Well, one person fell into a lorry once, but it wasn't serious and it had nothing to do with handling waste; he was just taking a break. It's not related to his work, but it's the only incident I've heard of in years. I think they're well trained and have good electronic lifting equipment. I've heard nothing. In any case, maybe that was the case years ago. Nobody got burnt by leaked products. On the other hand, customers have found metal waste storage cabinets with acid leaks many times. So there really needs to be another intervention, but fortunately, I haven't heard of that happening in our day-to-day work in 7 years.

Is there any useful information that you don't currently have?
Well, yes, if I understand you correctly. As I said at the beginning, if the customer doesn't provide us with enough information, it can be problematic. Yes, several times the driver has gone to the site, phoned me and said, 'I'm not taking this because the information wasn't clear enough.' On the whole, it was clear, but there were one or two pieces of rubbish that we didn't know what they were. Obviously, the driver doesn't take it because it's not on his CMR. Yes, that happens quite often. It's also happened that the customer has sent us fairly general photos of waste that wasn't identified at all in the photos. When the driver arrives, he realises that the drum is not transportable because it has a hole in it or no lid, or is not strapped. That happens quite frequently. Yes, and obviously he doesn't accept it. So there are two types of driver: one who's really nice and wants to please customers so much that he sometimes takes things. When we get to the centre, we think, 'We should have refused. We should have told the customer that it's not right.' He's just too nice. Fortunately, we've never had any problems, and the things he's taken haven't been very dangerous. But in the event of a roadside check, there might not have been any labelling. Sometimes you need a certain type of cap, even if the packaging is empty and has a very small base. He's happy to oblige with little things like that. Then there's the other type of driver, who's ultra rigorous. He's never going to oblige, and he categorically refuses the slightest little thing that isn't provided for on his CMR or that wasn't completely identified in the offer. And that's it.

Do you only accept returns of packaging that you have supplied?
No, we can take any type of packaging as long as it conforms to the specifications. We only take prepared waste, either prepared by the customer on a pallet with their own film – most companies have pallets and film to ensure the waste is firmly attached to the pallet – or prepared by our driver at the customer's site if they don't have the necessary equipment. We often take drums or small cans, for example. The customer then restocks them in a storage bin. In fact, they're really plastibac bins, or acuboxes. There are lots of different names for collectors, but it's about 700 litres. It's the one with the tarpaulin and lid that's compliant and standardised, and you can put any small container in it. Of course, you must never transport anything that leaks or is in poor condition. In that case, all the reconditioning work is done on site. It's often the chemist. If there are really dangerous substances or leaks, the chemist goes there. They are equipped with the necessary protective clothing and equipment.

Introducing smart packaging.

Could it be useful for hazardous waste?
I'll tell you what. It's a good question, but I'd rather consult my chemist colleagues internally, because I don't see how measuring oxygen or heat could help with the waste I usually transport or use. All the casks and packaging we use are very conventional and simple, and are designed to withstand high temperatures. All we do with the waste is dispose of it, just like us. There's no need for the structure to change, because I don't think it will ever reach 50°C for several weeks, in which case the waste could change appearance. But these normal daily fluctuations are not a problem for the final treatments of the waste we use on a daily basis. Perhaps in the future, there will be different acceptance standards at the centres. What if the waste no longer meets the required standards? Yes, I think it's possible that, in the future, if we're still faced with a lack of space, there may be plants that will have to modify their

acceptance parameters or perhaps have different infrastructures. Yes, and perhaps if the climate continues to evolve like this — strictly speaking, for hazardous waste in any case. I don't see how these indicators could be useful, but I'll ask the chemists and send you another message. They obviously have a different perspective because they know the treatment centres better and can therefore suggest what would be useful — it's more a question of sensors and indicators. I'm familiar with large skips that already have a fill indicator, which is useful for us. I'll ask the question. I don't see it, but it's true that my job stops at a certain point, and we don't communicate much with those who take care of the rest and take over from the treatment centres. So I'm going to ask the question.

When waste is incinerated, is the packaging incinerated along with it?
That's a good question for the drums. All the acids, bases, organic liquids, everything that we transport to our plant from Germany, yes, and so that bothers me a little for the ecology because the customer has to have a lot of drums, blue 60L drums like that, with double strapping. So they're sealed, they're all clean, they're all new, they're all blue. Probably all good plastic, but it goes straight to incineration. And that, to me, is a complete aberration. But in any case, there's no other way, there's nothing that's standardised for transport and over there they can't be bothered to open it anyway, you'd have to break the strapping to get the waste out. So it's all burnt with the pallets. In this case the pallets too. And anyway, it all has a high calorific value. But then for the small waste, for all the good packaging, so the plastibac ones, we keep them because we use them anyway, we reuse them very often, they have a fairly long life, 5 years in any case.
As for bulk waste, that goes straight into the incinerators. It's been years since I joined Remondis, around seven or eight years ago. I visited all the plants back then.
Not all of them, but at least the three main ones. So I don't quite remember what was said there. Besides, everything changes so quickly. In any case, we send all these good packages, as well as everything that is acid-base, liquid laboratory waste and organic liquids, to our US plant.
Yes, unfortunately, all of that is incinerated from Earth V.

Yes, of course it will be more expensive for the outer packaging. In my opinion, that is.

- *Interview of P6:*

Could you tell me a bit about the company and what you do there?
I've been a salesman with Revatech for 16 years now. It's a waste treatment company, so we have 2 plants, one in Monsin and one in Engie, where we treat around 1,500 different types of waste, so it's pretty varied. I could give you a detailed presentation of what we do, but that would take a bit of time, so I can send you a video if you like. We have a really general presentation video. I look after the big accounts in Wallonia and Luxembourg, and I have to develop France in particular. The Belgian market is limited in terms of waste, so we're growing. I'd say it's normal, so we have to move into other countries, of course.

Is your role as a sales representative to canvass customers, or is it more of an advisory role?
I'm a chemist by training, so when it's mainly industrial customers who have a problem managing their waste and meeting their environmental obligations who come to us for a solution, we help them by offering them our services. And if we don't know how to handle all the waste, because there are a few things we don't know how to do, we can refer them to other contacts we have in the sector.

Can you describe the different stages? Finally, when the waste arrives at the company, how does the processing work?
In fact, we always start with an initial contact with the customer who has a problem. As far as possible, we ask for as much information as possible from the safety data sheets and, if possible, a sample. The sample, of course, is representative of the material. We ask the customer what process the waste comes from, i.e. the process that generates it. We know the industry well, so we know the parameters

we're going to have to measure, so we don't have to do a whole battery of useless analyses, so depending on that, we receive the analysis results from the production and safety chemists. Finally, the various parties involved have determined whether or not we are able to process the waste at Revatech. We establish a price with acceptance conditions. From there, if the customer agrees with this offer, he sends a purchase order or we sign a contract. It depends on the tonnage, of course. Then, if everyone agrees, the waste arrives, generally in bulk form, either in a truck or in packaging. So the packaging ranges from small 20-l cans or bags to 1,000-l IBCs, whether hard or soft, big back, metallic barrels. Whatever they are, all types of packaging. Acceptance of treatment waste: from the moment the waste enters the site, chemists are on hand to check that the small packaging and bulk waste conforms to the waste used to draw up the basic offer and, lastly, the preliminary acceptance certificate. Once this check has been carried out, the waste is directed to the unloading areas. Finally, to the various treatment units, where the treated waste is sent to different processes. I can explain the processes to you, but it's going to take a bit of time for the small packaging part.

How do you identify waste? I think you have a barcode system now.
We created QR codes with the product reference, the date of arrival, the truck number and in fact all this, we scan it with small scanners and it comes into a special program. So they can put it where they store it. When they move it to another place, they also scan it again to tell us where it's going to be stored, in other words, where it's going to be put, and also in the mediums, in the outlets. You can choose if you're going to empty it somewhere. We go directly to a dump, we scan, we put the name of the dump and that way we know that part of it is a choice of treatment. We know that the product has been emptied for traceability purposes, so all the waste that comes in, has a specific reference which contains, in part, the number corresponding to the customer and another part which corresponds to the waste that this customer brings in, because they obviously bring in a lot of different waste. So there's already an identification. And then there's the whole safety aspect, and I imagine the protective equipment that operators have to use. They have a whole range of information to help them handle the waste safely and empty it at the right places.

When they scan the QR code, they have access to all this security information?
In terms of safety, it's not necessarily in the QR code, it's more in terms of management, but the labels already contain information on the means, dangers and PPE to be used. Yeah, well, there has to be a compulsory visual on the packaging, so that firefighters can see the danger signs, so that you don't have to scan the QR code in a hurry to see what you're doing. The QR code is more for management, internal traceability, and then we have SharePoint, where we add a little more basic seated detail and more specific annotations.

Is this QR code actually in the form of labels that you stick on at a certain time when it arrives in the company, or at what point is this QR code affixed?
As soon as it arrives, as soon as the truck passes the scale, it's weighed. We know roughly how many packages they have in the truck, so all the labels in the right number are already printed. He leaves on the slab, that's what we call on we're going to unload. The storage area and then the workers over there, according to the reference number they've given, stick on the right labels. The customer must have the Revatech reference and then it must match. They have to see the same ones and stick on.

OK, and so it's thanks to this QR code that you know the traceability?
Yes, well, normally, in any case, according to the analyses we carry out, the cubi must follow the treatment we've given even if there was no QR code, but with the QR code it's easier. You can see when it's been moved, even if we play too much with palettes, what time, and what day it was in the outlet.

Do you do this for all your incoming waste, or do you only do it for hazardous waste?

It's always interesting to know when you've finished a delivery. And we're obliged by the authorities to issue certificates of destruction or recycling. In the near future, producers who evacuate waste via collectors like Remondis, Renewi or others, will have to make a declaration. We receive the waste as a treatment centre, and we also make a declaration to the authorities. And it has to match, it has to be the same. Now, it's not super well done yet, I'd say, there's work to be done for various reasons. Because I don't think everyone uses the same software. We need to reunify, quite simply, it's not yet the case.

It's when it comes to declarations that you have a bit of trouble, I mean it's a bit complicated when it comes to regulations?
We don't really have a problem, but sometimes there are discrepancies, not in the weights, because that's more or less the same. It's just a question of tipping the scales, maybe a few kilos difference, but that's not serious. On the other hand code level, the codes chosen, treatment codes, what we call 6-digit waste codes if you know them.

Do you sometimes disagree with the basic code assigned to you?
Well, it's not that we don't agree, we at Revatech are lucky enough to have all the codes, so after all, almost all the codes, but there are collectors who don't have them all. It's not very well done, you can put 5 people around the table and put a waste in the middle and say, which code should we put, we might not have 5 different codes, but we might have 3 what? So it's not super well done for choosing the right code in any case, but this is just an example where there are points for improvement.

How do you choose the type of treatment? I mean, whether it's going to be recycled, recovered, etc., that's up to the chemist to decide?
In fact, several people are involved. So we receive an analysis and, depending on the results, we work with the chemists and the production people to determine the best way to process the product. Then, at the commercial level, in agreement with production, we look at the price, we establish a price, we see if it's profitable or not, obviously, and we make sure that it's profitable. But sometimes there's also the customer's choice. Some customers require recycling or recovery solutions, and therefore R codes. So it's not always possible, it's not always the cheapest, because recycling solutions are sometimes more expensive than destruction solutions, where there is no solution because they don't exist, and then there's also the distance aspect, because sometimes there are recycling or recovery solutions, but they're too far away to be ecologically interesting, given that you have to travel thousands of kilometres by truck to get the waste to that place, so it's the CO2 footprint that's not great. We're trying to follow what we call the Lancing's scale, so the best thing is not to produce the waste, so try to guide the customer and help him improve his process so as not to produce waste or to produce as little as possible. And then there's the last thing, which is landfill. Unfortunately, at Revatch, we receive more or less 240,000 tonnes of waste a year and we dispose of more or less half of it. No more than half, yes. After treatment, it's not just landfilled without doing anything after treatment, we add what's needed to ensure that when it's landfilled, controlled landfills, or what we call CETETs, so that the pollutant isn't released when it rains on it, what's that called alexiliation.

And is there a certain type of waste with which you have the most difficulty and which is more complicated to treat?
There's a lot of waste that's difficult to treat. We receive waste containing cyanides, for example or ammonia, because standards evolve over time, and we have to take into account all the new environmental constraints imposed on us. And then, for example nitrites have also evolved. What kind of waste is still complicated? Detergents, yes, everything pephaceous, which is the subject of a lot of media coverage at the moment. All the heavy metals, cadmium and molybene are elements that are really very complicated to control. I mean, and to precipitate in the different processes we have. The more complicated it is, the more steps are involved, the more expensive it is.

You do have quite a few constraints when it comes to environmental regulations, etc.?
Yes, in fact, we have a permit to operate a plant like ours, well any plant has a permit to operate but it's not for an unlimited period, in fact it's for 20, 30 years. At the end of the permit, you have to reapply for a renewal, but the constraints are more and more complicated each time. Which is logical, isn't it?

Do you have any concerns about storage or handling with workers? Are there certain problems that come up quite often?
Yes, there are plenty. It's a daily occurrence, everyone. Well, already in storage. We had a lot of comings and goings, you can carry a pallet around for a long time. Already, that's not great. We also had problems with labelling. Because you also have to find good labels. It's a good price to pay to find something that sticks and lasts, because we're in the open air. We also have, sometimes, outlets that can take longer, so sometimes the products can remain for a very long time, and this can sometimes cause damage depending on the product it contains, the packaging and the wrapping. Now when it comes to handling too, we'd say that anything under 100 l becomes complicated, the manual handling is complicated in terms of ergonomics. We're making progress, but we're not yet at the top of our game when it comes to offloading handling, so men still have to do it by hand for certain tasks, and that's it, it's restrictive, but we're working on the subject, with exoskeletons. I think we're going to use exoskeletons, we're going to use the grinder, we've got pumping now directly into the small cans and we're going to go into cubicles too. We have fast drum pumps that can be unloaded, the milk to move the PL to avoid backache.

Are there any incidents or accidents that happen frequently?
Accidents. Yeah, we had them in the beginning. Well, I'm talking about the 80s and 90s, but now we're part of the group. I mean, formerly Suez and Veolia, which, are big companies that put a lot of emphasis on worker safety and well-being. So we have a lot of conditions that have been improved, I'd say, we have very few accidents, we still do. However, it's more incidents than accidents. But the activity is obviously very dangerous. I think we work very well in that respect.

Are these incidents due to human error, or are they technical or machine problems?
Ohh both. On this site I don't know how many accident-free days we have. It's already been several years since we've had any accidents warmly. We call it, we can have incidents where someone gets hurt, but they still know how to keep working. It's not a serious incident, they're still recorded, but not as an accident. We haven't had any of those for several years now. On the other site, we've just had one after 15 years without an accident. We've just had a fairly major accident, which means that, well, we're never quite there yet. And this is human error, I mean, we're in the process of analysing the accident, but it's more an indication of human error than anything else.

This have a certain cost? I mean, I imagine it might stop certain types of waste from being processed, or maybe you can estimate the cost of this kind of incident?
If there was a serious accident involving breakage of the plant, well, a fire for example, or something like that, it's certain that there would be a production stoppage, but it depends, we haven't had any for years, we've had some, but we haven't had any for years. So the good thing is that we have 2 sites. We've got 2 sites that are complementary they can help each other, so they can both do more or less the same treatments. Not in the same way, but a few years ago we had a shutdown at one site. Well, we evacuated all the waste to the other site, having 2 factories in 2 different locations helps us to alleviate this kind of problem.

Smart packaging explained.

Do you see any benefit in using this packaging?
As far as I'm concerned, the only interest we could have, at least for the time being, is in terms of traceability. As I was saying, it's in terms of logistics, for example. Like Remondis, you asked Caroline.

They make reusable packaging available to various customers. They need to be able to manage their stock. It's easy to say, "Well, I've had this much packaging with this customer for this many days now, and I can invoice him for this much. For us, well, in terms of traceability, depending on the container, I can imagine waste, for example strong acids or very very very dangerous waste contained in packaging that has reached the end of its life. Having a smart packaging that says “be careful because this packaging is no longer up to standard and there's obviously a risk of spillage or of explosion or it no longer meets ADR standards. Well, I don't know if I had another idea, it's that for example, for waste that is really very radioactive for example, or explosive waste, we don't have that but things that are really need to pay a lot of attention to.

In terms of safety, if, for example, we realize that there's too much oxygen inside the packaging, we could try to remove it to prevent inflammation. Could this kind of thing be interesting?
If you remove the oxygen, there's no problem. What we've had instead is gas, but we don't have flammable waste, so we can't receive waste with a flash point. We sometimes receive, for example, metal dust like aluminum which, in contact with humidity, produces hydrogen. So there's a major risk and it could be useful. Detecting gases. It could be useful. We come to certain firms that have a lot of dust with heavy metals. I think that might interest them. In fact, industrialists aren't always aware of the danger. For example, you see people who make window frames out of aluminum, they machine so they work the metal, they're going to end up with aluminum dust, it's hyper powdery. If it's poorly stored, if it's put in places outside or even damp or whatever. We've received swollen packages before, and we know because we've had experience. But what the swelling is due to is hydrogen production. I'm not going to draw a picture, it's hyper-reactive and hyper-explosive, in this context of injections, it could be in our interest to use smart packaging or even if it ever heats up, because we've already had products that heated up. Oh yes, so many drivers. Apart from getting your hands on it if it starts to heat up in a cubicle, which you can't see, it would be nice to know. That's what it's heating up and we could pull it out and treat it as soon as possible. Something like that, yeah, the heat, that's also interesting to know the temperature. Yes, for some waste, not for all, but it's interesting. For certain types of waste, it can be interesting.

It would have to detect but also alarm you in some way?
Oh yes, if it's on our premises. It's interesting to have the information to be able to intervene. What, you'd have a thumbnail that changes colour. You know what I mean. We're all going from green to red.

Indicator, you'll find that interesting, wouldn't an alarm be necessary?
No, and maybe we don't, but I think that in certain sectors there are, there are things that are worth a lot of money or the risk is high. Everyone's like in concrete things, so it was catching fire, but in our 3 places it wasn't going so well. I don't know if it would be any use to us directly, but I'm trying to be a little more general.

Apart from traceability, you won't necessarily see the point. Inevitably, it's going to be a bit of a safety issue, isn't it?
Gas. I think it should be compulsory, because right now we're working with waste. So, waste is really the last thing that industrialists are interested in, because it's a cost, and their aim is to produce, well, to create a product, not to incur the costs of waste disposal. As a result, we often end up with packaging that is not only unsuitable for road transport, but also no longer valid, so they think, well, let's put it in here. But the packaging no longer conforms. So the fact that it's no longer compliant can be a risk, because plastic, gets damaged. So it could also have an interest in having a quicker view, I'd say, of the packaging used to store the waste. No, I have to say that it's useful to know how long you can store it, but still traceability is important, because how many customers ask me, would you have xxx, would you have xxx, and me if I don't sort and if I'm not aware of what they've sent me.They're often a bit lost. That's why we switched to QR codes. Traceability is super important and that's why we switched to the QR code because barcodes, they have to be at least 80% legible to be secure, whereas

QR codes make all the difference. Even 20% of printed matter on a whole QR code is enough, it's fine, and it’s a wide, wide margin of error. I'm taking the case of the collector, I'm picking up on what Charlotte is saying, but more generally, in fact the collector, like Remondis, is going to go for example, a drum or a plastiback or anything else at a customer's premises, the customer needs a certain amount of time to fill it. Once it's full, he places an order for the collector to come and collect it, but the collector, he doesn't just go to what's there that day, he goes to different customers' premises and collects the waste. And then he takes it either to their grouping centre, or he takes it directly to the treatment sites. There's a lot of data, the packaging travels a lot, so having a tag or a beacon that tells you where the packaging is, well, it would help them, it would really help them. No, we don't need it, but I'm thinking more generally of the collector you had the other day. Well, for the traceability of their packaging and invoicing. It's much simpler, isn't it?

Is it still an additional cost?
We just had to invest in one printer, but we'd already invested in another printer, that's true. And the team. We've just invested in a program, that's true, which is much, much simpler than SharePoint. It's not the enormous costs given the ease it kind of facilitates plus the scanner obviously buy scanners, buy tablets because well here we have to modernize a bit. It's just that you have to invest a little. It's really in terms of cost, would it still be worth investing in this kind of packaging? Would it be profitable in some way? We're going to say, we are, that's clear. I don't know how much they cost. I don't really look. But here we are, reconditioned tablets, we've taken, then we've also taken back mobile phones to go for small portable scanners, there you see, I don't remember the courses, we'll say that for €10,000 in total yes it's really useful to us and then it even puts for the people who use them, it really makes you feel a bit in the 21st century. It gave the staff a lot more motivation to see that we were doing things differently and that we were investing in modernizing their work. Well, that's just it, it makes a difference in terms of cost for us compared to what we earn, I'd say, isn't much.

Sometimes the packaging ends up being incinerated with the waste, so in that case smart packaging is not necessarily interesting, isn’t it?
Yeah, in that case it's a shame to go and ruin a tracker. Unless you know, remove it if necessary. To reuse it, that's all. In customs cases or things like that, because they're not on a few dollars. I mean, they're not sure if they really want to know how far the product has gone to still put it on, and if it's destroyed, it could be gone as a result of what. I don't know about that.

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EXECUTIVE SUMMARY

Hazardous waste poses a significant risk to human health and the environment, if it is not managed properly. In the European Union, industrial sectors generate most of this waste, and ensuring its proper handling involves several stages, from identification to final disposal. Despite strict regulations, important challenges remain, including traceability issues, illegal practices, regulatory complexities, and accidents during transport. Smart packaging technologies could be a valuable solution to these challenges. Already widely used in sectors such as food and pharmaceuticals, smart packaging incorporates sensors, indicators and other tools to enhance safety and quality throughout the supply chain.

This thesis aims to investigate the potential use of smart packaging in the management of industrial hazardous waste.

To this end, a literature review was conducted to compare the challenges of hazardous waste management with the benefits of smart packaging. Five hypotheses emerged from the review and were discussed with professionals from both sectors to obtain their expert opinion on the matter. These hypotheses were explored further through a qualitative study based on interviews.

The results revealed two areas in which smart packaging could be beneficial: security and identification. However, the results also raised ecological concerns, given that much hazardous waste is incinerated with its packaging.

In conclusion, smart packaging could help to address some of the challenges faced in the hazardous waste sector. Nevertheless, further research into feasibility, environmental impact and costs is required before any significant development can be considered.

KEYWORDS: Hazardous waste, waste management, industrial waste, smart packaging, regulatory issues, traceability, safety, transport, environmental and health impacts, illegal practices

WORD COUNT: 239

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