Fields of Research in Optical Sorting of Different Types of Waste

Antoine Bourely

1. Applications in Optical Waste Sorting

Optical sorting appeared for the first time in 1994 in Germany, France, and in the USA.

Initially, it was limited to the recognition of the main packaging types, as found in the *yellow bin*, using the NIR spectroscopy to differentiate molecular bonds : PET, HDPE, PVC, Tetrapak were the main targets. Colour sorting was later introduced for very fine colour nuances (e.g. clear vs light blue bottles). *Today, most MRFs in Europe use Optical Sorting for packaging.*

A second sorting stage in recycling plants was needed, in order to be able to recycle high quality resins in a true closed loop: **bottle to bottle PET recycling** required less than 50 ppm final contamination, especially in PVC. This was achieved as early as 2001 in France, and a guaranteed contamination level of 10 ppm was achieved in 2011. However, the difficulty remains, as new types of bottles with specific challenges keep appearing: multilayers, blends, PVC labels, etc. Almost all recycling plants use Optical Sorting, but new problems keep arising every year.

The collection of all dry recyclables (packaging and paper / board) into one *single stream* is very common, especially in North America. In a Material Recovery Facility (MRF), a mix of mechanical solutions separates this stream into two fractions: flat bodies (paper/board), and hollow bodies (packaging). Optical sorting is then used for clean-up, e.g. removing remaining papers in bottle streams.

The next topic was the **separation of paper streams into De-inking and Cardboard** streams. It is very challenging because the materials to separate from each other are mainly the same: cellulose and/or lignin. NIR spectroscopy and MIR thermography have been proposed for these tasks. Although a lot of progress has been made, the Optical Sorting of paper streams is still less efficient than for packaging.

Industrial waste became a major target in 2005, with the German Law prohibiting waste dumps. Dry streams containing mainly paper, plastics, textiles and wood were collected. The initial target was to recover heat energy, and sorting essentially aimed at removing chlorine, to avoid creating dioxins and furanes during combustion. PVC recognition by NIR was the main tool to achieve this.

Many operators then tried to recover more value by selling specific materials separately: wood, mixed papers, HDPE or PP, plastic films. The extreme variety of the input streams, together with very dusty environments, makes these applications difficult. Material recycling from Industrial waste is an area of progress for Optical Sorting.

Plastics are also widely found in WEEE (**E-waste**) and in Automobile Shredder Residue (ASR) in **automobiles**. Here, the situation is very complicated: many plastic types exist: ABS, ABS/PC, HIPS, SAN, PP, PE, etc. and they contain critical additives, most notably the brominated flame Retardants (BFR), that are not detected by NIR spectroscopy. Finally, half of them are black: there is still no efficient technology to sort black plastics from each other today.

WEEE and ASR also contain many metals, and **metal recycling** is an old process. Alongside traditional metal separation (Overband magnets and Eddy Current sorters), sensor based sorting has made a very significant contribution: induction sorts metals from non metals: as it uses electromagnetic sensing and is contactless, it is assimilated to optical sorting. **X-Ray transmission (XRT)** can differentiate heavy from light metals, and **X-Ray Fluorescence (XRF)** individual metals from each other. However, these technologies are not very precise (XRT) or rapid enough (XRF), and are a very active research topic. WEEE and ASR recycling plants are emerging concepts, with many unsolved sorting issues.

Bio-Waste is mostly processed through methanisation and or composting. In order to optimize these processes, foreign materials (glass, stones, plastics) should be removed. XRT has been used to remove minerals (a costly approach when compared to the value of the products), and more recently NIR spectroscopy for positive sorting of organics. The very high number of *dirty MRFs* or non selective collection schemes around the world makes this approach a key issue for the coming years. Bio-Waste is a promising emerging field for Optical Sorting.

2. Technology Portfolio

The above description of the sorting challenges explains that a wide portfolio of optical sorting technologies is expected from a supplier. It can be summarized by the figure below, showing the current offer of our company.

Not only many technologies, but also a variety of machine structures is needed.

For instance, we offer anywhere from 800 to 2,800 mm sorting widths, in 400 mm increments.

Different resolutions are needed for all object sizes, from 2 to 500 mm: we offer nozzle spacings of 25, 12.5, and 4 mm.

Finally, customers expect a machine to do more than a binary sort: three way sorting in one channel, as well as multiple channels in one machine are required features today.

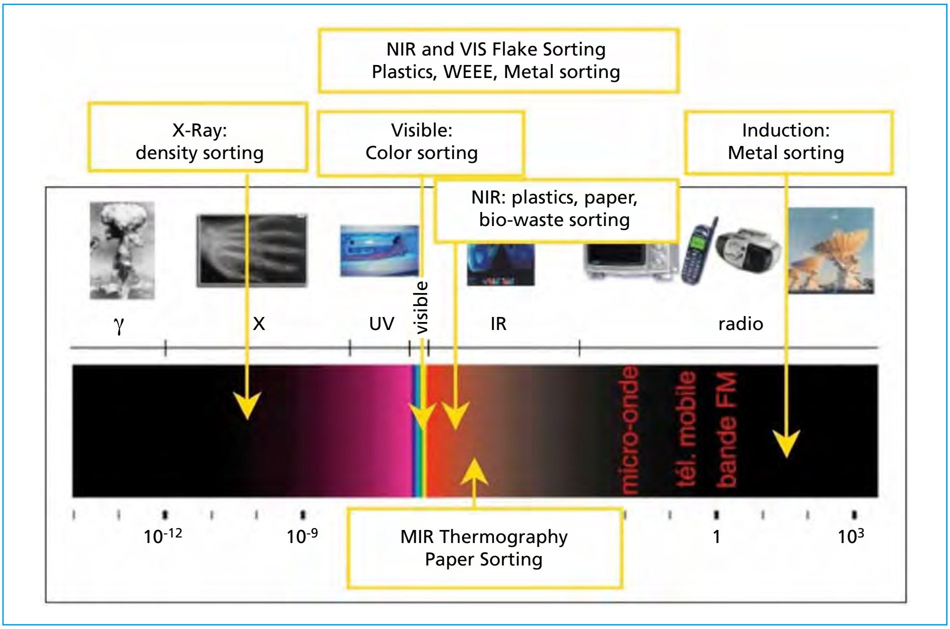

Figure 1: Our technology portfolio

Very few suppliers in the world offer such a comprehensive range of solutions.

Structure of an optical sorter: an example is shown below: products are spread in a single layer on a quick sorting belt (2 to 4.5 m/s speed). Two products are blown at the same time in opposite directions: here bio-waste (organics) to the top with a nozzle bar under the stream, and plastics & papers to the bottom with a nozzle bar above the stream.

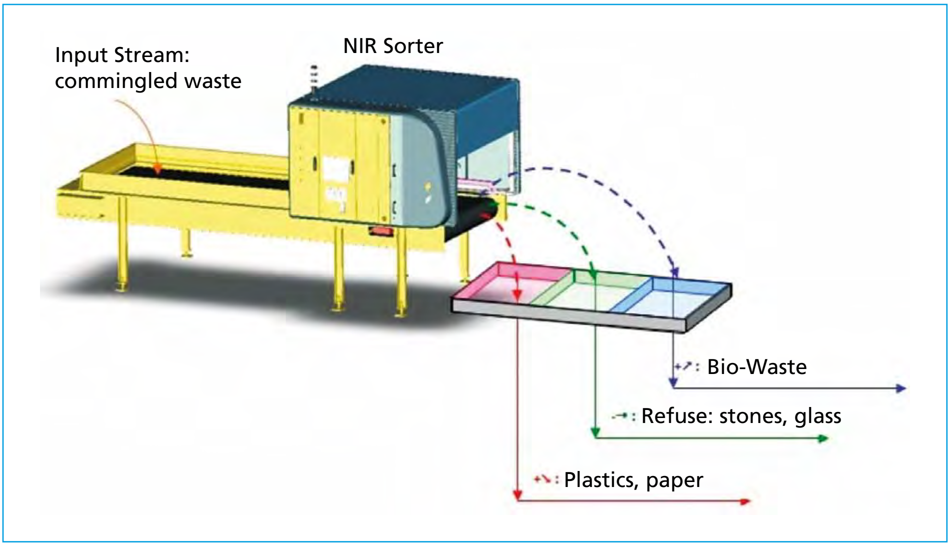

Figure 2: Positive sorting of Bio-Waste

3. Research Hot Topics

3.1. NIR Spectroscopy

The NIR domain is broadly defined as wavelengths between 750 and 2,500 nm. For waste sorting, it is more restricted to 1,000 to 2,000 nm. Chemical bonds in plastic molecules, especially C-H and O-H bonds, are the main features used to differentiate polymers from each other: their vibration wavelengths change significantly between polymers, like: 1,660 nm for PET, 1,715 nm for PVC, 1,730 nm for HDPE.

At first glance, NIR sorting of containers seems easy. However, many issues appear if we look at related tasks, where differences are not so obvious. The key parameter for success is then the signal to noise ratio (SNR). Examples are listed below.

Labels on bottles: container walls are around 300 µm thick, and NIR light penetrates the whole layer, providing a strong signature. Labels, often made of a different plastic, are only 10 to 20 µm thick: NIR light goes through them, and the resulting signal is a mix of the label and the underlying bottle. This mix varies in proportion, depending on how well the label sticks to the bottle.

A good detection of labels on bottles requires a very good SNR and a processing algorithm that can unscramble the mix of two materials.

Our State of the Art solutions feature excellent detection of PVC, PE, PP, and PS labels on PET bottles. Only PETG labels on PET bottles remain challenging, since the two materials are very close.

Other issues of material mixes are even more difficult: **multilayer bottles** often use a nylon sheet between two PET layers to create a barrier. This sheet is less than 20 µm sheet, and it is not on the surface. Another solution uses **blends**, where two materials are mixed in the same resin. In both cases, existing technologies do not currently enable detection at industrial throughputs.

Plastic films are a key progress area to increase plastic recycling rates. PE, PP, PVC are commonly used for these films. They are 10 to 15 µm thick, are often folded and/or dirty.

They must be sorted in two steps:

- first, they must be separated from containers in MRFs, although their constituent polymer is the same: fine differences in spectra have to be detected.
- Then, in recycling plants, PP and PVC contaminants have to be removed from PE film streams.

Since these materials are very light, machine structures must be adapted to handle industrial thoughputs (1 ton/hour or more): they must be spread on very large conveyors, and stabilized with appropriate air streams (like our TurboSorter).

Solutions for both sorting stages have been successfully implemented in 2011 in French industrial facilities.

Bio-Waste (or food in general) is an unusual field for NIR spectroscopy. Water essentially absorbs all NIR radiation, and it looks very difficult to analyse products like vegetables or fruits with water contents of 50 % and more. Because of this need of transparency to water, the food industry uses another NIR domain, namely from 700 to 1,100 nm.

Again with very good SNRs, we have been able to adapt our technology to detect wet products. We can positively sort bio-waste, i.e. essentially vegetable rests, but also bread, and other dry foods. It should be noted that they are distinguished from papers: some customers require this feature, because they do not want to include too many papers in a methanisation process. Also, in the future, we can think of removing food from commingled waste, while keeping the paper inside for further sorting and recycling.

Papers are mostly made of cellulose, but many different paper types can be manufactured. They differ in **lignin** content (mechanical pulp versus chemical pulp), **fillers** (used to enhance brightness on printed boards and on magazines), or in **ink** composition: petroleum based inks for offset printing, and water based inks for flexographic printing.

Woods are made of the same base constituents, and must be sorted from papers. Moreover, natural woods are more valuable than treated woods, which contain additives such as **varnishes, paints** of **glue** for particle boards.

For all these components in papers and woods, we are looking for very low material contents: from 20 % in the case of lignin, to 8 % for a glue, 2 % for a varnish, and less than 1 % for inks.

Industrial solutions exist for most of these tasks, but improving their performance is still a research area. Here are some typical industrial performances:

• Paper vs wood in industrial streams:	> 90 % detection rate
• Natural wood in mixed wood stream:	> 80 % detection rate
• Printed container board in a paper stream:	> 60 % detection rate
• Flexographic inks in De-Inking streams:	> 90 % in the lab, but still unsolved at industrial scale.

A very active research area to enhance these small differences is to use the higher range of the NIR domain: from 2,000 to 2,500 nm. However, sensors are expensive and difficult to use there, and SNRs are poor.

Minerals do have signatures in the NIR domain, and important distinctions relevant to the mining industry have been made: **limestone/talc/clay/silica** show clear differences. These can be used for sorting in mining operations and/or for construction/demolition applications.

This review shows that after 15 years of success in waste sorting, NIR spectroscopy remains a very active research domain, with a rapidly expanding range of applications.

3.2. Colour Sorting

With the explosion of the digital camera market, colour cameras have become cheap and very reliable. They provide very high spatial resolutions, and use 3 colour channels (RGB), similar (but not identical) to the human eye.

A very large image processing industry has appeared in the last 20 years. Less than 20 % of it is dedicated to colour images, and most of it is concerned with image rendering to provide good visual effects. The main tool is colorimetry, first defined in the 1930s for the invention of colour TV. RGB cameras have been used extensively in waste and food sorting and provide good sorting results.

However, this traditional approach has shown limits when sorting industrial objects by colour. Unlike natural products, the colour in a man-made object is often provided by just one colouring agent. It can be more efficient to characterize the signature of this agent than its resulting colour.

This point of view brings **visible spectroscopy** in the forefront: Like for NIR, we look for products of different chemical composition, which exhibit very specific spectra in the visible domain.

This approach has had a growing importance in the last ten years, as manufacturers have reduced the amounts of colouring agents used to become *greener*. For instance, a light blue water bottle in the year 2012 contains less than 25 % of the colouring agents of a light blue bottle in the year 2000. Visible spectroscopy enables a very clear distinction between clear and light blue PET bottles, even when an RGB camera sees no difference.

In the printing industry, very few different inks are used for creating the main colours : Cyan, Magenta and Yellow agents have easily recognisable spectra. A brown cardboard can be easily differentiated from a brown skin colour printed on a magazine.

Many more examples could be given and explain the success of visible spectroscopy. Despite a slightly lower spatial resolution than RGB cameras, this is the leading approach today.

3.3. Scanning Systems Versus Spectral Imaging

There are two main solutions for on line spectrometer designs: spectral imaging and scanning systems. Spectral imaging is a fashionable design, because it requires no moving parts in the optical head. It is available both in visible and NIR versions.

However, it has significant drawbacks:

- Acquisition times are on the order of 1 to 2 ms, corresponding to a displacement of 2 to 6 mm of the objects. This means that the images are blurred in the displacement direction. This is especially limiting in the case of flake sorting, i.e. with object sizes around 5 mm.
- If we want to use the higher wavelength range (above 1,650 nm), where most of the spectral information lies, spectral imaging cameras are very expensive and need to be refrigerated with several thermo-electric cooling stages.
- Finally, it requires a complex electronic subsystem for the acquisition and processing of huge quantities of information, most of which are not very useful: it can be safely said that 90 % of the wavelengths in one spectrum do not provide useful information for a given sorting task.

Our alternative is to use high speed, high quality scanning mirrors. At any given time, light is gathered from the detection spot only, within a few microseconds. There is no risk of blurring.

The light is fed through an optimized optical stage into a dedicated spectrometer. In the figure below, light is carried via an optical fibre bundle from the gathering optics to the spectrometer, which is safely placed in the temperature controlled electrical cabinet of the machine.

This spectrometer restricts acquisition to a few dedicated wavelengths, optimized for the most significant portions of the NIR spectrum, and processing is also optimized with these wavelengths.

Typically, 16 pieces of information for each spectrum are processed, to be compared to 256 for a complete spectrum:

- The processing is much simpler and much faster.

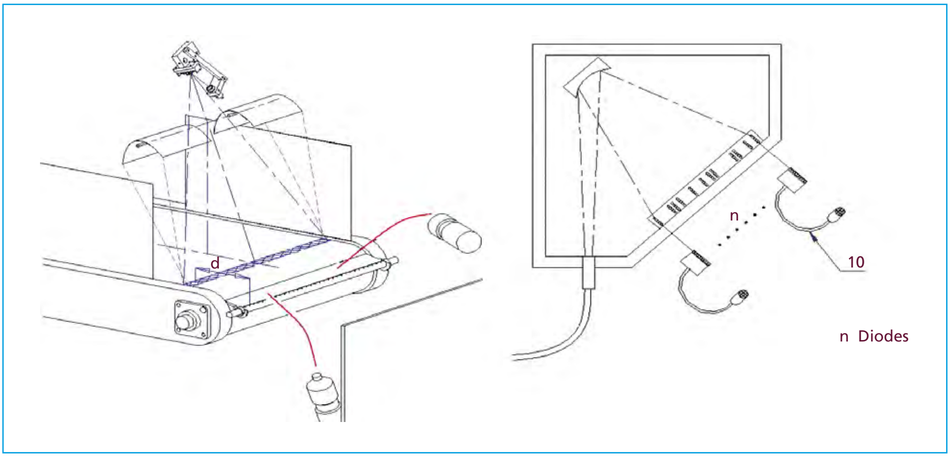

Figure 3: Optical scanning with focussed illumination line (left) and dedicated spectrometer (right)

- The quality of the optical signal is better, not worse, since the wavelength choice is optimized in function of the detection task required.

3.4. Flake Sorting With NIR and VIS Spectroscopy

Flake sorting is well known in various industries, e.g. the food industry, where it is used to sort small fruits, rice, tea, etc. In this case, color vision is sufficient, with occasional use of simple NIR.

The PET recycling industry uses these flake sorters to scan for color differences and opaque objects, but they cannot tell the difference between materials of different composition and same color, e.g. transparent PVC and PET flakes. Some NIR flake sorters have appeared in the last 3 years on the market, but have not been very efficient and/or successful, notably those based on spectral imaging.

We are the leading supplier of optical sorters for the PET recycling industry: for instance, we have equipped the biggest PET recycling plant working on the bottle to bottle process, the Artenius plant in Beaune, France. It processes 45,000 t of recycled PET per year into bottles, all the way to the preform level. Therefore, we have decided to adapt our well proven NIR technology (described above) to the flake size (2-12 mm), while providing it with simultaneous color detection.

The PET industry was not the only target: E-waste and ASR plastics are always sorted after shredding (5-60 mm): we are handling a mixture of plastics and metals, mixed with some glass, rubber, wood, or paper. The physical behavior of these products is extremely different from each other, leading to challenges to feed the products into sorting machines.

There is a size continuum from 2 x 2 to 60 x 60 mm^2, and a single sorting architecture that can handle all these sizes is desirable. The architecture chosen (no chute, products stabilized on a flat conveyor, short distance to nozzles) ensures a uniform handling behavior of different materials, shapes and sizes.

Difficult to detect objects are well identified, such as the examples below:

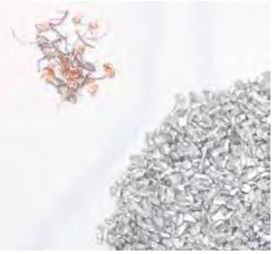

Figure 4: Copper wires in alu. stream and PP flakes

Figure 5: Transparent PVC flakes

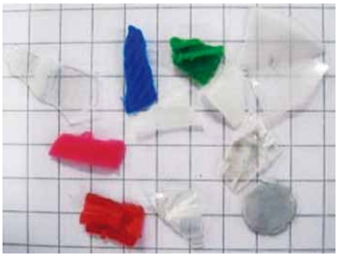

Figure 6: PE

Sorting results are very consistent across different stream sources.

- If we pre-screen products above 4 mm,
  - * the measured removal efficiency is above 90 % for contaminants in PET flakes
  - * Corresponding throughput is 2 tons/hour for a 1,200 sorting width.
- When we screen at 2 mm, i.e. for 2 to 12 mm flakes:
  - * global efficiency > 80 %.
  - * Loss ratio (good products lost versus contaminants ejected) = 2 to 3.

Another example in copper flake sorting (3 to 5 mm) in a 2 shift operation in France yields:

Input purity: 99.7 %; Output purity: 99.95 %; removal efficiency: 81 %

In parallel, research will continue to handle ever smaller objects, since demand is already appearing in the range of 1 to 2 mm products.

3.5. Thermal Imaging

In order to separate objects of the same nature, like papers and cardboards, spectroscopy is not efficient. Thermal imaging has proven to be an efficient alternative. The principle is active thermography: products are illuminated with Middle Infra-Red (MIR) radiation. In this range, they are all black bodies: object colour plays no role, and all the radiation is absorbed. The products are imaged a few tens of milliseconds afterwards, at a time where energy has evenly spread across the first layer, but not moved to neighbouring layers. Thick products such as cardboards exhibit a smaller temperature increase than thin products such as papers.

The result is shown below:

The patented principle also applies to plastic containers present in the same stream: they are thick and are detected like cardboards. It is therefore possible to clean in one step a mixed paper stream from most contaminants.

Such a system is for instance in operation in one MRF in London on 6 optical sorters.

Removal efficiencies in one step are up to 80 % of the contaminants.

The technology has been made robust in industrial environments.

- It works with all outside temperatures between -10 and +40 °C. It works at high speeds (4.5 m/s) providing high throughputs (10 tons/hour on 2.8 m wide machines).

Figure 7: Product illumination

Figure 8: An advertising leaflet, and a board packaging of similar colours (above), and as seen with the thermal camera (below): yellow = paper, blue = board

- It operates best on true flat bodies, such as paper streams that have gone through preparation with disk screens, rather than trommels.
- It is the only technology that can sort white boards of all types (including pizza packs) or black packagings (not seen by NIR), and it can work on any type of grey boards.
- It can be combined with NIR and visible spectroscopy in multiple stage sorting, in order to take advantage of the complementarity of the technologies.

3.6. X-Ray Sorting

When atoms rather than molecules need to be detected, X-Rays are a good choice.

The principle of Dual Energy X-Ray Transmission (DE-XRT) has been well described by the Delft University in the Netherlands. It is an adaptation of the luggage sorting machines in the airports: X-Ray systems work in transmission, with the source above the stream, and a line camera as a detector under the conveyor belt. By comparing transmission in two energy bands, the effect of thickness can be eliminated through mathematical processing, and the resulting value is a function of the average atomic number of the products located between the source and the detector.

When looking at complete objects, a 2 dimensional density image is created: image processing can improve detection results on entire objects.

The main sorting applications to date are:

- Heavy (Cu, Fe) from light metals (Al, Mg), especially on dirty products from incinerators;
- Inert (stones, glass) from organic materials (wood, bio-waste);
- plastics containing brominated Flame Retardants from plastics free from these additives; see example below:

Although the principle is rather simple, the technology is difficult to master and to implement, because of radioprotection issues. It is true that no radioactive source is present in the machine: X-Rays are electrically generated with an electron gun, and the machine is safe

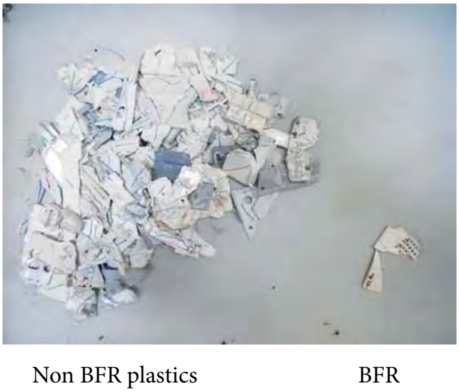

Figure 9: Negative stream

Figure 10: Ejected stream

when turned off. But shielding has to be carefully designed for a safe operation around the machine by non-qualified workers. The machines must be declared to the Nuclear Safety Authorities, and regularly checked up. As a result, one 1,200 mm wide machine, including infeed conveyor and output container (both shielded) weighs 6 to 7 tons:

Figure 11: A fully shielded de-xrt sorter with integrated sorting conveyor and output box

Research issues: X-Ray photons are very energetic, but very few in numbers. It means that SNRs are not very good (< 100): when looking at small objects at high speeds (3 m/s), it is difficult to find low percentages of a given additive. Detection limits are an ongoing issue.

X-Ray Fluorescence

This technology also works on atoms: although it shares safety issues with XRT, it has a very different principle: when illuminated, each atom re-emits at a specific energy, as shown on the figure on the left.

An individual signature is obtained. One can separate Copper from Steel, from brass, etc, and find impurities in glass.

Research concentrates on high speeds (10 m/s acquisition time or less) to achieve useful results.

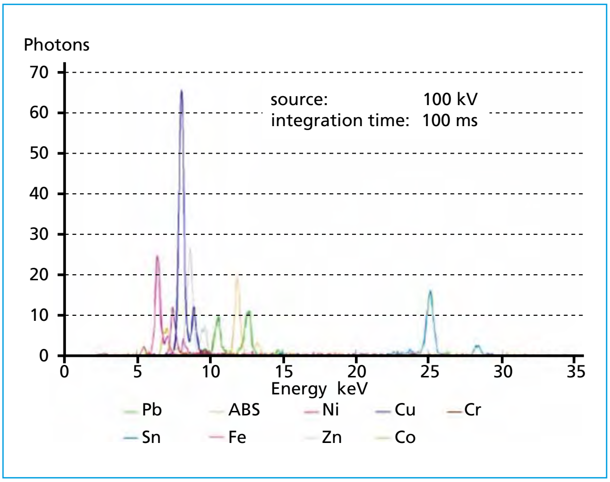

Figure 12:

X-Ray fluorescence of some elements

3.7. Emerging Technologies

If we refer to the technology portfolio diagram in part 2, it is clear that other domains of the electromagnetic spectrum can be explored:

- **Gamma** rays are already used in a similar fashion to X-Rays to scan entire shipping containers in harbours. Safety issues are even tougher than for X-Rays.
- **UV transmission and fluorescence** are widely used in biology, and are already applied in glass sorting: issues are very similar to visible spectroscopy.
- **Far Infra-Red (Terahertz)** has been investigated by some laboratories, but so far, no spectral effects (absorption at specific wavelengths) have been reported.
- **Microwaves** have been used to heat products and perform active thermal imaging.
- **Electromagnetic (Induction) sensors** exist in different flavours: instead of the simple metal/non metal diagnosis, sophisticated devices analyse the signal phase shift, which provides more information on the nature of the metal: stainless steel can be separated this way.

In the previously explored spectral domains, **laser technologies** have received special attention, mostly LIBS, and Raman. **LIBS** stands for Laser Induced Breakdown Spectroscopy: one creates a plasma with a high energy laser pulse on the surface of the object, and this plasma tells the atomic composition of the object through a UV-visible spectrum. It is a complicated point to point technique, and requires aiming at the objects before firing the laser on them. It has been proven efficient on some metal sorting tasks, but not on plastics so far.

Finally, **Raman** is an alternative to NIR spectroscopy for organic materials: it provides a rich information, but it interferes with fluorescence issues, and it requires very high energies for meaningful signals. It has only enjoyed limited success up to now.

4. Conclusion and Perspectives

The field of Optical Sensing is extremely rich, and is increasingly applied to various sorting domains. As we gradually move away from the point of view of waste elimination, and we think more at the elaboration of secondary raw materials, more technologies, previously considered as too expensive or too slow, will enter the industrial scene.

The growing scarcity of raw materials around the world, as well as a higher price of energy, should ensure a continued demand of optical sorting solutions. Today, if we only consider the developed world (OECD) together with the main emerging countries (BRICS), it can be said that the level of automation through optical waste sorting is just 2 to 3 %: there is a lot more to do!

Every manufacturer of optical sorters will have to supply a comprehensive set of solutions for the sorting needs of a given industry. This implies to master many detection technologies, as well as their integration in very tough environments. And of course, as the field matures, research will have to concentrate on cost savings to make the technology more affordable.

It is a very exciting field: if we look back at the beginning of the nineties, few industrial domains have brought so many changes in such a short time. Moreover, the whole domain is a major contributor to a sustainable economy for the planet.