RECYCLING: AUTOMATING THE SORTING AND SEPARATION OF E-WASTE

INDUSTRIAL, CONSUMER, ENERGY
EXECUTIVE SUMMARY

Converting e-waste back to raw materials offers a cost-efficient alternative to mining virgin materials, particularly as they become harder and more expensive to source. Resource bottlenecks drive up raw material prices and can inhibit innovation cycles.

In this paper we focus on the biggest challenges the e-waste processing industry is facing. We examine how these challenges could be overcome by leveraging technologies such as machine vision, machine learning, augmented reality and robotic systems. We also present a vision for how these technologies will be brought to the market through a stepwise progression.
1. INTRODUCTION

The availability of critical, virgin materials for the fabrication of new high-tech products is a major supply chain issue, as European and North American manufacturing is dependent on imports of virgin materials to fuel their economies. Rare earths, for example, are either mined in politically unstable countries, or in countries that have sporadically applied export restrictions. Consequently, commodity price fluctuations put additional commercial pressures on OEMs and reduce their margins. The conversion of waste streams back into raw materials offers an opportunity for OEMs to radically reduce this dependency, while extracting additional value from their sold products that have reached end-of-life (EoL). To do so, technological innovation and optimisation of the recycling value-chain is needed.

Overall the e-waste recycling value-chain consists of three major stages, see Figure 1:

- E-waste collection
- Mechanical pre-processing (device dismantling and/or shredding, sorting of e-waste fractions)
- End-processing/Refinement (refining of e-waste fractions into raw materials)

The key commercial challenge the recycling industry is facing is that valuable target materials are lost into side-streams during mechanical pre-processing, and can’t be recovered during end-processing, significantly reducing financial returns.

To maximise recycling efficiencies and consequent raw material recovery, mutual optimisation across this logistic chain is needed. For example, the reduction of EoL devices into material fractions: printed circuit boards (PCBs), wiring, ferrous metals, plastics, glass etc. is key to effective recovery of the embedded precious and/or critical materials. Inefficient
separation causes loss of material fractions into side streams from which they cannot be recovered, for example, plastics fragments contaminating the purity of a collated PCB stream and vice versa.

This raises the question, what can be done to improve processing efficiencies?

To put this into context, across all e-waste categories 48% of the monetary value is embedded in the PCBs fraction, yet PCBs account for only 8% of the overall e-waste mass, see Figure 2. For IT and Telecommunications equipment, or consumer electronics, this PCB mass fraction is even higher, typically 13% – 14%. PCB fraction recovery rates can vary greatly. While 100% recovery can be achieved through labour intensive manual disassembly and separation, mechanical shredding or crushing, coupled with automated flake sorting, results in poor recovery – typically 30% – 80%. About 20% of precious metal content is lost to non-recoverable output side-streams such as plastics, process residues or saleable metals when e-waste items are mechanically pre-processed.

Per ton of PCB mix, end-processors pay pre-processors only the net value that is the precious metal content minus treatment costs for sampling, assaying, smelting and refining. For a tonne of typical PCB mix, the net value can vary between £2,500 – £5,900.

We will now look at some of the current challenges that pre-processors are facing, new emerging technologies and how these technologies could be integrated into current systems to fully unlock the potential that circular economy provides.
2. PROCESS CHALLENGES

We have identified six challenges that pre-processors are likely to face:

- **DATA SECURITY**: Concerns over data security stop consumers from handing over their end-of-life devices for recycling. A recent survey, conducted in September 2017, suggested that 69% of consumers had concerns over data security. Up to a third would keep hold of old devices, effectively withholding them from recycling and metal recovery.

- **PRODUCT COMPLEXITY**: Each generation of electronic devices delivers greater functionality which is normally achieved through more integrated design at reduced cost. Bulk shredding of these fully integrated electronic devices creates a homogenous mix of waste fragments. Sorting these generated small waste fragments into groups such as ferrous and non-ferrous metals, plastics, PCBs etc. is becoming increasingly difficult. For example, the purity of the plastic output waste stream is 95%. Consequently, only high value items are manually pre-processed.

- **HUMAN TOUCH POINTS**: To complete repetitive but variable tasks, such as sorting or disassembly, e-waste collectors and/or pre-processors rely on manual labour. Staff availability and retention is a major challenge due to the monotonous nature of the tasks. To put this into context, the estimated raw material value of an iPhone 6 is £0.73, while the UK minimum wage is £7.83 per hour – manual pre-processing is not a commercially viable option.

- **THROUGHPUT**: An increasing number of electronic devices are being sold. At the same time, recycling targets are being increased. This puts significant pressure on the e-waste recycling industry to upscale and increase throughput. The overall requirement is that by 2019 65% of all new e-waste items sold should be reclaimed for recycling in the UK. With 2015 UK reclamation rates of 37.5% processing capacity has to almost double to achieve this.

- **PURER OUTPUT STREAMS**: Most low value e-waste items are currently shredded in bulk and ground into a fine powder. During the conversion of this powder into new materials, only some of the embedded critical materials can be recovered. To improve recycling efficiencies, components fabricated with similar base materials, such as aluminium housings or printed circuit boards, require targeted conversion. This is a challenging task even for human operators.

- **UNKNOWN VALUE**: Insufficient information about the actual composition of the selected e-waste fragments, such as PCBs, that are to be converted back into raw materials makes physical sampling and analysis necessary. As the raw value per ton of PCBs can vary from £2,500 to £10,000 for 'low grade' and 'high grade' PCBs respectively, pre-processors have very little financial planning security.

Although these challenges are apparent for e-waste processing, they are not exclusive to e-waste processing only. Such technological developments can have multiple deployments in the recycling industry to enable even faster return on investment.
3. RELEVANT TECHNOLOGIES

Overall, the waste management industry has a track record of being entrepreneurial, developing highly bespoke first-of-its-kind solutions to tackle new process challenges. Traditionally the equipment design has been undertaken by specialist suppliers who are heavily dominated by classic, heavy duty mechanical engineering. More recently, early adopters have begun to unlock the potential that new digital technologies provide.

In the context of digital transformation, we believe that four technologies – machine vision, machine learning & artificial intelligence, augmented reality and energy efficient robotic systems – will have a big impact on the waste management business in the coming decade.

MACHINE VISION: Machine Vision (MV) has become a key technology in the area of manufacturing and quality control. For automatic inspection, cameras have been mounted over processing lines in order to capture digital images and to inspect features to predefined tolerance. Alternatively, robotic systems can be controlled to perform process operations without human intervention. In essence, the machine vision system consists of a number of cameras and control units that interpret and signal individual operating instructions.

For example: Tracking and analysing the size of chicken nuggets during manufacturing; instructing a machine to reject the nuggets that don’t fit acceptable criteria.

MACHINE LEARNING & ARTIFICIAL INTELLIGENCE: Rather than building a control system that works to rigid tolerances, pre-defined by human analysis, Machine Learning (ML) could be used to define tolerances for industrial control systems with little data. In addition, ML could be used to progressively improve the performance of a specific task using an ever-increasing amount of data captured through MV. Machines will be able to ‘intelligently’ identify and disassemble e-waste items and sort sub-assemblies and components into categories without human intervention.

For example: Control systems will be able to identify devices, laptops and their state of damage or components on a PCB and their estimated material value.

AUGMENTED REALITY: With the aid of Augmented Reality (AR) glasses that use cameras, motion and depth sensors, additional operating information can be overlaid onto the real-world environment during work. Operators will be instructed in real-time on how to de-manufacture end-of-life items, while training times will be reduced. Ultimately the operator will be able to see the location of screws, prying points and suggested critical parts to be retrieved, while receiving instructions on how to disassemble a specific device.

ENERGY EFFICIENT ROBOTICS: Recent advances in robotic systems have pushed down maintenance intervals and energy requirements further. As robotic systems can work 24 hours, 7 days a week, the operational cost is pushed beneath that of human labour. At a reported average picking rate of 65 picks per minute a robot can already handle the workload of two manual picking stations.

These four digital technologies have the potential to transform how e-waste, and in the wider sense all waste streams, will be cost effectively processed in the coming decade.
4. PROCESS IMPROVEMENTS

The process steps of disassembly and sorting are likely to be transformed first. At a later stage, full analysis and valuation of the waste stream will become the gold standard.

Not only will efficiency improvements occur in real-time, but the full potential of circular economy will be unlocked and new value streams created in the process.

4.1 DISASSEMBLY

Tasks that require a degree of decision taking, such as the ability to disassemble a device, were once only possible for humans. As high-end CPUs and GPUs become available at lower costs, robotic systems will be able to perform complicated tasks.

The ability to disassemble a device relies on skilfulness and knowledge. Skilfulness can be described as a set of repeatable actions used to perform a task, such as a single disassembly operation. Knowledge is the information required to plan such operations as taking a specific device apart. In real life, both skilfulness and knowledge are acquired and refined through demonstration (training) and practice (learning).

Like humans, a robotic system can, however, be trained to learn a disassembly operation. This remains challenging and relies on a dedicated physical training environment to record the manual operating procedures and later translate them into robotic control instructions. Once developed the system can be improved with every operating procedure captured. Unlike with manual labour, this skilfulness and knowledge is permanently stored and instantly sharable across the global workforce.

4.2 SORTING

Objects are not always easy to differentiate, with even humans making mistakes. At the same time, a robot can pick items at twice the speed of a human, as mentioned earlier.

Machine vision has been successfully deployed to identify different types of fruit in the agricultural industry. Paired with lightweight actuators, requiring far less energy to operate, the hourly operating cost can drop below the equivalent minimum wage at higher picking rates. Our work in agricultural robotics has demonstrated that intelligent robotic systems perform more accurate and repeatable sorting operations. Transferring this knowledge to e-waste pre-processing would make purer output waste streams possible.

4.3 VALUE ANALYSIS

At present, little information about the composition and material value of the produced waste output streams is captured during pre-processing. Therefore, the actual composition remains unknown. This limits the opportunities for meaningful commercial negotiation. As a result, both the pre-processors and end-processors rely on sampling and physical analysis to determine the shipment value.

During automated disassembly and sorting, valuable information about the waste output streams can be gathered and recorded. This data can be further analysed and the value predicted in real time. At present, however, the actual value of a recycled PCB is estimated by an experienced operator.

Recent research has proven that it is possible to analyse how a PCB is populated by means of Machine Vision. Combined with additional information, such as overall PCB dimensions, track layout and connector quantity, the intrinsic “embedded” material value can be predicted accurately and repeatedly. The predicted value can be exchanged in real-time between pre-processors and end-processors to optimise forecasting, refining and to speed up payment.

4.4 RE-USE & RE-MANUFACTURING

At the end-of-life of a product not all components or device modules disposed of are necessarily waste. Components such as heat sinks may be perfectly fine for reuse. In fact, it is more energy efficient to salvage an aluminium heat sink from a de-manufactured device and re-use it, than it is to fabricate a new one from virgin materials. However, this treatment is currently only reserved for high value items, as targeted de-manufacturing is not cost efficient for small devices.

As technology matures and facilities leverage the potential of flexible de-manufacturing lines, new value streams and business models will be unlocked. As second-hand components are typically cheaper than new ones, using salvaged components and modules to repair devices can bring down the cost of product ownership.

In the near future, e-waste recycling facility operators are likely to become skilled device de-manufacturing and re-manufacturing service providers. Flexible automatic disassembly and sorting systems are a first step to realising this change.
5. ROUTE TO MARKET

At Cambridge Consultants we work with clients in markets that undergo rapid technological transformation, such as logistics, agriculture or surgical robotics. Having developed breakthrough robotic systems for these clients, we have an appreciation of the technical and commercial challenges involved. Any system needs to be accurate, reliable and robust, easy to maintain and with low energy consumption, while also providing a fast return on investment. In short, any new product or equipment needs to be both commercially viable and technically feasible.

When working with our clients to help them improve their business, we focus on areas that offer rapid returns by improving processing efficiencies and reducing operational costs, using technologies that have recently become readily available. In the case of e-waste processing we anticipate a stepwise transformation in order to establish what is technologically feasible and to focus on the areas that offer immediate returns.

We anticipate the following stepwise transformation:

WASTE STREAM ANALYSIS: Capturing the manual sorting process with dedicated camera systems, Machine Vision and Machine Learning will be leveraged to train a system to automatically identify and value the components and sub-assemblies.

SEMI-AUTOMATIC DISASSEMBLY: Augmented reality will be leveraged to provide workers with disassembly instructions in a dedicated environment, speeding up manual operations in the process and reducing training cost.

TRAIN ROBOTIC SYSTEMS: At the same time vision systems can be leveraged to record how the operator is actually disassembling an item. While workers disassemble products in a dedicated environment, unknowns such as device specific disassembly steps can be recorded and used to improve the cognitive ability of a robotic system.

FULLY-AUTOMATIC DISASSEMBLY: With sufficient disassembly skills and knowledge copied from humans to ‘train up’ a robotic system, full automation becomes feasible. Initially with human oversight, increasingly phased out until the process is fully autonomous.

Automating the way e-waste is pre-processed offers rapid commercial gains, nonetheless successful machinery development will involve competent management of commercial and technical risks.

6. CONCLUSION

In the developed world the e-waste and waste management industry is under pressure to improve recycling efficiencies. At the same time, end-of-life (EoL) devices are not effectively converted back into raw materials. Fully exploiting the ‘value’ of waste, while being under external pressure, will force the industry to radically innovate in order to survive.

For waste management to be economically viable in the future it must embrace recent technology advances and become part of a circular economy. This in turn will help ensure that raw materials remain available to fuel future cycles of rapid innovation.

Recent technological advances unlock the potential to automate complex tasks that were previously undertaken by humans. This makes flexible automatic disassembly of e-waste to create purer output waste streams both technically feasible and commercially viable. Fully analysing the waste stream and valuing it in real time will improve cash flow and logistic planning. Overall these advances unlock the potential that circular economy provides.

To keep commercial risk low, the industry will be transformed through stepwise transitions as technology matures. At first humans will be assisted with operating instructions to speed up the process. Disassembly operations will be captured through demonstration and recorded, to fully automate the process using robotic systems. The captured images will be used to analyse the waste stream and predict its embedded material value.
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**TERMINOLOGY**

**EoL**: End-of-life  
**MRF**: Material Recovery Facility  
**Virgin Material**: Materials produced from raw natural resources  
**Recyclate**: Used material collated in bulk for refining into new materials  
**New Materials**: Materials produced by refining recyclates for use in new products  
**Recyclate Pre-processing**: Collection, sorting and grouping of similar recyclates  
**Recyclate Processing**: Refining and processing of bulk recyclates into new materials  
**Recycling**: Pre-processing, processing and refining of waste to recover materials for second use  
**Virgin Material**: Materials directly sourced from nature in their raw form  
**De-manufacture**: Reducing a device or appliance to its base components, disassembly without destruction.  
**Re-manufacture**: Refurbishing an appliance or device to brand new quality with warranty to match  
**WEEE waste**: electrical and electronic waste  
**E-waste**: electronic waste  
**BoM**: Bill of Material

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