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Cyber-Physical Systems in the re-use, refurbishment and recycling of used Electrical and Electronic Equipment

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A B S T R A C T

The aim of the research outlined in this paper is to demonstrate the implementation of a Cyber-Physical System (CPS) within the End of Life (EoL) processing of Electrical and Electronic Equipment (EEE). The described system was created by reviewing related areas of research, capturing stakeholder's requirements, designing system components and then implementing within an actual EoL EEE processer. The research presented in this paper details user requirements, relevant to any EoL EEE processer, and provides information of the challenges and benefits of utilising CPSs systems within this domain.

The system implemented allowed an EoL processer to attach passive Ultra High Frequency (UHF) Radio Frequency Identification (RFID) tags to cores (i.e. mobile phones and other IT assets) upon entry to the facility allowing monitoring and control of the core's refurbishment. The CPS deployed supported the processing and monitoring requirements of PAS 141:2011, a standard for the correct refurbishment of both used and waste EEE for reuse. The implemented system controls how an operator can process a core, informing them which process or processes should be followed based upon the quality of the core, the recorded results of previous testing and any repair efforts. The system provides Human-Computer Interfaces (HCIs) to aid the user in recording core and process information which is then used to make decisions on the additional processes required.

This research has contributed to the knowledge of the advantages and challenges of CPS development, specifically within the EoL domain, and documents future research goals to aid EoL processing through more advanced decision support on a core's processes.

1. Introduction

The volume of Electrical and Electronic Equipment (EEE) placed onto the UK market continues to grow. A total of 1,761,233 tonnes was introduced in 2015, a 5% increase from 2014 (Environment Agency, 2015), whilst 93% of the UK population now own or use at least one mobile phone, amounting to total of 83.1 million mobile phone subscriptions (Ofcom, 2014). After use much of this EEE is disposed at landfill or *recycled* (separated into recyclable materials), however some items can be successfully *repaired*, *refurbished*, *reconditioned*, *remanufactured or reused* (All-Party Parliamentary Sustainable Resource Group, 2014). Reuse can create environmental savings compared with the production of new devices as the material content and the embedded energy from manufacturing processes are recovered (King et al., 2006). The reuse of a product will extend its useful life and in the case of a smart phone extending this by just one year can cut its $C0_2$ impact on the environment by 31% (Benton et al., 2015). The resale value of Used Electrical and Electronic Equipment (UEEE), such as smart phones, can be much greater than the value of recycling its materials, with one example of a mobile phone originally retailing at £599, having a reuse value of £290 but a material value of just £0.72 (Benton et al., 2015). This example highlights that whilst reuse is better for the environment, it also presents a business opportunity. Evidence of this opportunity can be seen in the growth of the market for UEEE prepared for reuse, which is now seen as limited

Abbreviations: BoL, Beginning of Life; CPS, Cyber-Physical System; EEE, Electrical and Electronic Equipment; EoL, End of Life; HCIs, Human-Computer Interfaces; RFID, Radio Frequency Identification; UEEE, Used Electrical and Electronic Equipment; UHF, Ultra High Frequency; WEEE, Waste Electrical and Electronic Equipment.

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by supply, not demand (Coats and Benton, 2016) and is growing 4–5 times faster than the market for new devices (Lee et al., 2016).

Whilst reuse is the most desired waste management method when dealing with physical waste (European Commission - Environment Nuclear Safety and Civil Protection, 1999), it is perhaps the most difficult to achieve successfully due to a number of challenges including (i) poor consumer perception of reuse (Guide, 2000; Östlin et al., 2009), (ii) high levels of product obsolescence (Ayres et al., 1997; Guide, 2000; Ijomah et al., 2007; Östlin et al., 2009) and (iii) coordinating complex material flow (Guide, 2000).

Potential customers' are not always able to distinguish between low and high quality reuse because of levels of consumer awareness and industry regulation. Poor consumer perception also includes the amount of confidence and trust placed in a refurbisher's ability to correctly handle any personal and sensitive data. Owners of devices which could be reused often prefer to destructively dispose or store their products due to the belief that there is a risk of someone else accessing confidential information. Attempts to combat such barriers to reuse are being made through the introduction of standards, such as PAS 141: 2011 (Department for Business Innovation & Skills, 2011). These standards require high levels of traceability within a defined set of refurbishment processes aiming to give the customers assurance that the used device will meet a certain level of quality (i.e. function correctly and confidential data erasure). The value of EEE and UEEE, in particular telecommunications equipment, can change rapidly due to the short product life cycles created by the high rate of technological change and industry competitiveness (Manners-Bell, 2014). Refurbishment decisions need to be based upon accurate and up-to-date information to ensure their activities are economically viable. The flow of cores through the refurbishment process is complex due to their high variability in type, model and condition, requiring unique sets of activities which are determined during processing. This requires high levels of information transparency and control to ensure cores are not processed incorrectly (i.e. activities are not repeated or missed).

Cyber-Physical Systems (CPSs) are a recent system classification which can address some of these challenges through improved traceability, decision making and control. CPSs create a two-way link between the virtual and physical world (Kagermann et al., 2013) enabling accurate digital representations of real objects (Conti et al., 2012). These representations are then able to be manipulated (i.e. using simulations and models) with the system actuating and changing the physical world to reflect any changes in the virtual model (Wang et al., 2015). CPSs benefit from being able to comprise of multiple types of technologies, allowing them to be adapted to most scenarios, whether in small scale applications such as pace makers or large ones, such as power networks (Wang et al., 2015). CPSs are also a key concept of an emerging paradigm called “Industrie 4.0”. Industrie 4.0 claims to aid manufacturing firms in; meeting individual customer requirements, increasing flexibility, optimising decision making, increasing productivity and resource efficiency as well as uncovering new value opportunities through new services (Kagermann et al., 2013).

Whilst systems with similar characteristics have been described within the literature (see Section 2), there is a lack of reports discussing the implementation and performance of such systems within the specific challenges of Waste Electrical and Electronic Equipment (WEEE) businesses. This research was conducted using a case study example to identify the benefits and challenges of a CPS in a real WEEE processing environment, highlighting;

- Business Requirement (Section 4.1.1)
- Design of a CPS for recovery of UEEE (Section 5)
- Analysis and discussion of system implementation (Section 6)

2. Review of Cyber Physical Systems within the recovery of electrical equipment

A review of literature regarding systems with characteristics similar to CPSs and designed for use within End of Life (EoL) (i.e. communication between real and virtual world, demonstrating core identification) was conducted. Areas assessed were the stage at which product identification technology was added to a device, information required, identification method, supporting services and the level of implementation.

Most reviewed research envisaged that unique identification technology would be affixed to EEE at the Beginning of Life (BoL), enabling recognition at the EoL (Table 1). Whilst most EEE already has some form of unique identification assigned at the BoL (i.e. serial number), the methods used require visual identification involving human interaction to read. Finding and capturing serial numbers can be time consuming due to the length, size and location of characters (i.e. the 15 digit IMEI printed numerically on a mobile phone). More sophisticated methods of identification have been researched and added at the BoL, such as RFID tags (Bindel et al., 2010), however their robustness and durability throughout the operation Middle of Life (MoL) is still unknown. The main reasons for research regarding the use of wireless technology such as RFID (e.g. Low Frequency, High Frequency, Ultra High Frequency and Microwave (Chawla and Ha, 2007)) over technology such as barcoding (White et al., 2007) are the automatic registration of items, a low probability of miss reads, no requirement for alignment and robust operation within harsh environments (design dependant (Chawla and Ha, 2007)).

Three common services have been identified; *sorting* (Luttropp and Johansson, 2010; Rudiger et al., 2012; Thoroe et al., 2011), *dismantling* (Luttropp and Johansson, 2010; Ostojic et al., 2008; Rudiger et al., 2012; Saar and Thomas, 2008; Stutz et al., 2004; Thoroe et al., 2011; Wang et al., 2014) and *cost determination* (Parlikad and McFarlane, 2007; Thoroe et al., 2011; Wang et al., 2014). *Sorting* services are focused upon the separation of cores, for example, by core type (Rudiger et al., 2012). *Dismantling* services have been employed to aid the disassembly of cores via the identification and removal of any hazardous components (Saar and Thomas, 2008). The *cost determination* services are used to calculate specific financial aspects of the WEEE process within three particular applications: (i) cost accounting, where the cost of disposal is calculated and allocated per unit processed (Thoroe et al., 2011), (ii) determining the financial benefits of reclaiming, reusing and reselling components (Parlikad and McFarlane, 2007) and (iii) “service packages” where the user could scan their products and be offered different WEEE recovery methods from different firms and have the ability to select their preference (Wang et al., 2014).

The information requirements of these identified services fall into four main categories: *global ID, manufacturer and model, Bill of Materials (BoM)* and *lifecycle data*. A *global ID* is required to uniquely identify and record its processes through the lifecycle and supply chain. *Manufacturer and model* are used to determine information associated with the core to ensure correct processing. A *BoM* enables the processer to understand which components are inside the core (information important for repairs), the determining of relevant processing steps due to material compositions and also to indicate the potential for harvesting valuable components. *Lifecycle data* can provide the user with information on how the core has been treated and used up until this point, allowing for informed decisions to be made on processing, repairs and component

Table 1
Summary of traceability and CPS within the WEEE domain.

Research Paper Reference	Stage of tagging		Information required				Product identification method					Support services envisaged				Level of system implementation				
	Identity from BOL	Identity added at EOL	Global ID	Manuf & Model	BOM	Lifecycle data	Barcode 2D	Barcode QR code	RFID UHF	RFID Passive	RFID Active	Sorting	Dismantling	Cost	Routing	Full implementation	Part implementation	Validation	None	RF tests
Thoroe et al. (Thoroe et al., 2011)	×		×	×	×				×	×		×	×	×					×	
Rudgier et al. (Rudiger et al., 2012)	×		×	×	×				×	×		×	×				×			×
Luttropp & Johansson (Luttropp and Johansson, 2010)	×		×	×	×				×	×		×	×						×	
Parlikad & McFarlane (Parlikad and McFarlane, 2007)	×		×	×	×	×			×[a]	×[a]	×[a]			×					×	
Saar & Thomas (Saar and Thomas, 2008)	×		×	×						×		×	×							×
O'Connell et al. (O'Connell et al., 2013)	×		×	×	×				×	×				×						×
Ostojic et al. (Ostojic et al., 2008)		×											×					×		
Wang et al. (Wang et al., 2014)	×		×	×				×					×	×					×	
Stutz et al. (Stutz et al., 2004)	×		×				×						×						×	
This Research		×	×	×					×	×				×	×	×				

[a] Type not specified.

harvesting.

It is important to note that none of the reviewed research had progressed to a factory-based implementation, the most advanced was a prototype system using a single conveyor belt for 2 to 3 operators, demonstrating the feasibility for a sorting system using RFID tags which would already be located inside products (Rudiger et al., 2012) (Note: for this study the RFID tags had to be attached and programmed prior to sorting). CPSs offer the added ability to control an extra service of *routing* which has been shown on Table 1, to reflect the requirements shown later in the paper.

3. Research methodology

A case study example was used in this research to assess the impact of a CPS within the EEE recovery domain. The approach used to investigate the impact of CPS development on a business is based upon the work of Adesola and Baines (2005) and is shown in Table 2.

The first step was designed to understand the case study's and domain's business model and main processes. Business models in this domain have changed since similar research (Canning, 2006) was undertaken as residual value in UEEE has dramatically increased, particularly since the widespread adoption of smart phones. This step enabled a comprehension of both the activities conducted and the opportunities for a CPS to be beneficial. Information was collected through interviews, with employees of the case study (including the managing director, operational manager, members of the sales and processing teams) and members of their supply chain, and walking through the process at the refurbishment facility. The information was then formalised using Business Process Modelling and discussed with the stakeholders of the case study to verify the results.

In the second step the requirements of a CPS are formalised, Unified Modelling Language (UML) Use Case diagrams (OMG, 2015) were used to highlight the specific scenarios in which a CPS would operate and highlight the different actors involved. A specification was then produced outlining the requirements of a system. After completion, this specification was verified by management at the case study firm to ensure they agreed with the findings.

Step 3 involved the design and implementation of the CPS, which supported the business services highlighted from existing research (i.e. sorting, dismantling, value, Table 1) and others discovered from the capturing of requirements (routing).

Step 4 evaluated the effect of the CPS on the business operations using a mixture of quantitative and qualitative methods. Quantitative methods included the manual timing of operations with and without the CPS to assess its impact, and the analysis of data collected by the CPS over 14 months to assess the impact on business growth. A qualitative assessment has also been conducted by gaining feedback on the system from the stakeholders through interviews.

4. Development & investigation

4.1. WEEE refurbishment case study

4.1.1. Company background

An independent, UK based, business which provides secure waste management solutions for UEEE and WEEE has been used as the case study. This research focuses upon the area of the business which recovers and refurbishes Information Technology (IT) assets, comprising of mobile phones (76%), hard drives (10%), base units (5%), laptops (5%), monitors (3%) and other miscellaneous items such as servers, printers and routers. Business activities can be split into three distinct sections: (i) sourcing, (ii) refurbishing and (iii)

Table 2
Summary of the research methodology based upon.

Step Name	Description	Techniques Used	Section
1. Understand business and processes	Capture both the business and process requirements of a CPS	Interviews with stakeholder, Business Process Modelling, Walkthrough the process	4.1
2. Formalise system requirements	Identify specific processes the CPS would support and formalise requirements	UML Use Case, Benchmark processes (time operations)	4.2 & 4.3
3. Design and implementation of CPS	Design CPS based upon requirements	N/A	5
4. Analysis of CPS	Analyse impact of CPS compared to benchmarked process.	Quantitative – Comparing time take, analyse data collected by CPS Qualitative – Feedback from stakeholders	6

selling of cores. Several stakeholders are involved in the coordination of each of these business activities, including; management, procurement, sales, operators and customers (both supplying cores and purchasing those refurbished). Each of the distinct business activities is explained in greater depth below with regards to the business process, stakeholder interactions, decisions and challenges.

4.1.2. *Sourcing cores*

Procurement and sales teams are employed to search for cores from the business market, where companies are looking to upgrade and replace their existing electronic equipment. Information discussed with potential suppliers at this stage includes; (i) how their cores will be handled, including how their sensitive data will be treated, (ii) estimated price for functioning cores and (iii) estimated time to process and receive payment. How a refurbisher handles sensitive data is particularly important to potential core suppliers whose data is deemed highly confidential (e.g. banks and accountancy firms). This drives a need for traceability (sorting and routing services) to ensure devices are securely data erased and a record of this process exists and can be retrieved. Cores are purchased from the supplier through a deposit system where upon the successful refurbishment, the customer is paid. There is a large degree of repeat business and combining this with new contracts can result in a variance on the input rate of cores to the facility. The shorter the time to payment the more attractive the refurbisher is to potential suppliers, therefore the refurbisher needs to process efficiently and have control over their processes. Viewing the status of the refurbishment process is a task completed multiple times a day by almost all types of user (including the Managing Director).

4.1.3. *Refurbishment process*

The refurbishment of cores takes place at a central facility where operators aim to recover as much value from a device as possible whilst under the constraint that all data from a device must be securely erased.

Two recovery methods are available for operators to choose between.

- High quality refurbishment (PAS 141)
- General refurbishment

Cores which are refurbished to either standard have to undergo a number of testing procedures to ensure that they are working and that any data have been securely erased, if possible, using CESG (Communications-Electronics Security Group) approved software, an example process flow for PAS 141 refurbishment of a mobile phone is shown in Fig. 1. Any failures in core functionality requires repairs to be made and a retest before it can be approved, whilst failure to erasure data means that the device cannot be reused and must be physically destroyed (with component harvesting and material reclamation where possible). Both methods require each core to be individually traced through every process, with the ability to generate a process history report. This process history report must not only contain a complete set of processes (which are specified) but also any test results.

High quality refurbishment conforms to the Publically Available Specification (PAS) 141:2011 standard (Department for Business Innovation & Skills, 2011) and aims to increase the cores' value as consumers are provided with more confidence that it is functionally operational and without any damage. PAS 141 does not allow the sale of cores which have not been completely refurbished and also requires more stringent functional tests, making the cost in performing this method of processing the highest of the two recovery options.

General refurbishment requires less stringent functional testing and cores can be sold with minor functional deficiencies and damage (e.g. cracked screens), any data must still be erased to the same standard. Typically cores recovered to this level have less residual value than those which are processed to the higher quality refurbishment method. The lower processing cost makes the general refurbishment an attractive option to these less valuable devices where the cost of processing can approach any potential profit.

Cores unable to be refurbished have components harvested and material recycled. Any non-data holding components (such as screens, buttons and covers) can be harvested from a core to be used in future repairs, whilst any data holding components are destroyed to ensure that there are no data breaches. Components unable to be harvested are recycled by material. There is a low material recovery value, but involves a low processing cost making it suitable for devices where resale value is either very low or where intensive repairs to a core are required and deemed Beyond Economical Repair (BER).

The decision of which process to conduct is initially taken by the operator at the beginning of recovery and happens at *Asset Track*. *Asset Track* is where a core's type, manufacturer and model are identified by an operator and recorded. The decision on which recovery process to conduct requires a high level of knowledge of potential device value, which can be difficult due the large variety in devices (over 600 different types of mobile phones were recorded on the system) and their constantly changing value due to the high level of obsolescence. The decision on whether to continue processing needs to be reassessed throughout the recovery process as more information is identified, such as failure of data erasure or functional testing. The critical decisions of the refurbishment process (shown as diamonds in Fig. 1) are decisions where the result either means the core continues processing or is recycled. *Visual Inspection* (Figs. 1–2) is the first critical decision, at this point the operator must input whether a core holds enough residual value for processing, this is done by visually inspecting the physical quality, i.e. cosmetic wear and physical damage. The majority of cores processed are ones with which operators have knowledge of (i.e. the common resale value and processing effort) and are trusted to

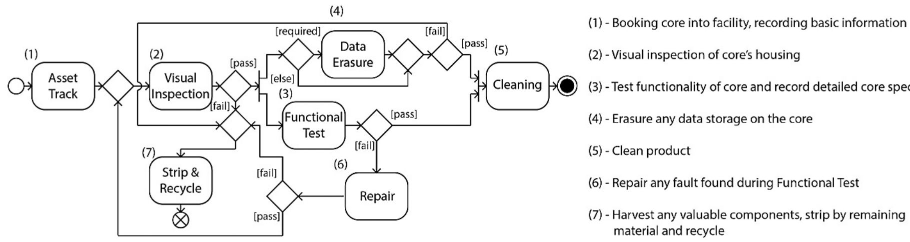

Fig. 1. Refurbishment process (PAS 141, Mobile Phone).

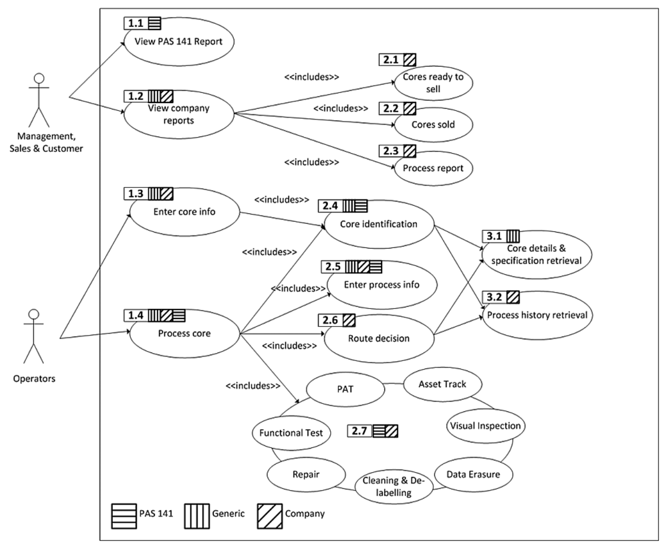

Fig. 2. Stakeholder use case diagram.

make the decision, for new cores (particularly IT assets with complex specifications) operators will query their supervisors who in turn may speak to either a member of sales or the operations manager to get an estimated resale value, awaiting this result cores will be quarantined. Other critical decisions include *Repair* (Figs. 1–6) where the operator decides if: (a) the expertise for the repair exist, (b) the components are in stock and (c) it is economical/possible to repair, and *Data Erasure* (Figs. 1–4) where is must be determined if the product has been erased successfully. The *Repair* decision is made by the operator, to be able to repair a device the operator already must be trained and have core knowledge, as such they are judged to be able to take on this responsibility. The *Data*

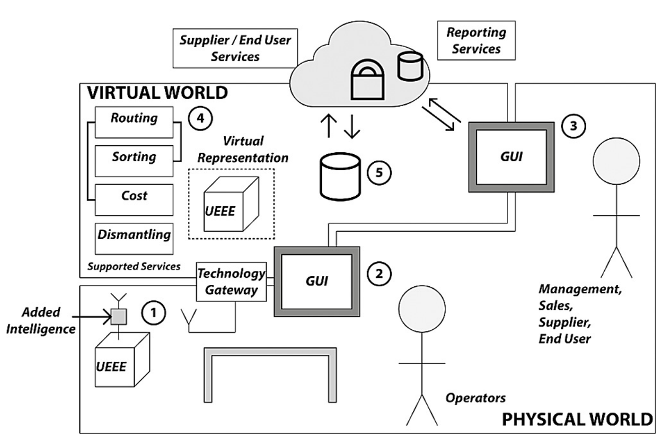

Fig. 3. Architectural overview.

Erasure decision is made by 3rd party software which is used to wipe data holding devices (i.e. mobile phones and hard drives).

4.1.4. Selling refurbished cores

Once successfully refurbished, cores are sold for reuse. Currently there are two channels that businesses use to sell refurbished assets, either individually via an online shop (typically for high value items) or in batches to international brokers. Sales staff require information from the factory regarding which cores have been successfully refurbished, the processes used and the core's level of quality. Additionally, sales staff may want to increase the priority level of particular cores to complete a batch prior to sale. Both tasks require communication with the factory, however due to the scattered nature of data storage, sales teams tend to acquire information through phone calls to the shop floor operators.

4.2. Business requirement

The refurbisher required a system which would enable the traceability and control of individual cores throughout the refurbishment process. The key drivers for this requirement were (i) improving customer confidence (both of the core supplier and the purchaser of the refurbished device) through increased transparency and traceability of the refurbishment activities and gaining PAS 141 accreditation, (ii) increasing processing efficiency by reducing errors (such as process duplication and miss-recording of serial numbers) and (iii) improving decision making at all levels of the business through greater insight into their refurbishment activities.

The business interactions have been summarised using the UML Use Case notation, shown in Fig. 2. The key stakeholders from this company were grouped into two categories; (i) *Management*, *Sales & Customer* and (ii) *Operators*. The *Management*, *Sales & Customer* group do not directly perform refurbishment operations, instead they request information from the shop floor, highlighted in Use Cases 1.1, 1.2, 2.1, 2.2 and 2.3. *Operators* perform the refurbishment operations, and therefore generate data in the form of traceability records and require support for decision making. The Use Cases identified have been divided into three categories depending on whether they were: (i) generic to any WEEE processor, (ii) PAS 141 specific or (iii) specific to the stakeholder.

4.3. System specification

4.3.1. System requirements

The Use Cases were used to generate a set of system requirements, shown in Table 3. Four high level requirements of the system were outlined: *core identification*, *interface*, *route decision* and *core details and specification retrieval*.

Core identification is a key characteristic of a CPS, enabling cores to be individually monitored in the physical world (i.e. the refurbishment line), and to be represented accurately in the virtual world. Graphical User Interfaces (GUIs) were required to enable

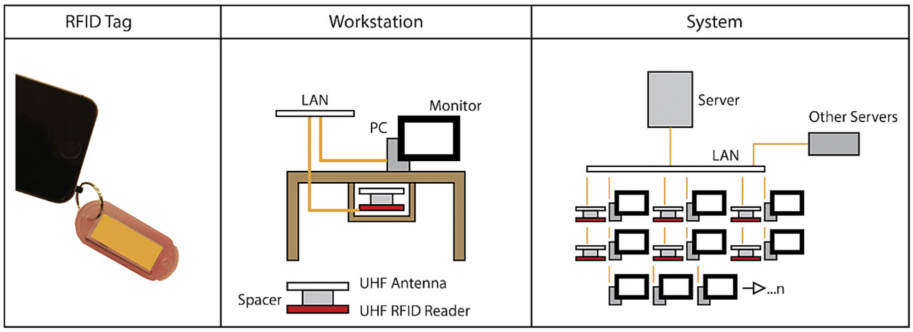

Fig. 4. RFID enabled workbenches.

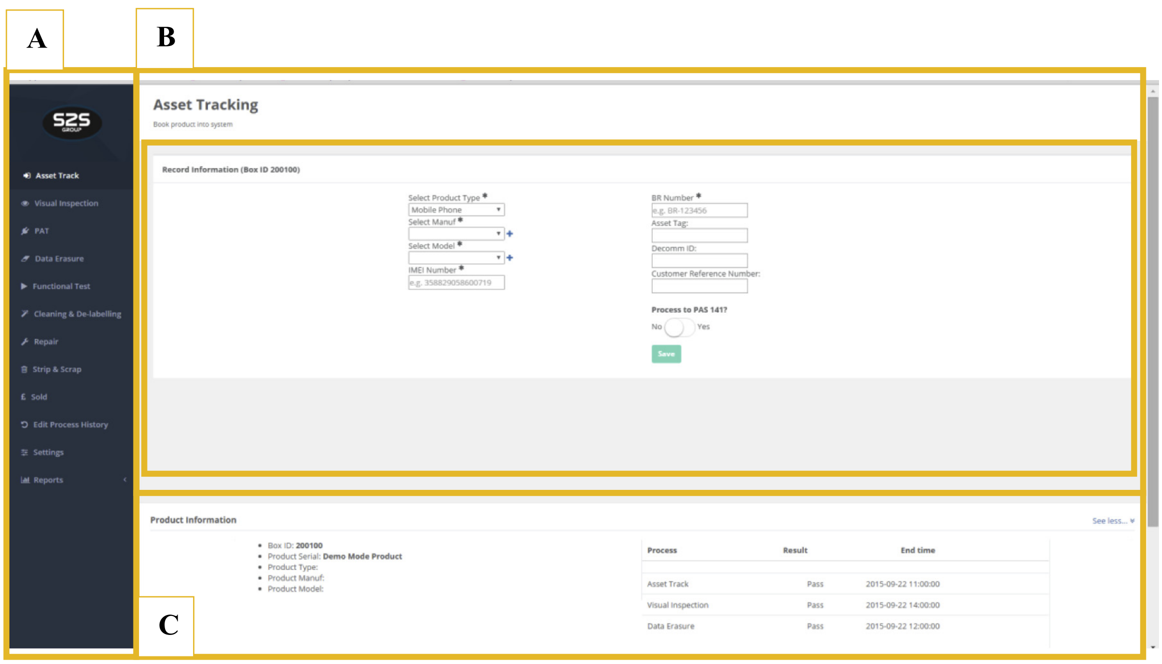

Fig. 5. Web application GUI layout for operator.

user interaction with the system, allowing operators to input information and to give *managers, sales teams* and *customers* the ability to access to a core's information. The initial services required were highlighted as (i) a method of providing automated *route decision* support, (ii) *sorting* to determine the initial route selection, (iii) *cost* to determine if the product has enough residual value to be profitable and (iv) *dismantling & repair* to aid operators in what to repair and how to correctly record their effort. Finally the system would be able to retrieve information from distributed data sources regarding *specific product details and specifications*. The sets of information required to be captured were; (i) product details (i.e. manufacture, model, device type, customer information, recovery process), (ii) activity information (i.e. activity type, location, start time, end time) and (iii) activity results (i.e. report details e.g. pass/fail and comments which are specific to each activity).

4.3.2. *Non-functional requirements*

Additional, non-functional or quality requirements of the system were (i) adaptability to changes in process route, generally required when new technology first arrives or when conforming to a new standard (Bharad et al., 2014; Shin et al., 2014). (ii) Scalability, any system should be easily saleable to meet with increased product quantities, i.e. more operators and workstations, from a growing market (Adolphs et al., 2015; Industrie 4.0 Working Group, 2013). (iii) Extendibility to include the addition of new product types (Industrie 4.0 Working Group, 2013).

5. Design and implementation of CPS for EEE

5.1. *System design & development*

The architecture for the system was developed to meet the requirements of EEE recovery, outlined in Section 4.3, shown in Fig. 3. The architecture comprised of five main components: (1) Core identification - a cyber to physical gateway to allow the system to communicate with the product. (2) Operator GUI, an interface for operators to use whilst processing the core and for entering information on both the core and process, and to access the business decision support services. (3) Reporting GUI, for stakeholders such as management and sales to remotely access reports for the overall factory, order, batch and individual core status. (4) Services, the main service implemented within this CPS has been a route decision service which guides the operator through the refurbishment process, using other services such as *sorting* and *cost.* (5) Data

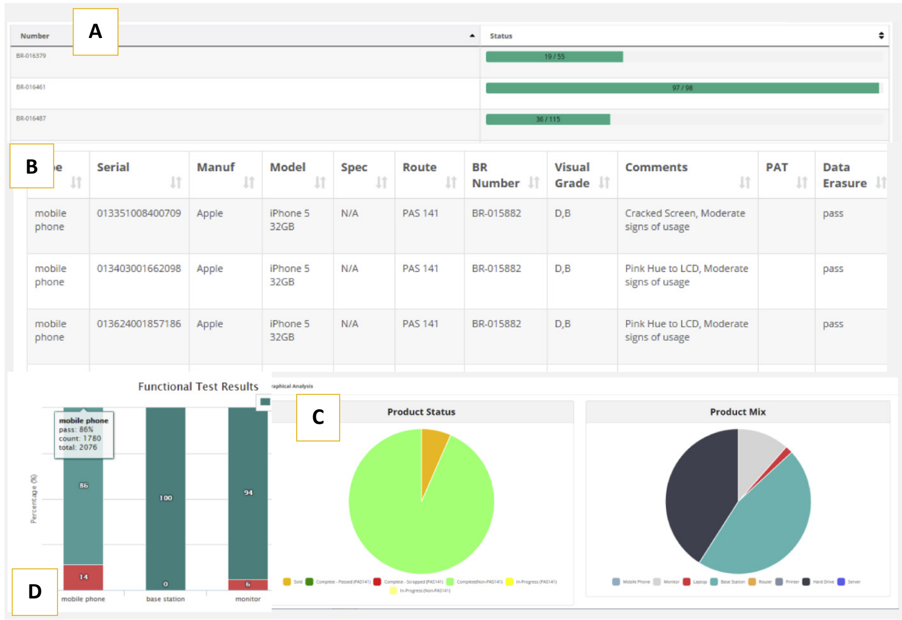

Fig. 6. Selection from the managerial, sales and customer interfaces.

Table 3
System requirements from Use Cases.

High level requirement	Detailed requirement	Related use case(s)
Core identification/traceability	System can uniquely identify individual cores and record their refurbishment operations	2.4
Graphical User Interface (GUI)	User can log into report interface	1.1, 1.2, 1.3, 1.4
	User can load PAS 141 report showing up to date information	
	User can load company specific reports showing up to date information	
	User is able to export any generated reports	
	User can log core information	
	User can log process information	
	System must display process requirements for product	
Route decision	System can determine required process from core's unique process history and product details	2.6
	Must be adaptable to cope with new standards, new core types and new processing decisions	
Core details & specification retrieval	The system can check whether a core is stolen	3.1
	The system can perform checks on serial numbers to ensure correct entry	
	The system can search for core specification using serial number entered	
	The system can check if a mobile phone is blocked from any networks	

Storage, a local database which could be accessed to store and recall information for the processing of cores and generation of management reports. A remote database also existed to record usernames, passwords and information for stakeholders not inside the company.

5.1.1. *Core identification*

Unique identification was added to a core once it entered the refurbishment facility. For this core-to-system communication, a passive UHF RFID system was chosen. Six RFID enabled workstations were constructed each consisting of: a UHF RFID reader, antenna, computer and monitor, shown in Fig. 4. These work stations provided the gateways for the cores to communicate with other components within the system. Both the computer and RFID reader were connected to the facility's Local Area Network (LAN) with a record of their Internet Protocol (IP) addresses stored in the database to link them together. This improved the scalability of the CPS as additional workstations could be added, either with or without an RFID reader, with minimal effort.

A reusable tagging method was chosen rather than permanently attaching an RFID tag to each individual core. RFID tags were embedded into key fobs, shown in Fig. 4, allowing a physical separation between the tags and the core, reducing the interference caused by the metallic content of the core. Passive UHF RFID Tags (Alien Technology, ALN-9715 ‘Glint’) were programmed and put into the label area of the key fobs, where a visual corresponding ID was also printed. The use of key fobs allowed different attachments to be used, i.e. 3.5 mm audio jack plugs, suction cups and USB caps, ensuring that the core was not only identifiable but also did not obstruct the refurbishment process.

5.1.2. *Human interaction/GUI*

Human interaction was a key component of the CPS, enabling users to obtain and input information. Two separate web applications were developed based upon the stakeholder groups: *Operators* where access to the system was only required on the workstations within the refurbishment facility (Fig. 3(2)), and *Management, Sales and Customers* where secure, remote access was required from outside of the facility (Fig. 3(3)).

5.1.2.1. Operator user. The operators' GUIs was used when wanting to record a refurbishment activity. The operator would choose an initial activity from the vertical navigation bar (Fig. 5-A), this then called the *route decision service* to determine if the user should be carrying out this process. If the selected process was expected by the system the *interface* would be displayed to the user allowing them to record process information (see Fig. 5-B). If it was an unexpected, unrequired process then the interface would inform the user the process/es that the system anticipated. The footer (Fig. 5-C) was presented to aid the operator in ensuring the core selected (virtually) matched the presented one (physically).

5.1.2.2. Managerial, sales and customers users. A selection of the interfaces available for the managerial, sales and customer users have been shown in Fig. 6. These interfaces displayed both real time and historical information, enabling users to make decisions, i.e. resource deployment based on Work In Progress (WIP). Fig. 6-A shows WIP and the batches currently being worked on, for example ‘BR-016379’ had 55 cores, of which 19 had completed the refurbishment process. Batches could both be reviewed in a tabular form, Fig. 6-B or to quickly review the status pie charts were used, one showing the status of refurbishment and one showing the mix of core type. The status of a type of process type could also be reviewed to see its performance. Fig. 6-D shows a report of the process *Functional Test*, displaying the number of cores tested and the pass/fail rate; this could be filtered by date and batch number. All these charts and tables, Fig. 6, showed real-time information as products were processed along the refurbishment line.

5.1.3. Services

The *route decision* service was designed to ensure that operators conducted the correct type, number and order of operations when refurbishing cores, adding a layer of control to the refurbishment process (required due to the high variability of cores types and conditions). Processing rules were encapsulated within the system using virtual “routes cards”. A unique route card was created for each different process variation (i.e. different core types and processing standards), containing information about the required operations (i.e. Asset Track, Visual Inspection), their sequence, and decisions taken including the rules dictating the resulting process routing. Each route card was visually developed using UML Activity Diagrams and converted into an XML representation, which would be interpreted by the *route decision* service. Upon detecting a core via the RFID system, the *route decision* service establishes the appropriate process route card and determines the next appropriate operation(s), based upon any previously recorded process results. By not allowing an operator to record an operation determined unsuitable enabled the CPS to control the refurbishment process. Upon completion, refurbished cores were removed from WIP and added to a ‘ready for sale’ stock list, automatically notifying sales staff.

The system supported *dismantling & repair* services by allowing users to record items used in repair, where they were sourced and by informing the operator as to the repair required (by summarising the functional failures recorded earlier in the refurbishment process). This information was then shown to higher level users through various reports.

Cores were *sorted* by product type and whether they were data holding, this linked with the process *route decision* service to determine which, and the order, of the following processes. Similarly, the system allowed operators to value a product, and depending on process results, the system derived whether the core was BER by cooperating with the *route decision* service.

6. Results and discussion

The results have been discussed with regards to the CPSs' impact on the case study's business and the challenges identified with the operation and implementation.

6.1. Assessment of CPS upon the business

6.1.1. Impact on operational time

The impact of process time before and after the implementation of the CPS was compared for key operations and shown within Table 4. The most significant impacts (financially) of the CPS came from the ability to quickly see the status of refurbishment and to retrieve product test reports (in this example data erasure certificates).

Implementation of the CPS has enabled the ‘silos’ of information, which were previously held in different information systems spread across the business and often in different physical locations, to become interconnected and assessable, significantly reducing the time to perform operational and managerial reporting activities (reporting, stock retrieval and process status). As shown in Table 4 core identification was reduced by 8 s per item (from 10s to 2s) as RFID tags allowed instant recognition and retrieval of relevant information, saving approximately 200hrs of operator time a year. However, the system did not offer benefits across the entire business. The initial process, Asset Track (Fig. 1(1)), became more time consuming as operators needed to additionally attach an RFID tag to each core, taking on average an extra 15s, which over a year negatively impacted the business by £1000.

6.1.2. Increased data visibility

The CPS enabled greater transparency of operations within the business through increased data capture and visibility of information. This led to the identification of inefficiencies within the original refurbishment process and improvements to the process being made. Two examples found in this case study were within the Functional Test (Figs. 1–3) of mobile phones, related to (i) high failure rates in specific models and (ii) test duration.

A review of functional failures showed Apple iPhones were suffering unusually low pass rates during functional testing compared to other manufacturers, as shown in Table 5. When looking at the causes of these failures the most common reason (42%) was due to the phone being locked to the previous users account. Disassociating the account from the device can only be performed by the previous user therefore, these phones had to be

Table 4
Comparison of processing times for key operations before and after CPS implementation (23,750 products).

Operational Tasks	User/Stakeholder	Operation Frequency (per day, 2016)	Original activity time	New activity time (CPS)	Savings per year (50 week year)[a]
Asset Track	Operator	95	90 s	105 s	−100 h, −£1000
Core Identification	Operator	360	10 s	2 s	200 h, £2000
Reporting	Operator	86	50 s	5 s	269 h, £2690
Stock Retrieval	Managerial, Sales	1	35 min	5 min (incl search)	25 h, £375
Process Status	Managerial, Sales and Customer	3	20 min	<1 min	250 h, £5500
TOTAL		–	–	–	644 h, £8665

[a] Value is calculated using a per hour rate for user type involved.

Table 5
Functional test pass rate by manufacturer.

Manufacturer	% Pass
Apple	61
Blackberry	92
HTC	77
Nokia	87
Samsung	76

scrapped. Prior to this research the stakeholder did not have access to these data and at the managerial level were not aware of the amount of potential revenue being lost through this oversight from the core supplier.

When first installed the system quickly highlighted that operators were taking approximately 5 min longer to undertake a functional test than expected. After an investigation, it was discovered that a lack of cellular signal in certain areas of the facility required operators to move to a different part of the facility where a signal could be established, adding time to the process. To correct this a cellular booster was installed, providing a saving of approximately £17,780 over 2016. It is important to note that this saving, unlike others was a saving which would not be lost with the removal of the system.

6.1.3. Facility throughput

The number of cores processed per month, as shown in Fig. 7, varied through the year and therefore to investigate any impact of the system a period of time longer than a year is required. November and December 2015 could be compared to November and December 2016 and both showed a positive increase (+12%,+7% respectively, Fig. 7) in cores entering the facility. There had been no extra appointments of operators, sales team or management by the case study firm within this period and so the increase could be attributed to gains in market share, (from offering a more secure and controlled service) and from an increase in capacity and efficiency due to the use of the described system.

6.1.4. Benefits summary

The use of the designed CPS within this case study provided yearly savings for at least 644 man hours (of various user types) equating £8665 (not all savings scenarios were quantified) and provided one off business savings of at least £17,780. The case study firm has increased their throughput from the use of this design, Fig. 7, more analysis would be required to determine the monetary value of this increased throughput. These benefits have indicated the positive business impact that a CPS offering traceability and control can have on a UEEE and WEEE refurbishing business.

6.2. Implementation challenges and future work

Several challenges and areas for future work were identified, including:

1 Identifying and retrieval of life cycle core information
2 Cost of collecting data
3 Communication between cyber and physical core
4 Intelligent decision making
5 Extending the CPS into the supply chain

6.2.1. Identification and retrieval of life cycle core information

The initial identification and retrieval of a core's information is still a challenge for the system as it relies upon an employee's understanding and knowledge, to recognise (Asset Track) and visually assess the cores (Visual Inspection). The effort to recognise the device is not with regards to RFID identification but the retrieval of device information generally either from expert knowledge or various 3rd party data services (i.e. specification, if core has been stolen).

For certain cores where globally unique identification exists, such as the IMEI number for mobile phones (Nnorom and Osibanjo, 2009), information could be retrieved via the internet through a licensed Application Programming Interface (API). This approach would automatically retrieve information such as manufacturer, model, product specification and could also contain useful life cycle information for example, if a mobile phone has been network blocked. However, there is often a cost to use these 3rd party services, therefore a decision is required to determine if the value of the information to the business outweighs the cost.

There was still limited information available regarding the material composition and the life cycle usage of the cores or their components, for example the reasons behind their physical condition or if any maintenance, upgrades or repairs had taken place.

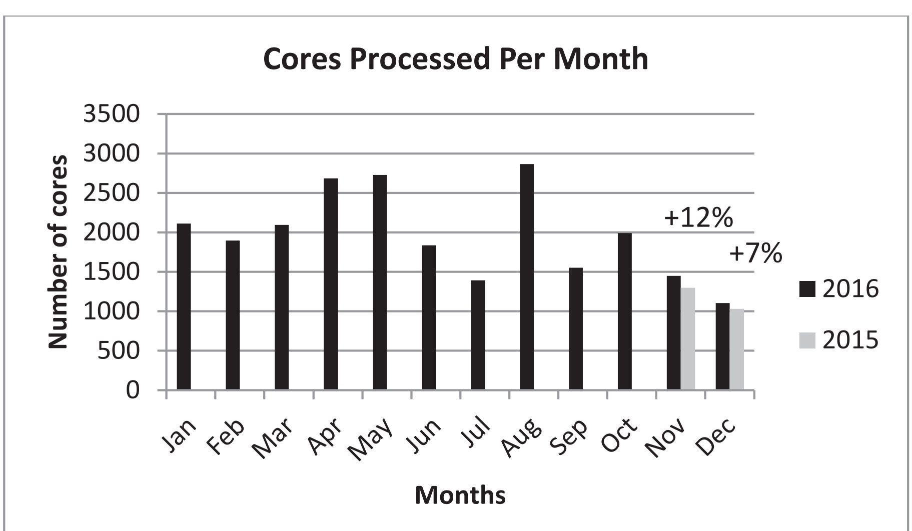

Fig. 7. Cores processed per month.

This information could be useful early in the refurbishment process, as it may enable businesses to remove unsuitable cores earlier in the processing before unnecessary resources are invested.

6.2.2. Cost of collecting data

A major challenge in deploying CPSs is the costs associated with collecting data, both in terms of the fixed costs of installing a system and the operational costs such as the additional time required to collect data.

6.2.2.1. Installation costs. The hardware costs for the installation described are shown in Table 6. The total cost was over £11,000 with the majority being consumed in the construction of the RFID workbenches used (Fig. 4). It was not possible to calculate a Return On Investment (ROI) for the stakeholder as a full quantitative analysis of the business benefit has not been completed and a licensing agreement had yet to be made.

6.2.2.2. Operational costs. The main operational cost has been attributed to the time required to capture data within the refurbishment process. The CPS implemented has looked to reduce this as much as possible, for example by using RFID to automatically recognise the core after its initial entry. Some processes were made more time consuming, as shown in Table 4 i.e. the process, Asset Track now had an extra step for attaching the RFID tag.

6.2.3. Communication between cyber and physical core

A key challenge for the implementation was to ensure communication between the core and system was robust and repeatable. The communication method adopted used passive UHF RFID tags inside key fobs which were then attached to cores. Whilst optical methods of unique core identification, such as barcode or Quick Response (QR) codes could have been used for the current application, the decision to use RFID tags was selected due to the operational performance benefits such as the time to identify and the reliability of the tags.

6.2.4. Intelligent decision making

The CPS could be expanded to enable further operational and tactical decision support services. Real time cost analysis could support operators when determining if a core should be refurbished by estimating the cost of processing. This would be calculated using data collected by the CPS such as average processing times and failure rates combined with real-time market prices. Simulation and optimisation could be used to assist with production planning and scheduling to improve overall efficiency of refurbishment operations, using information captured by the CPS regarding expected processing times, current Work in Progress (WIP) and operators and resource availability.

6.2.5. Extending the CPS into the supply chain

It is envisaged that the system could extend further through the supply chain, particularly to the transportation from the supplier of the core. Traceability through transportation is an important part of offering a complete, secure refurbishment service and the ability to identify products inside transportation will provide assurance of location, condition and integrity. Communication between the core and transport will be a challenge as it will require robust identification within a densely populated environment with RFID antennas at potentially greater distances. New methods of tagging may have to be explored to ensure secure attachment through these extra processes. The challenge of core identification will exist for any CPS being developed for a real application, particularly for products constructed out of metals or liquids or those operating in harsh environments.

Table 6
Installation costs.

Component	Cost per Item	Total
RFID Workbenches	£1,640[a]	£9,840[a]
RFID key fobs	£1.50[b]	£1500
Total Hardware Cost	–	£11,340

[a] Costs: RFID Reader 58%, Antennas 12%, Touchscreen Interfaces 12%, Computers 18%.
[b] Estimated manufacturing, incl. programming cost: 50%.

7. Conclusion

The research and development of a CPS to enhance the level of traceability and to support decision making within a WEEE refurbishment business has been described in this paper. Where previous research had been limited to theoretical and small scale testing of such systems, this research implemented a full CPS system into a real operational WEEE refurbishment business, enabling the identification of benefits and challenges of implementing such a system in the real world (Table 1). Services implemented aided the *sorting, dismantling & repair, cost* and importantly *routing*.

The CPS was developed to increase the traceability and support decision making within the refurbishment processes. RFID key fobs were used to automatically identifying cores within the process, retrieving previous information on which the CPS could guide the user on the next appropriate process. The impact of the system included an estimated time saving of 664 h of operational time and identification of process inefficiencies through increased data capture and visibility.

Further work is required to utilise the information captured through the development of suitable services to enhance decision making throughout the business and the supply chain. Dismantling and repair services could be expanded to include guides showing operators how to repair the core and estimate the costs involved.

CPSs, particularly in EoL refurbishment, are still in their infancy but this research has shown how a system could be developed and implemented to meet the requirements within this domain. As WEEE refurbishment is largely a manual process, automation of the physical world within the system is limited; rather systems need to guide operators through the tasks and directs cores through the process. CPSs such as the one presented, enhances the service that refurbishers and remanufactures can offer through increased visibility. Visibility gives confidence to users supplying cores (that their cores will be treated correctly with the maximum value recovered) and confidence to purchasers (that processed cores, will be to a known standard). The processing firm will also get the benefit of increased traceability and by reducing the risk of miss-processing, increase their overall efficiency, making the firm more profitable. Ultimately CPSs will aid the growth of the REEE market through correct and traceable refurbishment, not only benefiting commercial companies but also the environment. A viable solution for implementing a CPS has been described.

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