Waste Management xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Internet of things and Big Data as potential solutions to the problems in waste electrical and electronic equipment management: An exploratory study

Fu Gu [a], Buqing Ma [b], Jianfeng Guo [c,*], Peter A. Summers [a], Philip Hall [a]

[a] *Department of Chemical and Environmental Engineering, Nottingham University, Ningbo 315100, China*
[b] *Key Laboratory of Advanced Manufacturing Technology of Zhejiang Province, College of Mechanical Engineering, Zhejiang University, Hangzhou 310027, China*
[c] *Center of Energy and Environmental Policy Research, Institute of Policy and Management, Chinese Academy of Sciences, Beijing 100190, China*

ARTICLE INFO

Article history:
Received 25 March 2017
Revised 29 June 2017
Accepted 21 July 2017
Available online xxxx

Keywords:
Waste electrical and electronic equipment
Recycling
Big data
Internet of things
Radio frequency identification
Wireless sensor network

ABSTRACT

Management of Waste Electrical and Electronic Equipment (WEEE) is a vital part in solid waste management, there are still some difficult issues require attentionss. This paper investigates the potential of applying Internet of Things (IoT) and Big Data as the solutions to the WEEE management problems. The massive data generated during the production, consumption and disposal of Electrical and Electronic Equipment (EEE) fits the characteristics of Big Data. Through using the state-of-the-art communication technologies, the IoT derives the WEEE "Big Data" from the life cycle of EEE, and the Big Data technologies process the WEEE "Big Data" for supporting decision making in WEEE management. The framework of implementing the IoT and the Big Data technologies is proposed, with its multiple layers are illustrated. Case studies with the potential application scenarios of the framework are presented and discussed. As an unprecedented exploration, the combined application of the IoT and the Big Data technologies in WEEE management brings a series of opportunities as well as new challenges. This study provides insights and visions for stakeholders in solving the WEEE management problems under the context of IoT and Big Data.

1. Introduction

Waste Electrical and Electronic Equipment (WEEE), or known as e-waste, has become one of the largest and fastest growing waste stream in the world (Rahimifard et al., 2009). At global level, WEEE has an average annual growth rate of 3–5% which corresponds almost three times the growth of municipal solid waste in general (Rahimifard et al., 2009; Duygan and Meylan, 2015). The global quantity of WEEE is estimated to be 41.8 Mt in 2014, 43.8 Mt in 2015, and it is expected to grow to 49.8 Mt in 2018 (Baldé et al., 2015). With a rapid annual growth rate around 13–15% (Gu et al., 2016a), China generated approximately 8.53 Mt WEEE in 2014 and has already become the largest WEEE generator worldwide (Zeng et al., 2016a).

WEEE contains various valuable resources as well as a wide range of pollutants (Dewulf et al., 2010; Zeng et al., 2017b). Owing to limited reserves (Du and Graedel, 2011), recovering materials from WEEE is a promising practice for sustainable development of the related industry. For examples, the rapid development of electric vehicles demands a higher recycling rate (over 90%) for lithium (Zeng and Li, 2013) and cobalt (Zeng and Li, 2015), and recycling indium from spent liquid crystal displays (LCDs) is of critical importance to support continuous production of new LCDs (Zhang et al., 2015a). WEEE recycling is regarded as a profitable business (Cucchiella et al., 2015; Zeng et al., 2016a). Recovering precious metals such as gold, can sustain the profitability of a WEEE recycling plant (Cucchiella et al., 2016). Asides from resource sustainability and economical gains, environmental impacts of WEEE can be significantly reduced through recycling those metal contents (Wäger et al., 2011). Moreover, recycling is proved to be the best option of disposing polymeric fractions in WEEE from an life cycle environmental perspective (Wäger and Hischier, 2015), and the end markets of these recycled plastics are expanding (Gu et al., 2017a). However, improper treatments of WEEE lead to catastrophic results, as environmental pollutions caused by WEEE recycling are frequently reported (Tao et al., 2015; Awasthi et al., 2016; Wu et al., 2016). Consequently, physical health of the nearby

---

* Corresponding author.
E-mail address: guojf@casipm.ac.cn (J. Guo).

http://dx.doi.org/10.1016/j.wasman.2017.07.037

Please cite this article in press as: Gu, F., et al. Internet of things and Big Data as potential solutions to the problems in waste electrical and electronic equipment management: An exploratory study. Waste Management (2017), http://dx.doi.org/10.1016/j.wasman.2017.07.037

Nomenclature

Abbreviations

BAN	Basel Action Network
BDBA	Big Data Business Analytics
CE	consumer electronic
CGA	Customs General Administration of the People's Republic of China
CPS	cyber-physical system
CRT	Cathode Ray Tube
DfE	Design for Environment
EC	European Commission
EEE	Electrical and Electronic Equipment
EOL	End-Of-Life
EPA	United States Environmental Protection Agency
EPR	Extended Producer Responsibility
ERP	enterprise resource planning
EU	European Union
GFO	Green Fence Operation
GIS	Geographic Information System
GOSC	General Office of the State Council of the People's Republic of China
ICT	information and communications technology
IOT	Internet of Things
ITU	International Telecommunication Union
kt	kilo tonnes
L	litre
LCD	liquid crystal display
LTE	Long Term Evolution
MIS	Management Information System
MPA	Ministry of Environmental Protection of the People's Republic of China
MSW	municipal solid waste
Mt	million tonnes
NDRC	National Development and Reform Commission of the People's Republic of China
NGO	non-governmental organisation
NBS	National Bureau of Statistics of the People's Republic of China
OECD	Organisation for Economic Co-operation and Development
PBB	polybrominated biphenyl
PBDE	polybrominated diphenyl ether
POM	placed on the market
POP	persistent organic pollutant
RFID	Radio Frequency IDentification
RoHS	Restriction of Hazardous Substances
SC-SCM	Service and Manufacturing Supply Chain Management
SEPA	State Environmental Protection Administration the People's Republic of China
SVTC	Silicon Valley Toxics Coalition
WEEE	Waste Electrical and Electronic Equipment
WR2	WEEE recovery/recycling
WSN	Wireless sensor network
WTP	Willingness To Pay

residents and the workers is in great peril due to exposure to heavy metals and persistent organic pollutants (POPs) released from WEEE recycling sites (Huang et al., 2016; Lu et al., 2016a; Wang et al., 2016a), especially that of children (Tang et al., 2015; Zeng et al., 2016b).

Recognising the delicate nature and the importance of recycling, the management of WEEE has become a topical issue in solid waste management. In this study, we discuss the potential of using big data technologies in solving existing problems in WEEE management. This paper is organised as follows: the current problems are depicted and analysed in Section 2, the characteristics of the WEEE "Big Data" are examined in Section 3, the state-of-the-art communication technologies for acquiring the WEEE "Big Data" are illustrated in Section 4, the framework of implementing the IoT and the Big Data technologies in WEEE management is proposed in Section 5, two application scenarios based on real-world cases are delivered in Section 6, both the opportunities and challenges discussed according to different perspectives in Section 7, the conclusions are given in Section 8 while the shortcoming of this study is also identified.

2. Existing problems

2.1. Ineffective legislation

Across the globe, governments have proposed laws, regulations and policies to facilitate WEEE management. Yet, according to the extent literature, the effectiveness of these legislations remains questionable.

2.1.1. Low collection rates

WEEE Directive 2002/96/EC (European Union, 2003a) required all member states from 13th August 2005 to collect at least 4 kg per capita of WEEE from households annually and to ensure that 'producers provide at least for the financing of the collection, treatment, recovery and environmentally sound disposal of WEEE from private households deposited at collection facilities'. But the collection requirement does not reflect the actual situation of member states of European Union (EU) (Huisman et al., 2007). The upgraded version - Directive 2012/19/EU (European Union, 2012) applied a WEEE collection target which is based on volumes placed on the market (POM): 45 wt% of the EEE (Electrical and Electronic Equipment) POM in the past three years must be collected by 2016, and 'from 2019, the minimum collection rate to be achieved annually shall be 65% of the average weight of EEE placed on the market in the three preceding years in the Member State concerned, or alternatively 85% of WEEE generated on the territory of that Member State'. However, it was estimated that the collection rate was below 50 wt% and average for the entire EU was 38 wt% (Król et al., 2015). For consumer electronics such as laptops and mobile phones, their collection rate was even lower, as material flow analysis revealed collection rate for laptops and mobile phones were 35 wt% and 37 wt% in Switzerland, the state which has a well-established recycling system operating since 1992 (Duygan and Meylan, 2015). An exceptional example in EU is Finland, which has an average WEEE recycling rate of 92% (Ylä-Mella et al., 2014). Legislations similar to EU have been placed in the United States, such as *Electronic Waste Recycling Act of 2003* (California government, 2003). However, the WEEE collection rate is lower than 30%, and rest of WEEE ended up in landfill or exportation (Kahhat et al., 2008; Namias, 2013).

In China, a "Old-for-New" policy was used for collecting End-Of-Life (EOL) household EEEs including televisions, refrigerators, washing machines, air conditioners and personal computers, and this policy was in place from June 1st, 2009 to December 31st 2011 (Zeng et al., 2013b). This policy had facilitated the recycling of categorised WEEE, even after it expired (Cao et al., 2016a,b).

Please cite this article in press as: Gu, F., et al. Internet of things and Big Data as potential solutions to the problems in waste electrical and electronic equipment management: An exploratory study. Waste Management (2017), http://dx.doi.org/10.1016/j.wasman.2017.07.037

Administration Regulation for the Collection and Treatment of Waste Electric and Electronic Products was issued and enforced in 2012, which levies taxes from producers and importers of EEE to licensed WEEE treatment entities (Zhang et al., 2015b). The levies are set at 13 RMB, 12 RMB, 7 RMB, 7 RMB and 10 RMB, for each television, refrigerator, washing machine, air conditioner and personal computer, respectively, while the subsidies are 85 RMB, 80 RMB, 35 RMB, 35 RMB and 85 RMB for each unit of the above products (Zhang et al., 2015b). However, there is an obvious imbalance in levies and subsidies, which could affect the sustainability of this regulation (Zeng et al., 2017a). Besides, On 3rd January 2017, General Office of the State Council (GOSC) of China issued *Plan of Implementing Extended Producer Responsibility (EPR) System*, which requires the recycling rate of industrial products which include EEE should reach 50% by 2020 (GOSC, 2017). Although the estimated recycling rate reached 35% in 2014, the recycling rate for uncategorised WEEE is significantly lower such as batteries (Sun et al., 2015; Gu et al., 2017b).

Japan represents a good example of WEEE management, as Japanese recycling rates for televisions (Cathode Ray Tube, CRT), refrigerators, washing machines and air conditioners were 87%, 87%, 87% and 89% respectively (Menikpura et al., 2014). Recycling these four types of EEE are enforces in the Japanese *Home Appliance Recycling Law* enacted in 1998 (Kahhat et al., 2008; Yoshida and Yoshida, 2012). Hence, the majority of collected WEEE were these four types of EEE required by the law (Aizawa et al., 2008; Menikpura et al., 2014), and the collection rates for EEE which not listed in the law such as personal computers and mobile phones were much lower (Yoshida and Yoshida, 2012). In order to accomplish a higher collection rate, the maintenance cost of the recycling system in Japan is about 25% higher than that of EU's (Yoshida and Yoshida, 2012).

One critical issue closely associated with the low collection rates of WEEE is lack of available information on production, consumption and disposal of EEE. Due to lack of complete authentic information, it is impossible to estimate the in-use resource volumes, and current literature is mainly using some partial data to estimate the contents of resources in WEEE (see Dewulf et al., 2010; Du and Graedel, 2011; Zeng and Li, 2013, 2015; Zeng et al., 2016a). Those estimation results can hardly replace the role of actual figures, especially there are huge gaps exist between the estimations due to the various different statistic approaches were employed. In fact, the relationship between lack of information and low collection rates is a reciprocal causation. On one hand, without the support of complete authentic information, the effectiveness of legislation can be significantly compromised. For example, the operation efficiency of the EPR systems are largely affected by information availability, especially in distribution of subsidies (Cao et al., 2016b; Favot et al., 2016). On the other hand, low collection rates in the formal channels result in little available information on the disposal of WEEE. It is always impossible to calculate the volumes of WEEE end up in the informal sector (Cao et al., 2016a; Gu et al., 2017b), and it thereby cannot provide any credible data about the possible hazards and pollutions associated with informal WEEE recycling. As a result, only ex post analysis was carried out (see Tao et al., 2015; Tang et al., 2015; Wittsiepe et al., 2015; Awasthi et al., 2016; Wang et al., 2016a; Zeng et al., 2016b), as the environmental or health damage had already occurred. Since there are countless practitioners take part in the life cycle of EEE, i.e. there are more than 5000 mobile power pack manufacturers in China alone (Gu et al., 2017b), the traditional management information systems are incapable of processing such massive data. Cao et al., (2016b) reported that most formal WEEE disposers in China have implemented the information systems in accordance with the legal requirements, however, the EPR system is still suffered from the subsidy audit problem.

2.1.2. Active illegal transportation

Illegal transportation of WEEE is one of the major obstacles that prevent the states to fulfill their collection and recycling targets. A large amount of WEEE was shipped from developed countries to developing countries. For examples, 155 kt of WEEE exported from Germany in 2008 (Salhofer et al., 2016), 25% of total collected WEEE exported from Japan in 2009 (Yoshida and Yoshida, 2012), and 80% of the U.S. WEEE initially collected for recycling had been exported (Kahhat et al., 2008). The Basel Convention has attempted to prohibit the international exports and imports of WEEE (Alter, 2000), it is proved to be ineffective (Gioia et al., 2011; Breivik et al., 2014). The EU has adopted the Basel Convention to ban the illegal exportation of WEEE since 1994, but only 3% of the containers in Rotterdam were checked (Lewis, 2010). The US government even not ratified the Basel Convention (Zeng et al., 2017b).

China was once the largest importer of WEEE, and it was said that once 70% of global WEEE was shipped to China (Yu et al., 2010). Early on 26th January 2000, the first ban on WEEE has been issued by State Environmental Protection Administration (SEPA, later changed to Ministry of Environmental Protection, MEP). But in 2010, there were still at least 2 Mt of WEEE entered China (Sthiannopkao and Wong, 2013; Breivik et al., 2014). On 1st February 2013, Customs General Administration (CGA) launched the Green Fence Operation (GFO) for implementing higher standards on imports of waste materials and posing bans on imports of WEEE (CGA, 2013). From February 2010 to August 2010, more than 800 kt of recyclables have been rejected and the import licenses of 247 companies have been suspended during the GFO (Earley, 2013). In 2014, it was estimated that there were only 600 kt WEEE had imported to China (Zeng et al., 2016a), GFO has successfully stopped the WEEE importations. However, other alternative destinations could replace China, such as India, Vietnam, Ghana, Nigeria, South Africa, Turkey and the Philippines (Li et al., 2013; Margolis, 2014). Despite other destination countries such as India, Nigeria, Cambodia, Malaysia, Pakistan and Vietnam also have banned the importation of WEEE (Li et al., 2013; Sthiannopkao and Wong, 2013), WEEE flow continuously through loopholes as mislabeling WEEE as charitable donations, scrap metal, or reusable products (Manomaivibool, 2009). Without proper monitoring system that trace the life cycle of EEE and share of information, the illegal transportation of WEEE cannot be eliminated.

2.1.3. Difficult to enforce eco-design

Apart from recycling, another route to minimise the environmental impacts and human hazards of WEEE is to eliminate these threats at their sources. For this purpose, the hazardous substances used in EEE are legally restricted in many countries. Restriction of Hazardous Substances (RoHS) Directive 2002/96/EC (European Union, 2003b) was adopted on 27th January 2003 and took effect on 1st July 2006. In the recast version - RoHS Directive 2011/65/EC (European Union, 2011), the list of banned substances has expanded. Similar legal requirements were placed in the United States (California government, 2003) and China (Salhofer et al., 2016). However, heavy metals and POPs were still can be found in WEEE, including flame retardants contain polybrominated diphenyl ether (PBDE), lead and cadmium (Wäger et al., 2012; Peeters et al., 2014). A lack of enforcement and adoption of RoHS regulations was reported in China, even after these regulations has been enacted for over five years (Dou and Sarkis, 2013; Zeng et al., 2017a). One of the causes is that there is no official standard to recognise Design for Environment (DfE) (Cao et al., 2016b). Aside from restricting the use of the hazardous substances, there are two general routes of accomplishing eco-design: (1) substituting materials with more eco-friendly ones, i.e. replacing cobalt in lithium batteries with manganese or iron (Gu et al., 2017b); (2) mininsing waste generation, including reducing product size/mass, extending

Please cite this article in press as: Gu, F., et al. Internet of things and Big Data as potential solutions to the problems in waste electrical and electronic equipment management: An exploratory study. Waste Management (2017), http://dx.doi.org/10.1016/j.wasman.2017.07.037

life span, improving performance in use or reuse and in recycling (Gottberg et al., 2006; Zlamparet et al., 2017). It is worthwhile noting that reusing or remanufacturing of WEEE is gaining an increasing popularity (Wang and Wang, 2014; Zlamparet et al., 2017), which also can be greatly facilitated by the concept of eco-design. However, to our best knowledge, none of these measures has yet become a legal requirement in most countries. In addition, there is no international or national standard for adopting remanufactured WEEE, despite multiple practical cases have been reported (Zlamparet et al., 2017).

To sum up, there are some common flaws in implemented legislation systems. First and foremost, the scope of legislation is antiquated, and the limited scope has restricted the performance of WEEE management systems. This is particular obvious on collection perspective, as the collection systems tend to focus on the legal required targets while merging WEEE such as spent mobile phones has a much lower collection rate, even for model countries of WEEE management such as Switzerland (Duygan and Meylan, 2015) and Japan (Yoshida and Yoshida, 2012). Despite traditional WEEE (air conditioners, desktop personal computers, refrigerators, and washing machines) still took up the major of WEEE stream by weight, other "new" types of EEE are increasing (Zeng et al., 2016a). Second, controlling illegal international transportation of WEEE is beyond jurisdiction of any country or non-governmental organisation including Basel Action Network (BAN) and Silicon Valley Toxics Coalition (SVTC). Third, the legislation and its implementation require participations of stakeholders. A case studied showed that government expert may not understand the real requirements of companies which hindered the adoption of RoHS in product design (Dou and Sarkis, 2013).

2.2. Thriving informal sector

The informal sector dominants the WEEE recycling industry in most developing countries (Ardi and Leisten, 2016), as the informal sector treated 60% of WEEE in China (Chi et al., 2011) and 95% in India (Awasthi et al., 2016). The destination of illegal international WEEE transportation is the informal sector (Li et al., 2013), as famous WEEE recycling centres in China such as Guiyu and Taizhou are located in the coastal areas (Chi et al., 2011). Most of reported WEEE associated environmental pollutions are contributed to the informal sector (Tao et al., 2015; Awasthi et al., 2016), as well as human exposure (Tang et al., 2015; Wittsiepe et al., 2015; Wang et al., 2016a; Zeng et al., 2016b).

Economic is the primary reason behind the thriving informal sector. Four factors that drive informal economy are also applicable in the informal sector of WEEE recycling: (1) status of labour, (2) avoidance of income tax, (3) economies of scale and (4) evasion from registration and regulation (Chi et al., 2011). First and foremost, WEEE recycling is a labour-intensive industry (Breivik et al., 2014), and developing countries are where labour supply is abundant and labour cost is lower (Chi et al., 2011). For example, the output of the informal WEEE recycling sector in Guiyu was 800 million RMB in 2004, while the rural migrants employed for dismantling and processing WEEE got an average wage of 12 RMB per day (Chi et al., 2011). Another major reason is lack of formal recycling facilitates. The flow of WEEE lean towards countries with inadequate formal recycling facilities (Li et al., 2013). Some of the WEEE destination countries did not have formal recycling facilitates, including Nigeria, Thailand, Cambodia and Pakistan (Li et al., 2013). In India, only three such facilities are available, which resulted in a dominance of the informal sector (Sthiannopkao and Wong, 2013). Informal disposers usually clustered in certain areas, such as Guiyu and Taizhou in China (Chi et al., 2011), where economies of scale offer the significant cost advantages in purchase, transport and operation.

In December 2003, the National Development and Reform Commission of the People's Republic of China (NDRC) launched a national pilot program for WEEE recycling, and there are now more than one hundred formal recycling enterprises (Zhou and Xu, 2012; Li et al., 2013; Zeng et al., 2013a). The co-existence of the formal sector and the informal sector leads to a competition, and the formal sector still takes a larger proportion of WEEE (Chi et al., 2011), despite the formal sector has advantages in treatment processes (Yu et al., 2014). The competitive edge of the informal sector is collection. Formal disposers can ill afford competitive collection prices due to high treatment expenditure when competing with their illegal counterparts (Chi et al., 2011; Gu et al., 2016b; Liu et al., 2016). Asides from collection prices offered, informal collectors are advantageous in the other decisive aspects such as scope, convenience, flexibility, and accessibility (Chi et al., 2014; Gu et al., 2016b). Driven by profit-making intention, different informal practitioners have developed stable cooperation and thereby formed collection networks (Fei et al., 2016; Gu et al., 2016b; Steuer et al., 2017). ERP has already been implemented in many countries for fostering the formal collection system (Cao et al., 2016b; Fei et al., 2016; Gu et al., 2016b). However, the allocation of subsidies is found to be limited by the efficiency of audit system (Cao et al., 2016b; Zeng et al., 2017a), and the marginal effect of subsidy is not sufficient when the quality of WEEE is high (Liu et al., 2016). Besides, the collection channels can hardly be properly monitored (Cao et al., 2016b). Integration of the two collection channels is suggested by Fei et al. (2016), but the informal WEEE collectors are reluctant to be regulated (Orlins and Guan, 2016). Therefore, it is necessary to make the life cycle of EEE traceable.

2.3. Intention-behaviour gap

In the field of WEEE management, the public awareness has been identified as one of the key issues, and has been studied intensively. A brief literature review shows that according to most survey-based articles (see Huang et al., 2006; Wang et al., 2011; Chi et al., 2014; Yin et al., 2014; Islam et al., 2016; Sun et al., 2015; Cao et al., 2016a), public awareness such as Willingness To Pay (WTP) is related with the education and income level of the respondents. However, a gap was found exist between the public environmental awareness and the actual disposal behaviours, as a considerable amount of WEEE was still ended up in informal collection network (Wang et al., 2011; Chi et al., 2014; Cao et al., 2016a). It was found that income level has a positive impact on recycling behaviours (Hansmann et al., 2006; Wang et al., 2016b; Echegaray and Hansstein, 2017), while cost of recycling casts a negative impact (Wang et al., 2016b). Psychological reasons also play some part in recycling behaviours (Hansmann et al., 2006), as improving education has proved to be effective in promoting recycling behaviours (Hansmann et al., 2009). For some WEEE, lack of collection system is the primary cause of the intention-behaviour gap, such as mobile phones (Yin et al., 2014) and batteries (Sun et al., 2015; Gu et al., 2017b).

3. Big Data in WEEE management

All the articles focus on WEEE management offered recommendations from different perspectives. In principal, the WEEE recycling system is regarded as a reverse logistics system (Cao et al., 2016a, as shown in Fig. 1) and a supply chain (Georgiadis and Besiou, 2008; Gu et al., 2016a), and hence information is as important as material (Kaipia, 2013). Installing Management Information Systems (MIS) is a prerequisite for WEEE disposers to gain the subsidy from the Chinese government (Cao et al., 2016a,b), which is recommended as the solution to subsidy audit problem (Cao

Please cite this article in press as: Gu, F., et al. Internet of things and Big Data as potential solutions to the problems in waste electrical and electronic equipment management: An exploratory study. Waste Management (2017), http://dx.doi.org/10.1016/j.wasman.2017.07.037

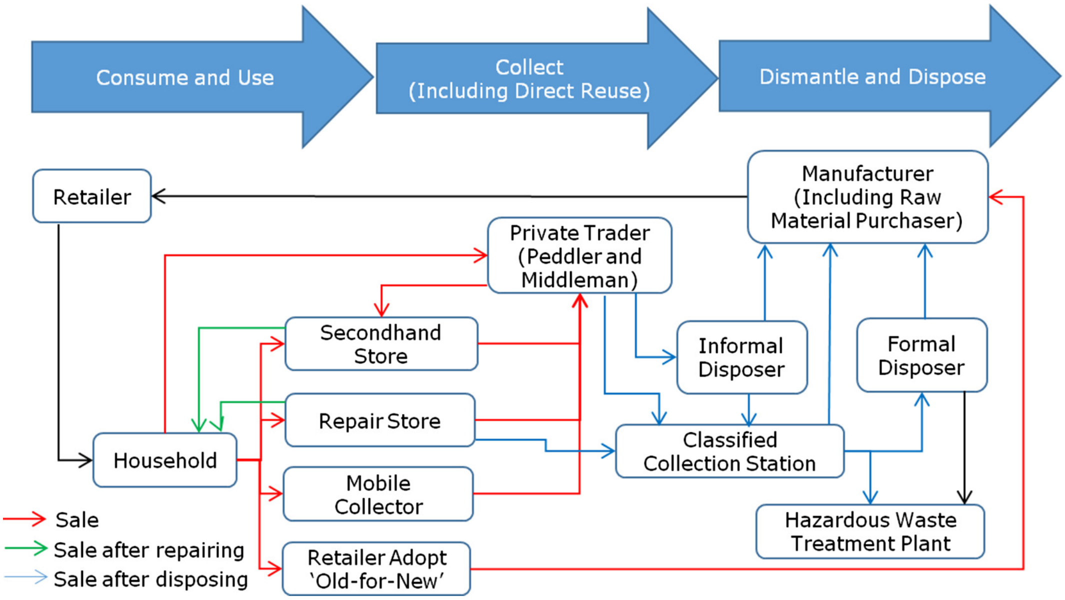

Fig. 1. The reverse logistics system of WEEE management (Cao et al., 2016a).

et al., 2016b). But a typical WEEE recycling system contains more stakeholders than disposers, such as consumers, manufacturers, retailers, second-hand stores, repair stores, collectors of multiple tiers, online platforms, researchers and legislators (Cao et al., 2016a; Gu et al., 2017b). Little attempt was made on integrating the whole WEEE recycling system using state-of-the-art information technologies. Wang and Wang (2014) and Wang et al. (2015) regarded the WEEE recycling system as a manufacturing system, and have proposed a cloud-based WEEE recovery/recycling (WR2) system which can track the material flow from manufacturers to disposers. Yet, the WR2 system is not sufficient to cover the current scale of the WEEE recycling system, thereby big data is introduced in this study. Characterised by huge volume, great velocity, high complexity and with an ever-increasing exponential growth rate (Gubbi et al., 2013; Wang et al., 2016c; Gani et al., 2016), big data is a better term to describe the information contains in the WEEE recycling system. The characteristics and features of the WEEE "Big Data" are discussed in as follows.

3.1. Data volume and velocity

Owing to rapid technological replacements, social-psychological reasons and service upgrades, global production and consumption of Electrical and Electronic Equipment (EEE) are increasing at a tremendous rate. Nowadays, seven billion people (corresponding to 95% of the global population) are using mobile phones (ITU, 2016), and the actual service life of a mobile phone is around two years (Chi et al., 2014; Gu et al., 2017b). As the largest EEE manufacturer in the world, China produced 144.76 million units of televisions, 79.93 million units of refrigerators, 72.75 million units of washing machines, 142.00 million units of air conditioners, 314.19 million units of personal computers, 174.36 million units of laptops and 1.81 billion units of mobile phones (NBS, 2016). That is 4.59 units of televisions, 2.53 units of refrigerators, 2.31 units of washing machines, 4.50 units of air conditioners, 9.96 units of personal computers, 5.53 units of laptops and 57.48 units of mobile phones per second. For the components used in EEE, the figures are even greater. In 2015, 108.72 billion integrated circuits was produced in China, which equals to 3447.49 pieces per second (NBS, 2016).

During recent years, the production of some EEE are decreased due to saturation of demand, including laptops and digital cameras (NBS, 2016; Gu et al., 2017b). But merging new consumer electronics (CEs) are quickly taking their places, and two typical examples are smart watch and mobile power source. The global shipments of smart watches were increased from 1.23 million units in 2013 to 24.92 million units in 2015 (Statista, 2016). The sale of mobile power sources in China was increased from 12 million units in 2010 to 138 million units in 2015 (Gu et al., 2017b).

Corresponding to the production and consumption statistics of EEE, the number of stakeholders in this supply chain is huge. According to the official statistics, there are 14,634 CE manufacturers, 55,155 CE stalls and 11,069 household appliance stores in China by the end of 2015 (NBS, 2016). Foxconn Technology Group, the world's largest contract maker of electronics (mobile phones in particular), have more than 1.2 million employees in China Mainland (China Daily, 2014). In addition to the astronomical figure of the stakeholders, the EEE manufacturing industry is a trade with rapid changes. For Taking mobile power source for example, there currently are more than 5000 manufacturers in China, which are increased from less than one hundred in 2010 (Gu et al., 2017b).

3.2. Data complexity

The complexity of the WEEE "Big Data" is attributed to the diversity and high dimensionality of the involving products, components and materials, as well as the related technologies. The technological advancement is one of the major forces that drives mobile phone manufacturers to launch new models. One of the illustrating facts is the implementation of new protocols resulted in launching of new product models. According to Ericsson mobility report (2016), Voice over Long Term Evolution (VoLTE) was firstly commercially launched in 2012, now there were more than 100 million VoLTE subscriptions and more than 340 VoLTE-enabled smartphone models by April 2016. Concerning recycling and recovery, the diversity in the compositions of EEE products and components is even more significant, especially under the context of rapid technological replacement. For examples, CRT is replaced by LCD due to less heavy metal content and slimmer size (Lairaksa et al., 2013), and nickel-cadmium, nickel-metal hydride batteries are replaced by lithium-ion batteries due to a higher

Please cite this article in press as: Gu, F., et al. Internet of things and Big Data as potential solutions to the problems in waste electrical and electronic equipment management: An exploratory study. Waste Management (2017), http://dx.doi.org/10.1016/j.wasman.2017.07.037

energy density and cell voltage, less memory effect, low self-discharge and environmental impact (Scrosati and Garche, 2010). Even the same components have different compositions in different models. Vats and Singh (2015) assessed the amount of gold and silver in Printed Circuit Boards (PCBs) of assorted mobile phone samples, and found that the gold content in PCBs of high-end mobile phones is higher than that in PCBs of low-end mobile phones. Several lithium transition metal oxides are used in LIBs, including $LiCoO_2$, $LiMn_2O_4$, $LiNiO_2$, and $LiCo_xMn_yNi_zO_2$ (Scrosati and Garche, 2010). Hence, the data associated with manufacturing these products and components is highly diversified and heterogeneous, which fits the characteristics of Big Data.

In addition, EEE relating services including repairing, second-hand trade, collection and disposal, also generate a huge volume of heterogeneous data as well as a great amount of WEEE. There are two causes of the WEEE "Big Data" generation during services. One is the variety of EEE products on the market, as discussed in above content. The other is due to various routes employed, such as different take-back schemes to collect spent mobile phones in the UK (Ongondo and Williams, 2011a,b), dozens of emerging online WEEE trading platforms (Gu et al., 2017b).

4. Communication technologies

Adapting the Big Data into WEEE management required for the involvement of several enabling communication technologies. In this section, the most relevant technologies are selected and discussed. Instead of providing a comprehensive survey of each technology, the aim of this section is to provide a picture of the roles they will likely play in the WEEE "Big Data" management framework, which is later presented in Section 5.

4.1. Internet of Things

Gubbi et al. (2013) defined Internet of Things (IoT) as ' Interconnection of sensing and actuating devices providing the ability to share information across platforms through a unified framework, developing a common operating picture for enabling innovative applications. The base idea of IoT is the interaction of variety of smart things or objects such as Radio Frequency IDentification (RFID) tags, sensors, actuators, mobile phones, etc, through unique addressing schemes to reach common goal (Atzori et al., 2010). It was forecasted that IoT devices will be the largest category of connected devices in 2018 (16 billion units) (Ericsson, 2016).

Currently, the potential application of the IoT in waste management have drawn some attention, and most literature focuses on smart waste collection (Anagnostopoulos et al., 2015). In the context of WEEE management, the information on the connected EEE devices is gathered and used by the administrators through IoT. Wang and Wang (2016) proposed a cloud-based IoT where WEEE recycle/recovery capabilities are also integrated and deployed as flexible cloud services. In this study, the scope of IoT application is extended, as information on all related activities in the devices' full life cycle are recorded and collected, including initial installation, maintenance, repair and disposal. Therefore, the generation of WEEE can be monitored. IoT is also applicable to both the production and disposing of EEE, which enables administrative authorities of different levels to monitor the actual situation and dynamic changes in processes. Administrators, researchers, designers and other practitioners can also be benefited from application of IoT, since authentic real-time information of recycling activities would be made available. With the aid of IoT, effectiveness of legislation, law enforcement, scheme design and research output can be significantly improved.

4.2. Radio Frequency IDentification

A key element in IoT is RFID systems which are consisted of readers and tags (Atzori et al., 2010; Gubbi et al., 2013). Based on electromagnetic fields, RFID is able to identify and track anything with RFID tags attached to them as long as the tags are visible (Hashem et al., 2016). The tags contain electronically stored information, and have three types of active, passive and battery-assisted passive (Hashem et al., 2016). The passive type uses the radio energy transmitted by the reader, which enables the passive tags can be used in many applications particularly in retail and supply chain management (Gubbi et al., 2013).

Labelling or tagging has been proposed as a potential way to promote the effectiveness and efficiency of the current WEEE recycling system (Gu et al., 2017b). Owing to its robust characteristics, the RFID technology is suitable for tagging EEE products and key components with the purpose of facilitating WEEE management (Li et al., 2012). The composition information can be stored in the RFID tags attached on the EEE products as well as the use and repair information (Li et al., 2012). When the products or the components come to their disposal phases, the collector can decide who is the potential customer and the disposer can decide what is the suitable treatment, based on reading the tags for obtaining the stored information. O'Connell et al. (2013) demonstrated the technical availability of RFID technology by achieving high read rates of RFID tags from mixed WEEE, and the economic viability was proved by Araujo et al. (2015) using Brazil as case study. Further, the actual amounts of WEEE ended up in different routes can be accurately calculated instead of rough estimation, and therefore the effectiveness of both legislation and law enforcement can be promoted. In addition, certified WEEE collection boxes, stores and any mobile collectors (Ylä-Mella et al., 2014; Zeng et al., 2015) shall be labelled by RFID tags, and consumers can identify the tag using readers. Thus, the informal sector can be successfully contained by controlling the supply at sources.

4.3. Wireless sensor network

Wireless Sensor Network (WSN) is another key element in IoT, which is defined as a network of spatially distributed autonomous sensors for monitoring physical or environmental conditions using low-power integrated circuits and wireless communication technology, and to distribute data through the network to designed destinations (Akyildiz and Kasimoglu, 2004; Hashem et al., 2016).

Since the WSN can be deployed in most environments, its potential applications in WEEE management are extensive. The WSN can deployed in EEE manufacturers to ensure the enforcement of RoHS Directive or other equivalent laws and regulations. The subsidy audit problem (Cao et al., 2016b) and other relating problems (Yu et al., 2014) can be solved by implementing the WSN. The procedures, inputs and outputs of the licensed WEEE recyclers can be monitored, hence the efficiency of the fund policy can be improved with the support of monitoring data. Deployment of the WSN in hotspots of the informal sector can comprehend real information on the informal WEEE recycling, which could facilitate the law enforcement and policy making procedure.

5. Framework for implementation

Big data collecting, Big Data processing, Big Data visualisation and Big Data analytics are the Big Data technologies used in Service and Manufacturing Supply Chain Management (SM-SCM) (Zhong et al., 2016a). As discussed above, WEEE management system can be regarded as SC-SCM, since it is heavily involved with in a wide range of equipments and human activities. A framework of imple-

Please cite this article in press as: Gu, F., et al. Internet of things and Big Data as potential solutions to the problems in waste electrical and electronic equipment management: An exploratory study. Waste Management (2017), http://dx.doi.org/10.1016/j.wasman.2017.07.037

menting big data and related technologies for WEEE management is proposed, as shown in Fig. 2. The framework can be divided into three major layers which enable the implementation of Big Data technologies for WEEE management: Big Data Acquisition, Big Data Processing and Big Data Utilisation.

The first layer is an WEEE IoT which based on embedment of communication technologies in the WEEE logistics system adopted from previous literature (Cao et al., 2016a). Compared to previous literature which focuses on one particular section such as collection (Anagnostopoulos et al., 2015) or recycling (Wang and Wang, 2016), the coverage of this WEEE IoT is extensive, as the whole life cycle of EEE products or components (adapted based on Fig. 1) is included. Thus, the generation and disposal of WEEE can be properly monitored. With utilisation of sensors, RFID tags and other devices, most of the related operations can be monitored, coordinated, controlled and integrated, and therefore cyber-Physical systems (CPS) are formed (Rajkumar et al., 2010). The un-structured data gathered through the first layer refers to the term of WEEE "Big Data", which is characterised by huge volume and heterogeneous nature, as discussed in Section 3.

Big Data technologies are employed to deal with the WEEE "Big Data" in the second layer, since these technologies are capable of processing distributed data (Zhong et al., 2015; Kang et al., 2016; Zhong et al., 2016b). In the second layer, all the collected unstructured data is firstly stored in big data collecting systems, such as Cassandra, CouchDB, DynamoDB, Hbase, MangDB, NoSQL, Redis and Voldemort (Hashem et al., 2016; Zhong et al., 2016a). Simultaneously, the stored data is processed using Big Data Processing technologies, such as Hadoop (Zhong et al., 2016a). MapReduce is the core of Hadoop, a programming paradigm which allows the models to process vast data sets with a large number of distributed clusters of servers (Zhong et al., 2016a). Other available Big Data Processing technologies include Spark, Storm and S4 (Hashem et al., 2016). Big Data Visualisation is essential for decision making support which makes vast data sets more approachable to general audience. It is applicable for big data in SM-SCM (Zhong et al., 2016a), as it can process the RFID Big Data from Cloud Manufacturing shop floors (Zhong et al., 2016b). Big Data Analytics or Big Data Business Analytics (BDBA) is a process to uncover implicit information and knowledge from immense data sets for facilitating decision making procedure. Big Data Analytics have attracted loads of attentions from researchers and decision makers from various organisations, especially in SCM (Wang et al., 2016c). Big Data analytics enable users to analyse huge volumes of heterogeneous data sets through a wide range of tools. These Big Data Analytics tools are categorised into platforms related tools, databases/data warehouse, business intelligence, data mining, and programming languages (Harvey, 2012). Currently, practices of Big Data analytics have been widely reported in the service, manufacturing and waste management sectors (see Lu et al., 2015, 2016b; Wang et al., 2016c; Zhong et al., 2016).

The third layer is the service level which supports the decision making procedures for multiple stakeholders in the WEEE recycling system. A wide range of decision supporting services are provided in this level based on internet applications, including public education, purchase recommendation, judicial suggestion, disposal illustration, market preference, behavioural analysis, performance evaluation, pollution surveillance, activity monitoring, fraud detection, mass balance analysis, intelligent logistics management, etc. By providing proper disposal illustration, the intention-behaviour gap can be diminished and hence the collection rates can be improved. Through mass balance analysis, the use of hazardous

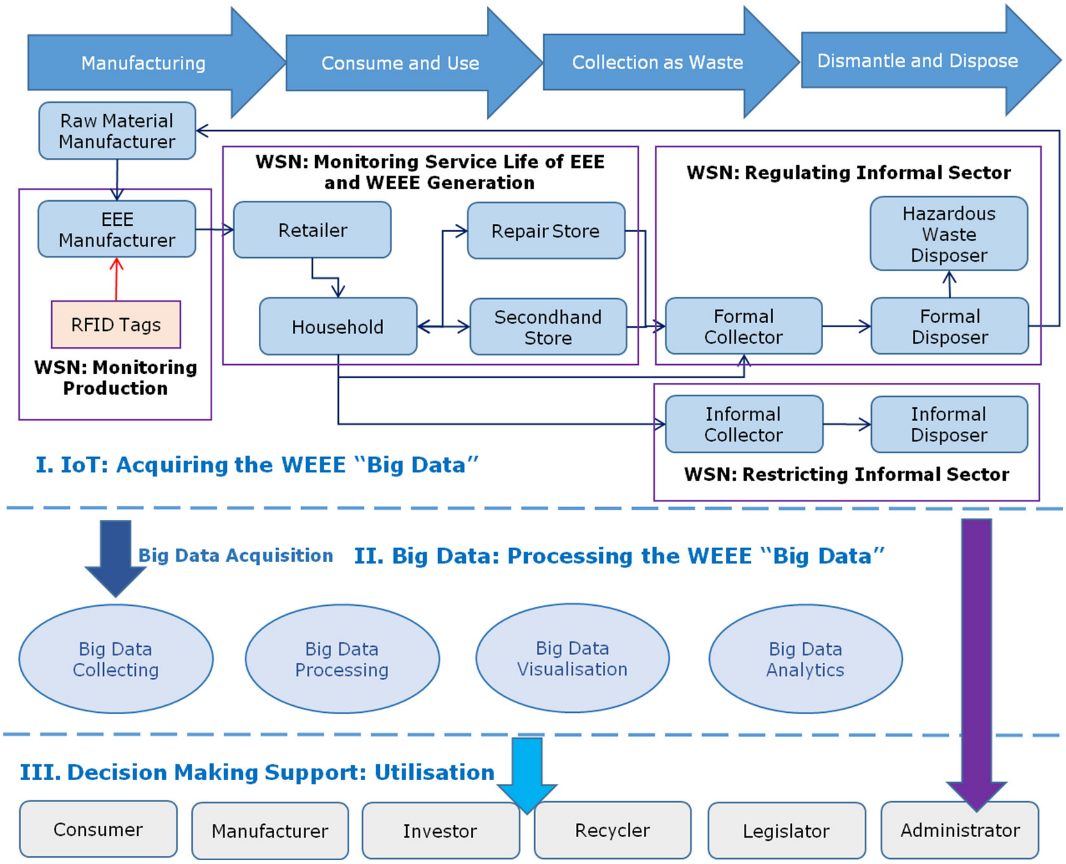

Fig. 2. The framework of the IoT and the Big Data implementation for WEEE management.

Please cite this article in press as: Gu, F., et al. Internet of things and Big Data as potential solutions to the problems in waste electrical and electronic equipment management: An exploratory study. Waste Management (2017), http://dx.doi.org/10.1016/j.wasman.2017.07.037

substances in production phrase can be easily identified, as the eco-design regulations can be enforced. The services provided are based on processed information, data or knowledge from the previous layers. For each category of stakeholders in the framework, their accessibilities to the WEEE "Big Data" are pre-determined by the system administrators. Therefore, in the proposed framework, the corresponding decision supporting services are provided to the corresponding roles: the customers receive public education, purchase recommendation and disposal illustration; the manufacturers and the investors receive market preference, behavioural analysis and judicial suggestion; the recyclers receive disposal illustration and judicial suggestion; the legislators and the governmental administrators receive performance evaluation, pollution surveillance, activity monitoring, fraud detection, mass balance analysis, intelligent logistics management, etc. However, during the actual operation, the roles of stakeholders are highly fickle and complicated, as overlapping can be found everywhere. Access control schemes should be developed and implemented in the framework, and a multi-label access control can be one possible candidate (Chen et al., 2014).

From application scale perspective, the implementing framework of smart WEEE management can be divided into four scales - embedded systems, local-networked embedded systems, cyber-physical systems and internet of things & BDBA services, as shown in Fig. 3. From ordinary household appliances to oncoming smart cities, separated, scattered and isolated practitioners, entities, activities and processes of different scales can be connected in the implementing framework using the state-of-art communication technologies. In this implementing framework, the WEEE "Big Data" generated from different application scales can be classified into three major categories which are also shown in Fig. 3: (1). Unsolicited data, which is provided by practitioners, such as purchase records, usage history and repair or disposal logs; (2). Passive data, which is recorded during performing related activities, such as extracting composition information in RFID tags on EEEs or their components, use of tools, equipments and facilities; (3). Process data, which is created by Big Data technologies during different Big Data processing phrases, including storing, preprocessing, visualising and analysing. Within the proposed framework, all the data that generated during the whole life cycle of EEE can be properly recorded, stored, processed and analysed, and is then used to support related activities or processes. Considering that even the accessing requests can be regarded as some sort of Big Data, data security has becoming a more challenging issue in the era of Big Data where attentions have been drawn (Yang et al., 2016).

6. Case studies

Implementing the IoT and the Big Data technologies will significantly reform the current WEEE recycling system towards sustainability. This section provides some case studies with the potential WEEE management scenarios of applying the framework of the IoT and the Big Data.

6.1. Incorporating repair

In previous research, the generation of WEEE is primarily estimated based on the amounts of EOL EEE (Cao et al., 2016a; Zeng et al., 2016a; Gu et al., 2017b). However, a large WEEE stream is generated from the repairing activities, and it has been ignored in current research. Quite often, EEE components are in need of replacements, such as dried LIBs or cracked LCDs. Sometimes, the whole machine is replaced by a new one according to service agreements. Taking a repair store in Hangzhou for example, a city which has around nine million residents, located in Zhejiang Province, China. The store focuses on repairing household air conditioners, and has eight branches in all the eight districts across the city. The store has a log database which has a data structure as shown in Table 1.

During the period from 1st July 2015 to 31th December 2015, the store got 57,108 repair requests recorded in the log system, averaging 39.2 requests per day per branch. Each request recorded has 23 columns of data in forms of binary and string as Table 1 shows, and therefore it has 1,256,376 data records in the log database. Considering the huge volume of the data accumulated by a single store in one city, the repair data fits the characteristics of Big Data. Among the 57,108 recorded repair requests, there were 3592 cases settled with malfunctioned components changed, and

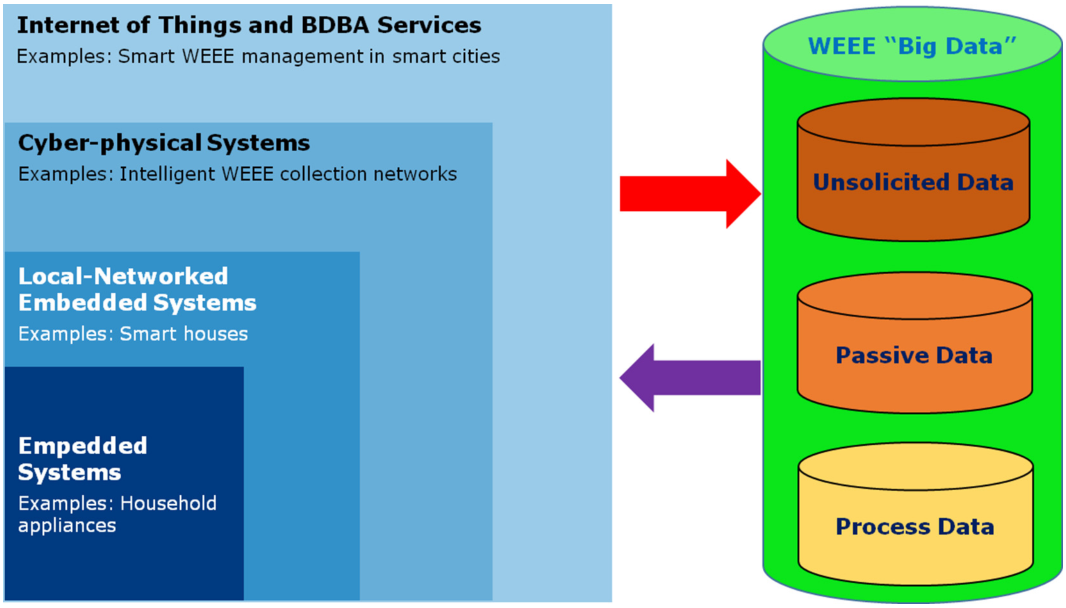

Fig. 3. Four application scales of the smart WEEE management framework and three categories of WEEE "Big Data".

Please cite this article in press as: Gu, F., et al. Internet of things and Big Data as potential solutions to the problems in waste electrical and electronic equipment management: An exploratory study. Waste Management (2017), http://dx.doi.org/10.1016/j.wasman.2017.07.037

Table 1
Data structure of the repair records stored in the log database.

Column no	Content
1	Serial number
2	Time of receiving call
3	Name of customer
4	Contact number
5	Location of customer
6	Operator
7	Brand
8	Type
9	Model
10	Complained problem
11	Time of sending Technician
12	Service content
13	Identified problem
14	Whether fixed?
15	Service completion time
16	Charge of service
17	Charge of parts changed
18	Total charge
19	Fee received
20	Whether case closed?
21	Whether repay a visit?
22	Audit

184 units were scrapped. The detailed information on components or products replacements is derived from the database and presented in Table 2.

During the selected period, the repair store generated more than 19 t of WEEE, as shown in Table 2. Among the scrapped components, the compressors, motors and evaporators consist of steel, aluminium and copper, the PCBs, valves, cables and aqueducts contain a considerable proportion of copper, and blades and drip trays are made of ferrous metals. Hence, the total weight of the scrapped components (compressors, motors, evaporators, PCBs, valves, cables and aqueducts) with copper content has exceeded 10 t. These components are usually considered as typical high value WEEE which require for material recycling, while the capacitors should be disposed as hazardous waste (Biganzoli et al., 2015). According to Zeng et al. (2016a), metallic content takes more than 70% of the average weight of an air conditioner. Therefore, the total metallic content could exceed 15 t in the WEEE produced by the repair store during the selected period. Currently, the staff of this store usually sell the scrapped components to peddlers or discarded directly, while only a very few of them are sent to the manufacturers. Thus, there is a need to monitor and control the WEEE stream generated from repairing activities. Based on the framework which is shown in Fig. 2, the scenario of incorporating the repair data into the WEEE "Big Data" is constructed and shown in Fig. 4.

The scenario is based on the assumption of the RFID tags have already been planted, onto the products and key components. The RFID tags on the replaced products or components are scanned, and then stored in the log system with current repair information. The log database along with other information generated in the scenario are adapted into a distributed storage module using the object-based mechanism, which gives each module an identifier to index the data and its location (Zhong et al., 2016a). The unstructured data is processed and visualised, and analytics are applied. In the service level, decision making support services are provided for corresponding audience, as shown in Fig. 3. In this scenario, the income of this repair store can be extended by implementing the IoT and the Big Data technologies, as the store can take a share from the part it plays in providing the services. A brief summary about WEEE "Big Data" in this application scenario is shown in Table 3, and a eight leveled hierarchy in BDBA of this application scenario are presented in Table 4. The eight leveled hierarchy in BDBA is adapted from the previous literature (Babu and Sastry, 2014), as repair is a vital part of WEEE management which can be regarded as a reverse logistics system.

As mentioned above, the current research and practices only focus on a limited area of the reverse logistics system of WEEE management (Cao et al., 2016a), usually the treatment of EOL products or components. By implementing the IoT and the Big Data technologies according to the proposed scenario (Fig. 4), the repair is included in WEEE management, as an important source of WEEE - the replacements of products or components have been properly monitored. Extending the current log database to WEEE "Big Data", all information and data generated from related activities are collected and processed for BDBA which used for decision making support, as Table 4 indicates. Various decision making procedures can be benefited from utilisation of BDBA, such as purchasing air conditioner, launching new product, marketing, modifying strategy, and disposal of replaced products or components, while the current log database could merely serve as a recording system which is even not sufficient to support the further development of the repair store.

Table 2
Detailed information on components or products replacements in the repair store during the period from 1st July 2015 to 31th December 2015.

Replaced components	Number of units[a]	Estimated average weight (kg)[b]	Accumulated weight (kg)	Contained resources[b]
Compressor	506	18.5	9361.00	Al, Cu, Fe
Electric motor	377	0.05	7.54	Cu, Fe
PCB	312	0.50	156.00	Ag, Cu
Remote Control	910	0.12	109.20	Cu, plastics
Display panel	118	0.25	29.50	In, glass
Capacitor	481	0.07	33.67	Al
Sensor	149	0.10	14.90	Cu
Valve	755	0.15	113.25	Cu, Fe
Blades	85	2.50	212.50	Fe
Evaporator	69	5.50	379.50	Al, Cu, Fe
Drip tray	93	1.50	139.50	Fe
Aqueduct	223	1.20	267.60	Cu, plastics
Acoustic Panel	476	0.30	142.80	Plastics
Pegboard	134	0.20	36.80	Plastics
Cable and switch	11	0.50	5.50	Cu
Whole machine	184	45.00	8280.00	Ag, Al, Cu, Fe, glass, plastics, etc.
Total weight			19290.57	

[a] In some cases, more than one unit of component needed to be replaced.
[b] Information provided by the technicians in the repair store.

Please cite this article in press as: Gu, F., et al. Internet of things and Big Data as potential solutions to the problems in waste electrical and electronic equipment management: An exploratory study. Waste Management (2017), http://dx.doi.org/10.1016/j.wasman.2017.07.037

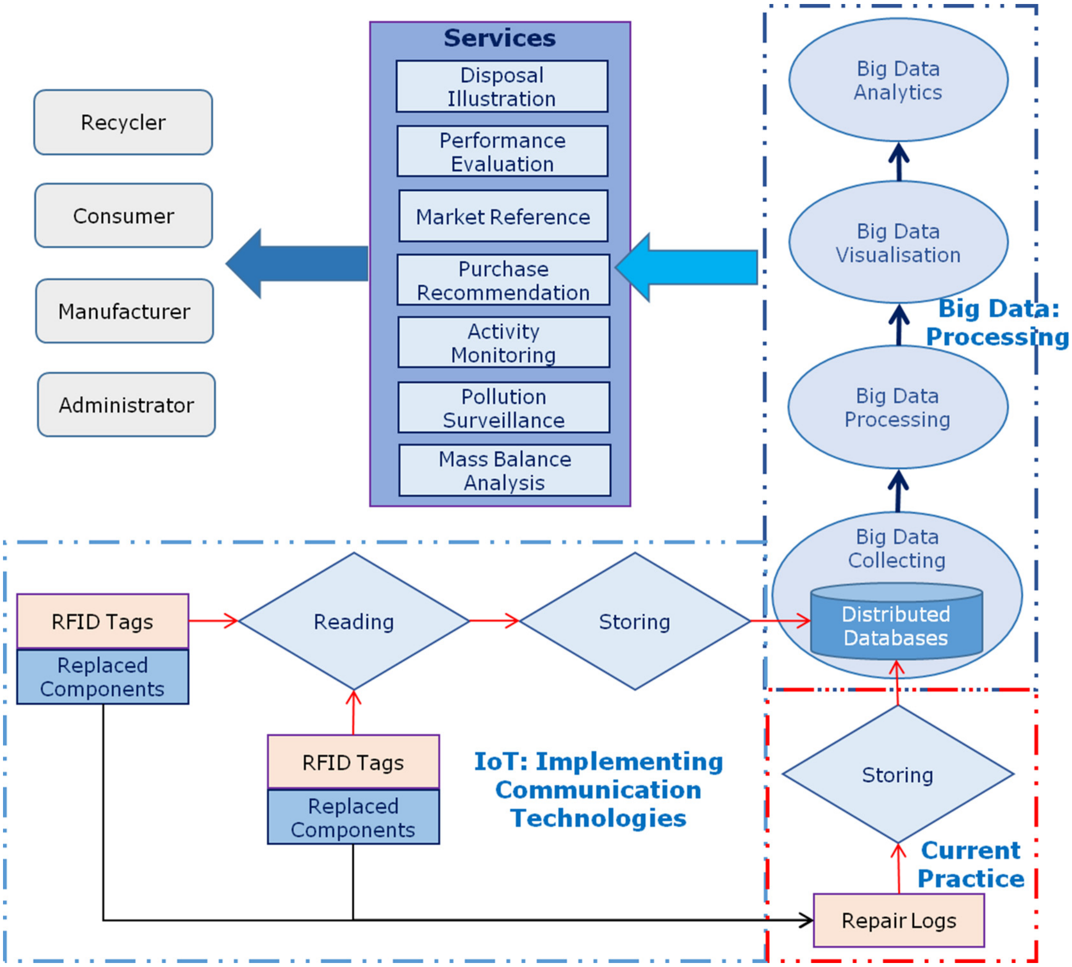

Fig. 4. The scenario of implementing the IoT and the Big Data technologies in monitoring the repair activities.

Table 3
A brief summary about WEEE "Big Data" in this application scenario.

Data classification	Data samples	Data sources	Data storage
Unsolicited data	Repair logs	Staff in the store	Log database
	BDBA reports	Distributed databases	Corresponding service databases
Passive data	Repair history	Repairing tools	RFID tags and client/ product management database
	Compositions of replaced components	RFID tags and reading equipments	WEEE monitoring database
	Usage logs	Repairing tools and equipments	Repair log database
Process data	Data locations	Big Data storing technologies	Indexing database
	Pre-processed data	Big Data processing technologies	Intermediate data storage

6.2. Restricting informal sector

As discussed above, the informal sector poses a serious threat to environment and human body. However, the informal sector is thriving due to economic profits, and there is little data about the actual activities of the informal sector (Zeng et al., 2016a; Gu et al., 2017b). Xing et al. (2009) reported there were once around 3000 illegal workshops in Guiyu doing toxic WEEE recycling. The other Chinese informal recycling centre, Taizhou, once dismantled more than 2 Mt of imported WEEE annually (Chi et al., 2011). The dismantling sites in Taizhou were located at coastal areas near ports where WEEE was illegally imported, as shown in Fig. 5.

During the GFO campaign in 2013, more than 1000 these WEEE dismantling sites in Taizhou were forced to shut down. Despite continuous efforts and stricter law enforcement, the informal sector remains active, as it was estimated that 600 kt of WEEE illegally imported into China in 2014 (Zeng et al., 2016a). Assuming Taizhou processed the same amount of imported WEEE as Guiyu did in 2014, that was 280 kt. Based on the heavy metal concentration in dismantling residues in Taizhou (Long et al., 2013), the scale of potential pollution is calculated and presented in Table 5. As shown in Table 5, even a significantly reduced amount of imported WEEE can cast huge impact on the local ecological systems. Moreover, domestic WEEE supply to the informal sector is becoming its primary source (Zeng et al., 2016a).

Taizhou covers 9411 square kilometers, and has a population of 5.69 million. It is impossible to carry out law enforcing campaign on monthly basis. A possible solution is applying the IoT and the Big Data technologies to set up smart environments for monitoring the informal WEEE recycling hotspots, the areas where the informal plants and workshops are clustered, such as Luqiao District where over 800 illegal workshops were shutdown during 2013 GFO campaign. Luqiao District has an area of 274 km^2 and a population around 413,000. The scope required for monitoring is con-

Please cite this article in press as: Gu, F., et al. Internet of things and Big Data as potential solutions to the problems in waste electrical and electronic equipment management: An exploratory study. Waste Management (2017), http://dx.doi.org/10.1016/j.wasman.2017.07.037

Table 4
Eight leveled hierarchy in BDBA of this application scenario.

Analytics level	Name of level	Typical information	Typical reports generated	Analytical capacities at the level
Level 1	Standard reports	Description of problems	Periodical general report	Useful for short-term custom reports
Level 2	Ad hoc reports	Repair technicians and activities	Performance assessment	Evaluation of repair business
Level 3	Query drilldown	Exact problems of the equipment	Root-cause analysis	Better understanding of products
Level 4	Alerts	Disposal of waste	Onsite scheduling	Aware of WEEE disposal
Level 5	Statistic analytics	Pattern of reported problems	Specific report for manufacturers	Enables complicated analysis and services
Level 6	Forecasting	Effects of current trends	Pre-scheduling arrangements	Incorporation of supply chain management
Level 7	Predictive modelling	Possible incoming changes	Investment and recruitment planning	Incorporation of strategy management and business projections
Level 8	Optimisation	Improving practices	Implications	Accomplishing goals

Fig. 5. A typical WEEE dismantling site in Taizhou, photos were taken in May 2013.

Table 5
The potential pollution caused by heavy metals in dismantling residues of illegally imported WEEE in Taizhou.

	Copper	Zinc	Lead	Nickel	Cadium
Amount[a] (t)	98.81	128.10	149.27	7.14	1.71
Potential polluted soil[b] (kt)	247.03	256.20	298.54	35.70	1710.00
Potential polluted ground water[c] (L)	N/A	2.56e13	1.49e15	7.14e13	1.71e14

[a] Dismantling residues are assumed to consist of 10 wt% of total imported WEEE.

[b] The results are calculated according to Grade III (least requirement) in *Environmental Quality Standard for Soils* issued by MEP (GB 15618-1995), http://kjs.mep.gov.cn/hjbhbz/bzwb/trhj/trhjzlbz/199603/t19960301_82028.htm (in Chinese).

[c] The results are calculated according to Grade V (least requirement) in *Quality Standard for Ground Water* issued by MEP (GB/T14848-93) under the assumption that the leaching rate to the ground water is 0.1 wt%, http://kjs.mep.gov.cn/hjbhbz/bzwb/shjbh/shjzlbz/199410/t19941001_66500.shtml (in Chinese).

siderably reduced by selecting such hotspots. Monitoring environmental changes is a traditional application of WSN (Akyildiz and Kasimoglu, 2004; Lazarescu, 2013). The scenario of implementing the IoT and the Big Data technologies in monitoring the informal WEEE recycling activities in the hotspots. For the purpose of restricting the informal sector, the logistics input and output of the hotspots are also monitored, which is an extension of previous literature (Lazarescu, 2013). Using different sensors to monitor environmental changes is a common practice. Among the existing sensing technologies, hyper-spectral imaging can be one of the most suitable candidates in monitoring the informal WEEE recycling hotspots. Hyper-spectral imaging is a non-destructive technology providing accurate and detailed information extraction, since the spectrum of each pixel is available in a hyper-spectral image (Palmieri et al., 2014). The technology is available for large scale area applications such as agriculture (Li et al., 2017), and has been applied in composition identification in WEEE recycling (Palmieri et al., 2014). Therefore, the use of hyper-spectral imaging in monitoring the informal sector is feasible. The big data and the service layers are also presented in Fig. 6, and Geographic Information Systems (GIS) based Big Data Visualisation enables fast decision making (Gubbi et al., 2013) which is particular suitable for this scenario. The scenario is mainly designed for achieving effective governance to restrict illegal WEEE recycling in hotspots, and is an extended framework of previous literature (Lazarescu, 2013) with incorporation of Big Data technologies.

According to the proposed implementing scenario (Fig. 6), the hotspots are monitored by the state-of-art communication technologies, including cargoes in logistics, gaseous emissions from informal WEEE recycling (incineration), heavy metal leakages in soil and water, and any suspicious human activities (washing and drying WEEE). Based on the real-time WEEE “Big Data” acquired from the proposed implementing scenario, BDBA services are supplied to administrator and legislator, and law enforcement and legislation can be more purposeful. Compared to traditional governance which based on human behaviours such as inspection and declaration, the efficiency of public administration is greatly improved. However, there are unsettled issues regarding economics of this technological implementation: on one hand, infrastructure construction, system integration, maintenance, upgrade and related training are costly; on the other hand, personnel expenditure could be largely reduced as conventional law

Please cite this article in press as: Gu, F., et al. Internet of things and Big Data as potential solutions to the problems in waste electrical and electronic equipment management: An exploratory study. Waste Management (2017), http://dx.doi.org/10.1016/j.wasman.2017.07.037

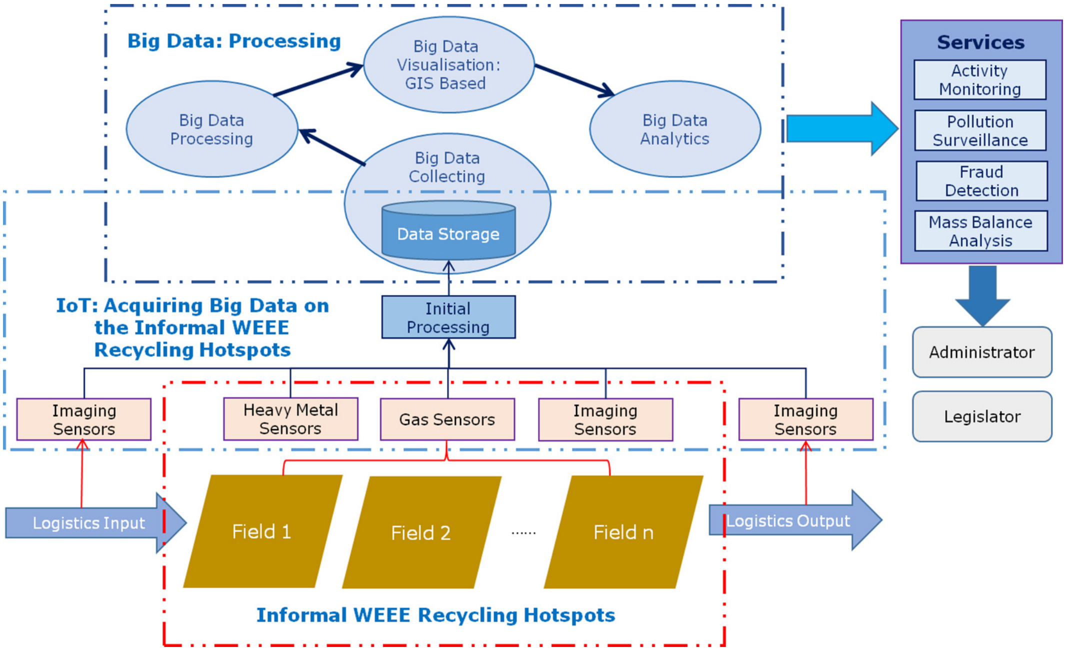

Fig. 6. The scenario of implementing the IoT and the Big Data technologies in monitoring the informal WEEE recycling activities in the hotspots.

enforcing activities can be minimised. Further analysis is required to verify the economical feasibility.

7. Challenges and research opportunities

Introduction of the IoT and the Big Data technologies in WEEE management brings plenty of potential benefits in improving the current system, expanding business model and increasing overall efficiency. However, there are some obvious challenges in implementing the IoT and the Big Data in WEEE management. Yet, challenges are accompanied by opportunities. In this section, the challenges associated with implementation of the IoT and the Big Data technologies are discussed. In general, the challenges and opportunities are divided into three categories: economical, technological and practical.

7.1. Economical perspective

7.1.1. Cost of implementation

The first and the foremost issue of technological implementation is always the cost. Software development, infrastructure construction and system integration are still of high cost, especially considering the volume, velocity and variety of the data being processed. Standarisation on robust open framework is a potential solution to the problem (Hashem et al., 2016), but hardware such as devices and tags could be another source of problem. Despite the price of RFID tags is decreasing during the recent years (from 0.50 USD ten years ago to 0.05 USD at present), it still could be higher than the marginal profit of some EEE components such as LIBs. Currently, the costs of some sensors are still very expensive, and customisation is always required for certain application such as hyper-spectral imaging. Intensive research is required for reducing the cost of these technologies.

7.1.2. Cost of operation

Aside from installation, the cost of running such state-of-art facilities is high, including personnel training, hiring specialists, infrastructure maintenance, systematic upgrades and component replacement/disposal. The operational cost could be even higher than that of implementation due to the two major concerns: geographical distribution of components and heterogeneous technologies employed. The application of the IoT and the Big Data technologies in WEEE management is based upon a vast range of components, such as RFID tags, sensors and servers, which are located in different geographical locations and are using different technologies. Maintenance of these components is becoming a challenging tasks, as multiple equipment and expertise are required, and the related operational cost is hence increased.

7.2. Technological perspective

7.2.1. Data collecting

Acquiring data of huge volume and velocity from distributed sources poses a serious challenge to the implementation of the IoT and the Big Data technologies. Similar to the operation problem, different geographical locations and different technological details make data collection even more difficult. Protocol is critical in data collecting, as it is supposed to be robust (Hayes and Ali, 2016), secure (Xie et al., 2017), efficient (Krichen et al., 2017) and energy efficient (Aslam et al., 2016; Mohemed et al., 2017) and so on. Yet, few research was carried out on collecting data of huge volume and velocity.

7.2.2. Data processing

Processing huge volume of heterogeneous data is always a difficult challenge, and it consists of three hierarchies: (1). Pre-processing, (2). Integration and (3) Analytics. Due to information is derived from different equipments in different environments, pre-processing is an essential procedure to obtain useful data. For example, hyper-spectral images are needed to be pre-processed to obtain desirable information, such as material compositions, and customised running platform is required. But customised development for each application is extremely costly, therefore it is in need of developing a robust model as the basis. Integration is a problem which is similar to data pre-processing. For Big Data Analytics in WEEE management, various new approaches are needed since there are so many services can be

Please cite this article in press as: Gu, F., et al. Internet of things and Big Data as potential solutions to the problems in waste electrical and electronic equipment management: An exploratory study. Waste Management (2017), http://dx.doi.org/10.1016/j.wasman.2017.07.037

derived from the implementing framework of the IoT and the Big Data technologies, as shown in Fig. 2.

7.2.3. Attaching and detaching

Implement technologies when needed and remove technologies when unwanted, that is the problem of "Attaching and Detaching". In the context of WEEE management, there are a series of "Attaching and Detaching" problems. RFID tags should be attached to the items during production, and they should be removed during material recovery process. The surveillance WSN should be constructed in the hotspots when required, and should be deconstructed when the hotspots are get rid of illegal WEEE recycling activities. Detached RFID tags, sensors and other related equipment can be regarded as WEEE, which require equal attention to deal with. The "Attaching and Detaching" problem is a merging and complicated issue with implementation of the IoT and the Big Data technologies, and thereby research and discussion are needed.

7.3. Practical perspective

7.3.1. Plan of implementation

As so many stakeholders are involved in the technological implementation and the current practicing patterns have to be greatly altered, the interest of the stakeholders must be taken into consideration in planning phase as well as the overall objectives. There always are conflicts between the interests of different stakeholders and reluctance exists in implementation, as sharing own information with others is not a preferrable practice amongst the business entities. It is important to plan the implementation, and three essentials should be considered: mechanism of business model, priority of implementation and cost-benefit analysis.

7.3.2. Privacy protection

Privacy is an important issue in Big Data implementation (Colombo and Ferrari, 2015; Hashem et al., 2016), and is a factor that lower the current recycling rates (Gu et al., 2017b). In WEEE management, there are more issues should be included. Securing vast data sets which stored on distributed storage modules is a challenging task, and it is becoming even more challenging when considering the information on discarded products and components is required for equal attention. Moreover, use of RFID tags could be another potential privacy breach, and thereby causes a public acceptance problem (Hossain and Dwivedi, 2014).

7.3.3. Definition of roles

It is important to define the roles in the implementation of the IoT and the Big Data technologies, as these definitions are associated with different levels and scales of access. Each stakeholder should be able to access the corresponding data and services, i.e. the recycler can check the input and the output of owned recycling facilities, the administrator can monitor the material flows and the changes in environmental indicators within the assigned area. Clear and precise definitions of the roles for various stakeholders are highly desirable in real practices to avoid any ambiguity and to minimise any overlapping. Regulations for possible and frequent shifting of roles should also be taken into consideration.

8. Conclusions

With increasing production and consumption, WEEE is becoming a major concern in waste management. The paper aims to provide a comprehensive view of the potential application of the IoT and the Big Data technologies in WEEE management. The problems in current WEEE recycling system are identified and discussed. Some selected communication technologies and their potential roles in WEEE management are presented. A framework of implementing the IoT and the Big Data technologies in WEEE management is proposed. Typical application scenarios are constructed and presented based on real-world case studies. The related challenges and research opportunities are addressed according three perspectives - economical, technological and practical. It can be concluded that combined the IoT and the Big Data would cast a positive impact in solving certain problems in WEEE management. The nature of this study exploratory, a theoretical and conceptual discussion on potential of using the IoT and the Big Data technologies in solving WEEE management problems. This is the major limitation of this study, and an intensive following research is highly desirable.

Acknowledgements

This work is financially supported by National Natural Science Foundation of China (71271200 and 71671180), National Science and Technology Major Project (2016ZX05040-001), Industrial Technology Innovation and Industrialisation of Science and Technology Project (2014A35001-2) and Green Manufacturing System Integration Project 2016 of Chinese Ministry of Industry and Information.

The authors would like to thank the Editor and the anonymous reviewers for their constructive comments and suggestions for improvement of this paper.

References

Aizawa, H., Yoshida, H., Sakai, S., 2008. Current results and future perspectives for Japanese recycling of home electrical appliances. Resour. Conserv. Recycl. 52 (12), 1399–1410.

Akyildiz, I.F., Kasimoglu, I.H., 2004. Wireless sensor and actor networks: research challenges. Ad Hoc Netw. 2 (4), 351–367.

Alter, H., 2000. Environmentally sound management of the recycling of hazardous wastes in the context of the Basel Convention. Resour. Conserv. Recycl. 29 (1–2), 111–129.

Anagnostopoulos, T., Zaslavsky, A., Medvedev, A., 2015. Robust waste collection exploiting cost efficiency of IoT potentiality in Smart Cities. In: Proceeding of 1st IEEE International Conference on Recent Advances in Internet of Things, RIoT 2015, Singapore.

Araujo, M.V.F. De, Oliveira, U.R. De, Marins, A.S. Fernando, M., Jorge, 2015. Cost assessment and benefits of using RFID in reverse logistics of waste electrical & electronic equipment (WEEE). In: Proceeding of 3rd International Conference on Information Technology and Quantitative Management, ITQM 2015, Proc. Comp. Sci., vol. 55, pp. 688–697.

Ardi, R., Leisten, R., 2016. Assessing the role of informal sector in WEEE management systems: A system dynamics approach. Waste Manage. 57, 3–16.

Aslam, M., Munir, E.U., Rafique, M.M., Hu, X., 2016. Adaptive energy-efficient clustering path planning routing protocols for heterogeneous wireless sensor networks. Sustain. Comput. Inf. Sy. 12, 57–71.

Atzori, L., Iera, A., Morabito, G., 2010. The internet of things: a survey. Comp Netw. 54 (15), 2787–2805.

Awasthi, A.K., Zeng, X., Li, J., 2016. Environmental pollution of electronic waste recycling in India: a critical review. Environ. Pollut. 211, 259–270.

Babu, M.S., Sastry, S.H., 2014. Big data and predictive analytics in ERP systems for automating decision making process. In: 2014 5th IEEE International Conference on Software Engineering and Service Science (ICSESS), pp. 259–262.

Baldé, C.P., Wang, F., Kuehr, R., Huisman, J., 2015. The Global e-Waste Monitor - 2014. United Nations University, IAS-SCYCLE, Bonn, Germany.

Biganzoli, L., Falbo, A., Forte, F., Grosso, M., Rigamonti, L., 2015. Mass balance and life cycle assessment of the waste electrical and electronic equipment management system implemented in Lombardia Region (Italy). Sci. Total Environ. 524–525, 361–375.

Breivik, K., Armitage, J.M., Wania, F., Jones, K.C., 2014. Tracking the global generation and exports of e-waste. Do existing estimates add up? Environ. Sci. Technol. 48, 8735–8743.

Electronic Waste Recycling Act of 2003. Available from: http://www.calrecycle.ca.gov/Electronics/Act2003/ (Retrieved on 20th, January 2017).

Cao, J., Chen, Y., Shi, B., Lu, B., Zhang, X., Ye, X., Zhai, G., Zhu, C., Zhou, G., 2016a. WEEE recycling in Zhejiang Province, China: generation, treatment, and public awareness. J. Clean. Prod. 127, 311–324.

Cao, J., Lu, B., Chen, Y., Zhang, X., Zhai, G., Zhou, G., Zhou, G., Jiang, B., Schnoor, J.L., 2016b. Extended producer responsibility system in China improves e-waste recycling: Government policies, enterprise, and public awareness. Renew. Sust. Energy Rev. 62, 882–894.

Please cite this article in press as: Gu, F., et al. Internet of things and Big Data as potential solutions to the problems in waste electrical and electronic equipment management: An exploratory study. Waste Management (2017), http://dx.doi.org/10.1016/j.wasman.2017.07.037

Colombo, P., Ferrari, E., 2015. Privacy aware access control for Big Data: A research roadmap. Big Data Res. 2 (4), 145–154.

Customs General Administration (CGA), 2013. Customs General Administration of the People's Republic of China. Official interpretation of Green Fence Operation (in Chinese). Available from: http://www3.customs.gov.cn/tabid/50104/Default.aspx (Retrieved on 23rd January 2017).

Chen, H., Bhargava, B., Zhongchuan, F., 2014. Multilabels-based scalable access control for Big Data applications. IEEE Cloud Comput. 1 (3), 65–71.

Chi, X., Streicherporte, M., Wang, M., Reuter, M.A., 2011. Informal electronic waste recycling: A sector review with special focus on China. Waste Manage. 31 (4), 731–742.

Chi, X., Wang, M., Reuter, M.A., 2014. E-waste collection channels and household recycling behaviors in Taizhou of China. J. Clean. Prod. 127, 87–95.

Foxconn plant to employ 20,000. Available from: http://www.chinadaily.com.cn/china/2014-08/30/content_18515457.htm (Retrieved on 23rd January 2017).

Cucchiella, F., D'Adamo, I., Lenny Koh, S.C., Rosa, P., 2015. Recycling of WEEEs: an economic assessment of present and future e-waste streams. Renew. Sust. Energy Rev. 51, 263–272.

Cucchiella, F., D'Adamo, I., Lenny Koh, S.C., Rosa, P., 2016. A profitability assessment of European recycling processes treating printed circuit boards from waste electrical and electronic equipments. Renew. Sust. Energy Rev. 64, 749–760.

Dewulf, J., van der Vorst, G., Denturck, K., van Langenhove, H., Ghyoot, W., Tytgat, J., Vandeputte, K., 2010. Recycling rechargeable lithium ion batteries: critical analysis of natural resource savings. Resour. Conserv. Recycl. 54 (4), 229–234.

Dou, Y., Sarkis, J., 2013. A multiple stakeholder perspective on barriers to implementing China RoHS regulations. Resour. Conserv. Recycl. 81, 92–104.

Du, X., Graedel, T.E., 2011. Global in-use stocks of the rare earth elements: a first estimate. Environ. Sci. Technol. 45 (9), 4096–4101.

Duygan, M., Meylan, G., 2015. Strategic management of WEEE in Switzerland-combining material flow analysis with structural analysis. Resour. Conserv. Recycl. 103, 98–109.

Earley, K., 2017. Could China's 'green fence' prompt a global recycling innovation? Available from: https://www.theguardian.com/sustainable-business/china-green-fence-global-recycling-innovation (Retrieved on 20th, January 2017).

Echegaray, F., Hansstein, F.V., 2017. Assessing the intention-behavior gap in electronic waste recycling: the case of Brazil. J. Clean. Prod. 142, 180–190.

Ericsson, 2016. Ericsson mobility report - on the pulse of the networked society. Available from: http://www.ericsson.com/res/docs/2016/ericsson-mobility-report-2016.pdf (Retrieved on 15th January 2017).

European Union, 2003. EU WEEE Directive 2002/96/EC. Available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32002L0096:EN:HTML (Retrieved on 20th, January 2017).

European Union, 2003. EU RoHS Directive 2002/95/EC. Available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32002L0095:EN:HTML (Retrieved on 20th, January 2017).

European Union, 2011. EU WEEE Directive 2011/65/EC Available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32011L0065:EN:HTML (Retrieved on 20th, January 2017).

European Union, 2012. EU WEEE Directive 2012/19/EC. Available from: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32012L0019:EN:HTML (Retrieved on 20th, January 2017).

Favot, M., Veit, R., Massarutto, A., 2016. The evolution of the Italian EPR system for the management of household Waste Electrical and Electronic Equipment (WEEE). Technical and economic performance in the spotlight. Waste Manage. 56, 431–437.

Fei, F., Qu, L., Wen, Z., Xue, Y., Zhang, H., 2016. How to integrate the informal recycling system into municipal solid waste management in developing countries: Based on a China's case in Suzhou urban area. Resour. Conserv. Recycl. 110, 74–86.

Gani, A., Siddiqa, A., Shamshirband, S., Hanum, F., 2016. A survey on indexing techniques for big data: taxonomy and performance evaluation. Knowl. Inf. Syst. 46 (2), 241–284.

General Office of the State Council (GOSC), 2017. Plan of Implementing Extended Producer Responsibility System (in Chinese). Available from: http://www.gov.cn/zhengce/content/2017-01/03/content_5156043.htm (Retrieved on 15th, January, 2017).

Georgiadis, P., Besiou, M., 2008. Sustainability in electrical and electronic equipment closed-loop supply chains: a system dynamics approach. J. Clean. Prod. 16 (15), 1665–1678.

Gioia, R., Eckhardt, S., Breivik, K., Jaward, F.M., Prieto, A., Nizzetto, L., Jones, K.C., 2011. Evidence for major emissions of PCBs in the west African region. Environ. Sci. Technol. 45, 1349–1355.

Gottberg, A., Morris, J., Pollard, S., Mark-Herbert, C., Cook, M., 2006. Producer responsibility, waste minimisation and the WEEE Directive: Case studies in eco-design from the European lighting sector. Sci. Total. Environ. 359 (1–3), 38–56.

Gu, Y., Wu, Y., Xu, M., Mu, X., Zuo, T., 2016a. Waste electrical and electronic equipment (WEEE) recycling for a sustainable resource supply in the electronics industry in China. J. Clean. Prod. 127, 331–338.

Gu, Y., Wu, Y., Xu, M., Wang, H., Zuo, T., 2016b. The stability and profitability of the informal WEEE collector in developing countries: A case study of China. Resour. Conserv. Recy. 107, 18–26.

Gu, F., Zhang, W., Guo, J., Summers, P.A., Hall, P., 2017a. From waste plastics to industrial raw materials: A life cycle assessment of mechanical plastic recycling practice based on a real-world case study. Sci. Total Environ. 601-602, 1192–1207.

Gu, F., Guo, J., Yao, X., Summers, P.A., Widijatmoko, S.D., Hall, P., 2017b. An investigation of the current status of recycling spent lithium-ion batteries from consumer electronics in China. J. Clean. Prod. in press.

Gubbi, J., Buyya, R., Marusic, S., Palaniswami, M., 2013. Internet of Things (IoT): a vision, architectural elements, and future directions. Future Gener. Comp. Syst. 29 (7), 1645–1660.

Hansmann, R., Bernasconi, P., Smieszek, T., Loukopoulos, P., Scholz, R.W., 2006. Justifications and self-organization as determinants of recycling behavior: The case of used batteries. Resour. Conserv. Recy. 47 (2), 133–159.

Hansmann, R., Loukopoulos, P., Scholz, R.W., 2009. Characteristics of effective battery recycling slogans: a Swiss field study. Resour. Conserv. Recy. 53 (4), 218–230.

Hashem, I.A.T., Chang, V., Anuar, N.B., Adewole, K., Yaqoob, I., Gani, A., Ahmed, E., Chiroma, H., 2016. The role of big data in smart city. Int. J. Inf. Manage. 36 (5), 748–758.

Harvey, C., 2012. 50 Top open source tools for big data. Datamation.

Hayes, T., Ali, F.H., 2016. Robust Ad-hoc Sensor Routing (RASeR) protocol for mobile wireless sensor networks. Ad Hoc Netw. 50, 128–144.

Hossain, M.A., Dwivedi, Y.K., 2014. What improves citizens' privacy perceptions toward RFID technology? A cross-country investigation using mixed method approach. I. J. Inf. Manage. 34 (6), 711–719.

Huang, P., Zhang, X., Deng, X., 2006. Survey and analysis of public environmental awareness and performance in Ningbo, China: a case study on household electrical and electronic equipment. J. Clean. Prod. 14 (18), 1635–1643.

Huang, C.-L., Bao, L.-J., Luo, P., Wang, Z.-Y., Li, S.-M., Zeng, E.Y., 2016. Potential health risk for residents around a typical e-waste recycling zone via inhalation of size-fractionated particle-bound heavy metals. J. Hazard. Mater. 317, 449–456.

Huisman, J., Ruediger, K., Mauer, C., 2007. Review of Directive 2002/96 on Waste Electrical and Electronic Equipment (WEEE). United Nations University, IAS-SCYCLE, Bonn, Germany.

Islam, M.T., Abdullah, A.B., Shahir, S.A., Kalam, M.A., Masjuki, H.H., Shumon, R.H., Rashid, M.H., 2016. A public survey on knowledge, awareness, attitude and willingness to pay for WEEE management: Case study in Bangladesh. J. Clean. Prod. 127, 728–740.

International Telecommunication Union (ITU), 2016. ICT facts and figures: the world in 2016. ICT Data and Statistics Division, Telecommunication Development Bureau, International Telecommunication Union (ITU). Available from: http://www.itu.int/en/ITU-D/Statistics/Documents/facts/ICTFactsFigures2016.pdf (Retrieved on 15th January 2017).

Kahhat, R., Kim, J., Xu, M., Allenby, B., Williams, E., Zhang, P., 2008. Exploring e-waste management systems in the United States. Resour. Conserv. Recycl. 52 (7), 955–964.

Kaipia, R., 2013. Coordinating material and information flows with supply chain planning. Int. J. Log. Manage. 20 (1), 144–162.

Kang, Y.-S., Park, I.-H., Rhee, J., Lee, Y.-H., 2016. MongoDB-Based repository design for IoT-generated RFID/sensor big data. IEEE Sens. J. 16 (2), 485–497.

Krichen, D., Abdallah, W., Boudriga, N., 2017. On the design of an embedded wireless sensor network for aircraft vibration monitoring using efficient game theoretic based MAC protocol. Ad Hoc Netw. 61, 1–15.

Król, A., Nowakowski, P., Mrówczyńska, B., 2016. How to improve WEEE management? Novel approach in mobile collection with application of artificial intelligence. Waste Manage. 50, 222–233.

Lairaksa, N., Moon, A.R., Makul, N., 2013. Utilization of cathode ray tube waste: encapsulation of PbO-containing funnel glass in Portland cement clinker. J. Environ. Manage. 117, 180–186.

Lazarescu, M.T., 2013. Design of a WSN platform for long-term environmental monitoring for IoT applications. IEEE J. Em. Sel. Top. C. Syst. 3 (1), 45–54.

Lewis, A., 2017. Europe exporting electronic waste despite ban. Available from: http://www.bbc.com/news/world-europe-10846395 (Retrieved on 20th January 2017).

Li, W., Chao, K., Jin, G., Xia, K., Gao, L., 2012. Sustainable information management for waste electrical and eletronic equipment. In: Proceeding of the 2012 IEEE 16th International Conference on Computer Supported Cooperative Work in Design (CSCWD), Wuhan, China.

Li, J., Lopez, B.N., Liu, N.L., Zhao, N., Yu, K., Zheng, L., 2013. Regional or global WEEE recycling. Where to go? Waste Manage. 33 (4), 923–934.

Li, Y., Liu, Y., Wu, S., Wang, C., Xu, A., Pan, X., 2017. Hyper-spectral estimation of wheat biomass after alleviating of soil effects on spectra by non-negative matrix factorization. Eur. J. Agron. 84, 58–66.

Liu, H., Lei, M., Deng, H., Leong, G.K., Huang, T., 2016. A dual channel, quality-based price competition model for the WEEE recycling market with government subsidy. Omega Int. J. Manage. Sci. 59, 290–302.

Long, Y., Feng, Y., Cai, S., Ding, W., Shen, D., 2013. Flow analysis of heavy metals in a pilot-scale incinerator for residues from waste electrical and electronic equipment dismantling. J. Hazard. Mater. 261, 427–434.

Lu, W., Chen, X., Peng, Y., Shen, L., 2015. Benchmarking construction waste management performance using big data. Resour. Conserv. Recycl. 105, 49–58.

Lu, S., Li, Y., Zhang, J., Zhang, T., Liu, G., Huang, M., Li, X., Ruan, J., Kannan, K., Qiu, R., 2016a. Associations between polycyclic aromatic hydrocarbon (PAH) exposure and oxidative stress in people living near e-waste recycling facilities in China. Environ. Int. 94, 161–169.

Lu, W., Chen, X., Ho, D.C.W., Wang, H., 2016b. Analysis of the construction waste management performance in Hong Kong: the public and private sectors compared using big data. J. Clean. Prod. 112, 521–531.

Please cite this article in press as: Gu, F., et al. Internet of things and Big Data as potential solutions to the problems in waste electrical and electronic equipment management: An exploratory study. Waste Management (2017), http://dx.doi.org/10.1016/j.wasman.2017.07.037

Manomaivibool, P., 2009. Extended producer responsibility in a non-OECD context: the management of waste electrical and electronic equipment in India. Resour. Conserv. Recycl. 53 (3), 136–144.

Jason Margolis. China's 'Green Fence' is cleaning up America's dirty recycling. Available from: https://www.pri.org/stories/2014-02-18/chinas-green-fence-cleaning-americas-dirty-recycling (Retrieved on 20th, January, 2017).

Menikpura, S.N.M., Santo, Atsushi, Hotta, Yasuhiko, 2014. Assessing the climate co-benefits from Waste Electrical and Electronic Equipment (WEEE) recycling in Japan. J. Clean. Prod., 74, 183–190.

Mohemed, R.E., Saleh, A.I., Abdelrazzak, M., Samra, A.S., 2017. Energy-efficient routing protocols for solving energy hole problem in wireless sensor networks. Comput. Netw. 114, 51–66.

Namias, J., 2013. The future of electronic waste recycling in the United States: Obstacles and Domestic Solutions. Columbia University, Master Thesis.

National Bureau of Statistics (NBS), 2016. Annual data of 2015. Available from: http://www.stats.gov.cn/english/Statisticaldata/AnnualData/ (Retrieved on 15th January 2017).

O'Connell, M., Hickey, S., Besiou, M., Fitzpatrick, C., Van Wassenhove, L.N., 2013. Feasibility of using radio frequency identification to facilitate individual producer responsibility for waste electrical and electronic equipment. J. Ind. Ecol. 17 (2), 213–223.

Ongondo, F.D., Williams, I.D., 2011a. Greening academia: use and disposal of mobile phones among university students. Waste Manage. 31 (7), 1617–1634.

Ongondo, F.D., Williams, I.D., 2011b. Mobile phone collection, reuse and recycling in the UK. Waste Manage. 31 (6), 1307–1315.

Orlins, S., Guan, D., 2016. China's toxic informal e-waste recycling: Local approaches to a global environmental problem. J. Clean. Prod. 114, 71–80.

Palmieri, R., Bonifazi, G., Serranti, S., 2014. Recycling-oriented characterization of plastic frames and printed circuit boards from mobile phones by electronic and chemical imaging. Waste Manage. 34 (11), 2120–2130.

Peeters, J.R., Vanegas, P., Tange, L., Van Houwelingen, J., Duflou, J.R., 2014. Closed loop recycling of plastics containing flame retardants. Resour. Conserv. Recycl. 84, 35–43.

Rahimifard, S., Abu Bakar, M.S., Williams, D.J., 2009. Recycling process planning for the End-of-Life management of waste from electrical and electronic equipment. CIRP Ann. Manuf. Technol. 58 (1), 5–8.

Rajkumar, R., Lee, I., Sha, L., Stankovic, J.A., 2010. Cyber-physical systems: the next computing revolution. Design Automation Conf., 731–736

Salhofer, S., Steuer, F., Ramusch, R., Beigl, P., 2016. WEEE management in Europe and China - A comparison. Waste Manage. 57, 27–35.

Scrosati, B., Garche, J., 2010. Lithium batteries: Status, prospects and future. J. Power Sour. 195 (9), 2419–2430.

Statista, 2016. Shipments of smart watches worldwide from 2013 to 2015 (in millions). Available from: https://www.statista.com/statistics/302722/smart-watches-shipments-worldwide/ (Retrieved on 15th January 2017).

Steuer, B., Ramusch, R., Part, F., Salhofer, S., 2017. Analysis of the value chain and network structure of informal waste recycling in Beijing, China. Resour. Conserv. Recy. 117, 137–150.

Sthiannopkao, S., Wong, M.H., 2013. Handling e-waste in developed and developing countries: Initiatives, practices, and consequences. Sci. Total Environ. 463, 1147–1153.

Sun, M., Yang, X., Huisingh, D., Wang, R., Wang, Y., 2015. Consumer behavior and perspectives concerning spent household battery collection and recycling in China: a case study. J. Clean. Prod. 107, 775–785.

Tang, W., Cheng, J., Zhao, W., Wang, W., 2015. Mercury levels and estimated total daily intakes for children and adults from an electronic waste recycling area in Taizhou, China: Key role of rice and fish consumption. J. Environ. Sci. 34, 107–115.

Tao, W., Zhou, Z., Shen, L., Zhao, B., 2015. Determination of dechlorane flame retardants in soil and fish at Guiyu, an electronic waste recycling site in south China. Environ. Pollut. 206, 361–368.

Vats, M.C., Singh, S.K., 2015. Assessment of gold and silver in assorted mobile phone printed circuit boards (PCBs): Original article. Waste Manage. 45 (11), 280–288.

Wäger, P.A., Hischier, R., Eugster, M., 2011. Environmental impacts of the Swiss collection and recovery systems for Waste Electrical and Electronic Equipment (WEEE): A follow-up. Sci. Total Environ. 409 (10), 1746–1756.

Wäger, P.A., Hischier, R., 2015. Life cycle assessment of post-consumer plastics production from waste electrical and electronic equipment (WEEE) treatment residues in a Central European plastics recycling plant. Sci. Total Environ. 529, 158–167.

Wang, Z., Zhang, B., Yin, J., Zhang, X., 2011. Willingness and behavior towards e-waste recycling for residents in Beijing city, China. J. Clean. Prod. 19 (9–11), 977–984.

Wang, X.V., Wang, L., 2014. From cloud manufacturing to cloud remanufacturing: a cloud-based approach for WEEE recovery. Manuf. Lett. 2 (4), 91–95.

Wang, X.V., Wang, L., 2016. A cloud-based production system for information and service integration: an internet of things case study on waste electronics. Enterp. Inf. Syst.

Wang, X.V., Lopez, B.N., Ijomah, N.W., Wang, L., Li, J., 2015. A smart cloud-based system for the WEEE recovery/recycling. J. Manuf. Sci. Eng.-T ASME, 137(6), 061010.

Wang, Y., Hu, J., Lin, W., Wang, N., Li, C., Luo, P., Hashmi, M.Z., Wang, W., Su, X., Chen, C., Liu, Y., Huang, R., Shen, C., 2016a. Health risk assessment of migrant workers' exposure to polychlorinated biphenyls in air and dust in an e-waste recycling area in China: Indication for a new wealth gap in environmental rights. Environ. Int. 87, 33–41.

Wang, Z., Guo, D., Wang, X., 2016b. Determinants of residents' e-waste recycling behaviour intentions: Evidence from China. J. Clean. Prod. 137, 850–860.

Wang, G., Gunasekaran, A., Ngai, E.W.T., Papadopoulos, T., 2016c. Big data analytics in logistics and supply chain management: Certain investigations for research and applications. Int. J. Prod. Econ. 176, 98–110.

Wäger, P.A., Schluep, M., Müller, E., Gloor, R., 2012. RoHS regulated substances in mixed plastics from waste electrical and electronic equipment. Environ. Sci. Technol. 46, 628–635.

Wittsiepe, J., Fobil, J.N., Till, H., Burchard, G.-D., Wilhelm, M., Feldt, T., 2015. Levels of polychlorinated dibenzo-p-dioxins, dibenzofurans (PCDD/Fs) and biphenyls (PCBs) in blood of informal e-waste recycling workers from Agbogbloshie, Ghana, and controls. Environ. Int. 79, 65–73.

Wu, Y., Li, Y., Kang, D., Wang, J., Zhang, Y., Du, D., Pan, B., Lin, Z., Huang, C., Dong, Q., 2016. Tetrabromobisphenol A and heavy metal exposure via dust ingestion in an e-waste recycling region in Southeast China. Sci. Total Environ. 541, 356–364.

Xie, K., Ning, X., Wang, X., He, S., Ning, Z., Liu, X., Wen, J., Qin, Z., 2017. An efficient privacy-preserving compressive data gathering scheme in WSNs. Inf. Sci. 390, 82–94.

Xing, G.H., Chan, J.K.Y., Leung, A.O.W., Wu, S.C., Wong, M.H., 2009. Environmental impact and human exposure to PCBs in Guiyu, an electronic waste recycling site in China. Environ. Int. 35 (1), 76–82.

Yang, K., Jia, X., Ren, K., 2016. Secure and verifiable policy update outsourcing for Big Data access control in the Cloud. IEEE T. Parall. Distr. Syst. 26 (12), 3461–3470.

Yin, J., Gao, Y., Xu, H., 2014. Survey and analysis of consumers' behaviour of waste mobile phone recycling in China. J. Clean. Prod. 65, 517–525.

Ylä-Mella, J., Poikela, K., Lehtinen, U., Keiski, R.L., Pongrácz, E., 2014. Implementation of waste electrical and electronic equipment directive in Finland: evaluation of the collection network and challenges of the effective WEEE management. Resour. Conserv. Recycl. 86, 38–46.

Yoshida, F., Yoshida, H., 2012. 25 - WEEE management in Japan. Waste electrical and electronic equipment (WEEE) Handbook, A volume in Woodhead Publishing Series in Electronic and Optical Materials, 576–590.

Yu, J., Williams, E., Ju, M., Shao, C., 2010. Managing e-waste in China: Policies, pilot projects and alternative approaches. Resour. Conserv. Recy. 54 (11), 991–999.

Yu, L., He, W., Li, G., Huang, J., Zhu, H., 2014. The development of WEEE management and effects of the fund policy for subsidizing WEEE treating in China. Waste Manage. 34 (9), 1705–1714.

Zeng, X., Li, J., 2013. Implications for the carrying capacity of lithium reserve in China. Resour. Conserv. Recy. 80, 58–63.

Zeng, X., Li, J., Singh, N., 2013a. Recycling of spent lithium-ion battery: a critical review. Crit. Rev. Environ. Sci. Technol. 44 (10), 1129–1165.

Zeng, X., Li, J., Stevels, A., Liu, L., 2013b. Perspective of electronic waste management in China based on a legislation comparison between China and the EU. J. Clean. Prod. 51, 80–87.

Zeng, X., Li, J., 2015. On the sustainability of cobalt utilization in China. Resour. Conserv. Recy. 104, 12–18.

Zeng, X., Song, Q., Li, J., Yuan, W., Duan, H., Liu, L., 2015. Solving e-waste problem using an integrated mobile recycling plant. J. Clean. Prod. 90, 55–59.

Zeng, X., Gong, R., Chen, W., Li, J., 2016a. Uncovering the recycling potential of "New" WEEE in China. Environ. Sci. Technol. 50 (3), 1347–1358.

Zeng, X., Xu, X., Boezen, H.M., Huo, X., 2016b. Children with health impairments by heavy metals in an e-waste recycling area. Chemosphere 148, 408–415.

Zeng, X., Duan, H., Wang, F., Li, J., 2017a. Examining environmental management of e-waste: China's experience and lessons. Renew. Sust. Energy Rev. 72, 1076–1082.

Zeng, X., Yang, C., Chiang, J.F., Li, J., 2017b. Innovating e-waste management: From macroscopic to microscopic scales. Sci. Total Environ. 575, 1–5.

Zhang, K., Wu, Y., Wang, W., Li, B., Zhang, Y., Zuo, T., 2015a. Recycling indium from waste LCDs: A review. Resour. Conserv. Recycl. 104, 276–290.

Zhang, S., Ding, Y., Liu, B., Pan, D., Chang, C., Volinsky, A.A., 2015b. Challenges in legislation, recycling system and technical system of waste electrical and electronic equipment in China. Waste Manage. 45, 361–373.

Zhong, R.Y., Huang, G.Q., Lan, S.L., Dai, Q.Y., Xu, C., Zhang, T., 2015. A big data approach for logistics trajectory discovery from RFID-enabled production data. Int. J. Prod. Econ. 165, 260–272.

Zhong, R.Y., Newman, S.T., Huang, G.Q., Lan, S., 2016a. Big Data for supply chain management in the service and manufacturing sectors: Challenges, opportunities, and future perspectives. Comp. Ind. Eng. 101, 572–591.

Zhong, R.Y., Lan, S.L., Xu, C., Dai, Q.Y., Huang, G.Q., 2016b. Visualization of RFID-enabled shopfloor logistics big data in cloud manufacturing. Int. J. Adv. Manuf. Technol. 84 (1), 5–16.

Zhou, L., Xu, Z., 2012. Response to waste electrical and electronic equipments in China: legislation, recycling system, and advanced integrated process. Environ. Sci. Technol. 46 (9), 4713–4724.

Zlamparet, G.I., Ijomah, W., Miao, Y., Awasthi, A.K., Zeng, X., Li, J., 2017. Remanufacturing strategies: A solution for WEEE problem. J. Clean. Prod. 149, 126–136.

Please cite this article in press as: Gu, F., et al. Internet of things and Big Data as potential solutions to the problems in waste electrical and electronic equipment management: An exploratory study. Waste Management (2017), http://dx.doi.org/10.1016/j.wasman.2017.07.037