Analysis of the influence of mobile phones' material composition on the economic profitability of their manual dismantling

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Highlights

- 100 waste mobile phones were identified, dismantled, and characterized
- trends related to their macro-composition over 28 years were compared and discussed
- electronics and plastics components' weight decreased, while metals increased
- a cost-benefit analysis of manual dismantling was performed
- manual dismantling was not found economically profitable in the EU context

Abstract

This work presents a systematic characterization of 100 waste mobile phones (73 feature phones and 23 smartphones) produced between 1989 and 2016. All items were inventoried and the evolvement of the relative abundances of their macro-components (mechanic and electro-mechanic parts, electronics and others) and materials was investigated. The average lifetime was 15.1 years for feature phones and 6.4 years for smartphones. The main component was plastic, on average 46%-wt. in feature phones and 37%-wt. in smartphones; over the years electronics' and plastic's amounts decreased (respectively 80 % and 70 %), while metal components' amount increased (12 %). A cost-benefit analysis explored the profitability of the management of waste mobile phones through manual dismantling followed by the sale of the separated components and materials. The average cost of manual dismantling was estimated as 6.93 € per item according to EU average labour costs and 1.50 € per item based on minimum EU labour costs. According to the performed economic analysis, the actual market prices for the potentially recoverable materials and components of waste mobile phones were not able (particularly mixed plastics) to counterbalance the costs of manual dismantling according to the European standard labour costs.

keywords: economic analysis, mobile phone, recycling, secondary raw material, smartphone, WEEE

1. Introduction

Waste from electric and electronic equipment (WEEE) is one of the fastest growing waste streams worldwide; its production soared from 44.4 Mt in 2014 to 53.6 Mt in 2019 and it is expected to reach 74.7 Mt by 2030 (Forti et al., 2020). WEEE management has always been a critical issue; in 2019 the recycling rate topped at 17.4 % of globally generated e-waste, leaving behind almost 44.3 Mt of residual waste dumped in landfills or improperly recycled (Forti et al., 2020). In the past decade WEEE generation rate and recycling quota increased at different pace; the annual growth of WEEE recycling from 2014 to 2019 was 0.4 Mt, while the generation rate increased almost 2 Mt each year (Forti et al., 2020). The highest collection and recycling rates have been reported in Western (54 %) and Northern (59 %) Europe in 2017 (Forti et al., 2020).

Among WEEE, small IT appliances as mobile phones (i.e., feature phones and smartphones) are recently gaining attention. According to most recent statistics (Eurostat, 2020a) in 2017 mobile phones represented less than 15 %-wt (equivalent to 0.55 Mt) of the total collected WEEE under the category “IT and telecommunications equipment” (3.76 Mt) in EU-27. This is due to their light weight compared to other larger WEEE. However, considering the number of waste items, mobile phones stand out because of two key issues. Firstly, the fast rate of new items put on the market (according to the United Nations, in 2017 Europe imported over 210 million mobile phones) (UN, 2017). Secondly, the consumers’ tendency to consider obsolete their mobile phones much earlier than their intended lifetime: after only 3 years in developing countries and 2 years in developed countries (Soo and Doolan, 2014). WEEE generation shows direct correlation with gross domestic product (Arya and Kumar, 2020; Torretta et al., 2013; Awasti et al., 2018): in the western world the average number of obsolete mobile phones owned per capita is higher than 1. In details, in high/middle income households (average purchasing power equal to 21,697 USD/y), the average number of owned mobile phones is 1.2 per capita; in high income households (average purchase power equal to 51,581 USD/y), the average number of owned phones reaches 1.4 per capita (Forti et al., 2020). The fast pace at which mobile phones are dismissed, combined with their peculiar composition of valuable and hazardous elements make their management a strategic issue. Small IT and communication waste appliances are often traded in international routes (Robinson, 2009). Uncontrolled recycling activities could be highly hazardous for human health and the environment (Cesaro et al., 2018), and they happen mostly in developing and underdeveloped countries (Man et al., 2013). A recent study (Liu et al., 2021) demonstrated that the key factors driving WEEE recycling are the incentives from the government and the producers taking responsibility for recycling. Another research (Yang et al., 2021) calculated that global WEEE recycling could provide 3 million job opportunities per year; the same authors also estimated an environmental load (i.e., the cost required to offset the environmental impacts) equal to 1-9 USD/kg, proposing a WEEE emission trading system aimed at reducing the related carbon emissions.

Electronics and ICT items are included in the key product value chains of the European Circular Economy Action plan and of the European Green Deal launched in 2020. In a circular economy perspective, waste mobile phones represent a valuable resource for urban mining, since precious metals and critical raw materials showed relatively high concentrations in waste mobile phones (among the others: Charles et al., 2020; Sahan et al., 2019; Tesfaye et al., 2017; Tunsu et al., 2015). Besides, mobile phones composition is characterised by roughly 40 %-wt plastics, mainly polycarbonate (PC), acrylonitrile-butadiene-styrene (ABS) and polymethylmethacrylate (PMMA) as housing components, (e.g., covers, cases and frames), and PMMA and silicone for display windows (Fontana et al., 2019). Specifically considering waste mobile phones' characterization, literature mostly focus on the investigation of the composition of single material components, as plastics (Martinho et al., 2012; Nnorom and Osibanjo, 2009; Palmieri et al., 2014; Sahajwalla and Gaikwad, 2018) or metals (Islam et al., 2020; Marra et al., 2018; Sahan et al., 2019; Tesfaye et al., 2017). When a more general characterisation is involved, the experimental activity reported in literature is limited to a narrow set of samples, from 2 (Bachér et al., 2015) to 10 (Tan et al., 2017) or 20 items (Fontana et al., 2019).

Waste mobile phones' management may happen appropriately or not. In the last case, the small dimensions of mobile phones make easier for them to be incorrectly discharged among municipal solid waste, with detrimental environmental and economic consequences for the society and health risks for the workers. Also appropriate WEEE treatment operations on industrial-scale are burdensome on the environment; damages to ecosystems due to Ag, Au, Cu, Pb and Sn release during Printed Circuit Boards (PCBs) recycling were observed (Yao et al., 2018), as well as environmental pollution due to Pb, Cd and Ni from the management of WEEE plastic components (Nnorom and Osibanjo, 2009). The health of the operators in charge of WEEE components dismantling could be affected too, mainly due to carcinogenic risk derived by Ni, Pb and Be and non-carcinogenic risk due to Ag, Zn, and Cu (Singh et al., 2019).

Current waste mobile phones treatment technologies at industrial scale consist of: pre-treatment via manual disassembly and shredding, followed by material separation based on different properties (dimensions, density, magnetic and electrostatic behaviours, etc.) and finally material recovery through acids extraction or purification of the metal concentrate (Gu et al., 2019). Disassembly is usually performed manually, as the high variability of items' design hinders the profitability of automatic disassembly (Bachér et al., 2015). Li-ion batteries may cause combustion hazard (Huang et al., 2018), thus they are removed before manual disassembly according to the EU regulations; in this case recycling has been reported to bring the highest environmental benefits (Gu et al., 2019). Automatic shredding is usually involved in waste mobile phones pre-treatment to facilitate the subsequent separations steps (Gu et al., 2019). The technical feasibility of mechanical pre-treatments has already been investigated, and manual dismantling showed to ensure better quality in the separated components compared to automatic separation (Bachér et al., 2015). Other studies investigated the economic aspects of mobile phones' recycling (Sarath et al., 2015), and reuse and recycling operations were compared (Geyer and Blass, 2010) based on datasets from UK in 2003 and US in 2006, concluding that the economic profit stems from mobile phone reuse rather than recycling, for which profitability could never be achieved even with minimized reverse logistic costs; however, an exhaustive cost/benefit analysis was not performed. The disassembly of the LCD screen of multiple mobile phones (Sawanishi et al., 2015), or of a whole single mobile phone was also investigated (Sebo and Fedorcakova, 2014) to identify the optimal management strategy considering the recycling of the camera and PCB, and the disposal of the remaining components. An estimate of the secondary raw materials potentially recyclable from mobile phones (Gurita et al. 2016) demonstrated positive environmental and economic outcomes if the collection rate is substantially improved and if the recycling operations are focused on precious metals and critical materials.

To our knowledge, literature on waste mobile phones is still lacking a detailed cost/benefit analysis of manual dismantling specifically aimed at optimizing secondary raw materials' recycling and components' recovery, also considering how the composition of mobile phones changed over the years.

Compared to existing literature, this work aims to answer 2 research questions (RQs): RQ1. how have mobile phones' composition evolved along 28 years on 100 waste items, in a recycle-oriented perspective? RQ2. is manual dismantling economically profitable according to actual EU labour costs and market values of recyclable and recoverable components? The main goal of this work is to understand the influence of waste mobile phones' composition on the economic profitability of their pre-treatment based on manual dismantling followed by the separate sale of single components and materials in a European context.

2. Materials and methods

2.1. Samples origin

100 waste mobile phones (73 feature phones and 27 smartphones) were provided in 2018 by a WEEE treatment plant near Turin, one of the largest in Italy. The waste mobile phones arrived at the treatment plant deprived of the batteries, according to the Italian regulations. The size of the sample (100 items) was equal to the inflow of waste mobile phones arrived at the plant in one week. The 100 items have been collected randomly within each of the two types of waste mobile phones, defining in advance the relative abundances of feature phones (5.56 kg) and smartphones (2.17 kg) according to the up-to-date input flows to the plant. The inflow of the WEEE treatment plant at the moment of the sampling was made of 70-75 % feature phones and 25-30% smartphones (% referred to the number of items, not to their weight).

2.2. Samples' characterisation

The first step was the setup of an inventory: the waste mobile phones were identified one by one, searching brand, model and year of production on technical databases available online (as an example, https://puntocellulare.it/cercafonino/index.html, *in Italian*). This information allowed to evaluate the lifetime of the single items and the relative abundance of items belonging to specific brands and models (without, of course, pretending to perform a market analysis). The lifetime was estimated as the difference between the year of production of a single item and the year of collection from the WEEE treatment plant (2018). Afterwards, the 100 items were manually dismantled into the following macro-components (Figure 1): mechanical parts (cases, covers, keyboards and buttons), electro-mechanical parts (microphones, speakers, displays and headpieces), electronics (printed circuit board, PCB) and others (batteries, SIM and SD cards). The single macro-components have been weighted through a PLJ42002F technical scale, and a mass balance was performed for each item and included in the inventory.

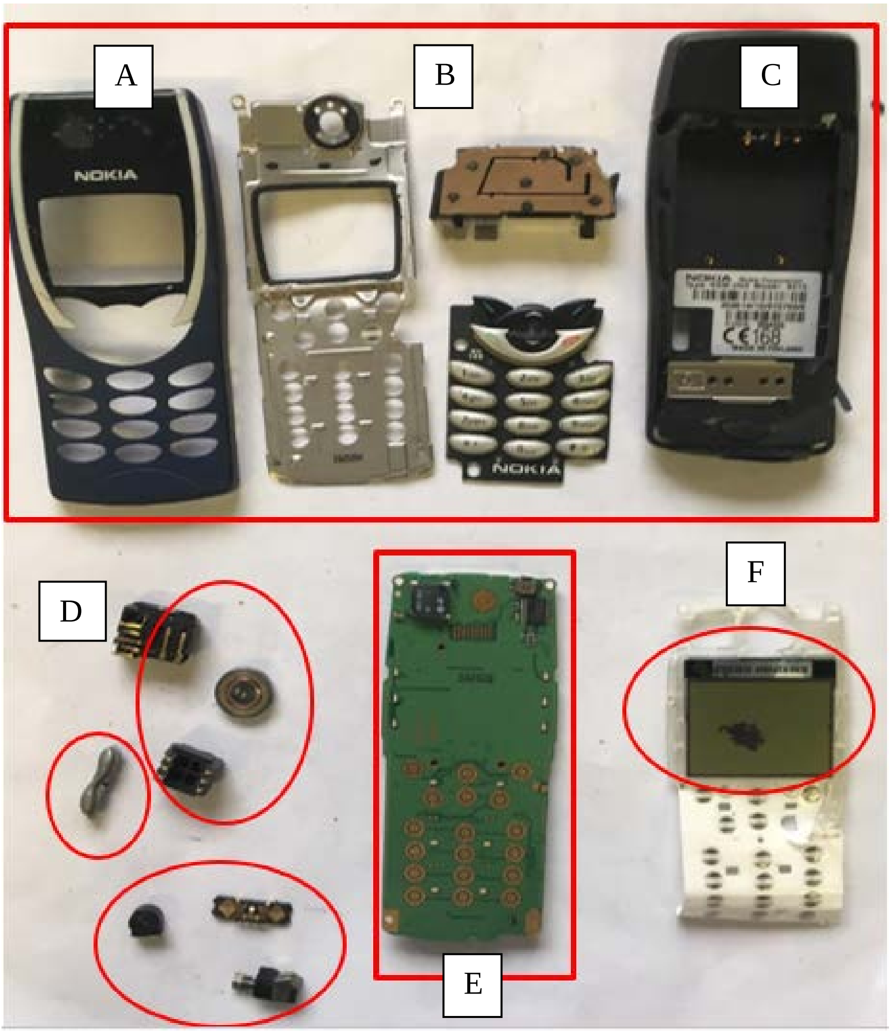


Figure 1. Details of the macro-components of a dismantled waste mobile phone: mechanical parts (cover [A], keyboards [B] and case [C]), electro-mechanical parts (microphones, speakers, displays and headpiece [D]), electronics (PCB [E]) and other components (display [F], batteries, SIMs and SDs)

The data related to the macro-composition (detailed in Figure 1) of the items commercialized in the same year were merged to achieve an "average composition", then different years were compared to evaluate its temporal evolution. The detailed composition of the single dismantled items was described according to literature (choosing studies spread between 2011 and 2020), with the approximation of considering the same average composition for each component along the whole period 1989-2016 for all the 100 items. In details, the plastic components of the feature phones were acknowledged as: 2.2 % ABS, 80.5 % PC, 8.2 % PMMA and 8.8 % silicone (Fontana et al., 2019). Since silicone was found exclusively in the keypads of the feature phones, the plastic components of the waste smartphones were described as: 2.4 % ABS, 88.3 % PC and 9.0 % PMMA, excluding silicone. For all items, the composition of the electro-mechanical parts was considered as: 2.00 g/kg Ag, 120 g/kg Al, 0.13 g/kg Au, 1.30 g/kg Ce, 37.00 g/kg Cr, 150 g/kg Cu, 2.00 g/kg La, 14.00 g/kg Ni, 2.60 g/kg Pb, 209 g/kg Si, 12.00 g/kg Sn and 3.00 g/kg Zn (Sahan et al., 2019). For all items, the composition of the PCBs was calculated as average from different literature studies (Jing-ying et al., 2012; Jyothi et al., 2020; Kasper et al., 2011; Maragkos et al., 2013; Sahan et al., 2019; Xiu et al., 2015; Yamane et al., 2011): 0.58 % Al, 2.61 % Au, 0.07 % Ca, 7.62 % Cu, 0.90 % Fe, 1.95 % Ni, 1.39 % Pb, 1.76 % Pt, 2.21 % Si, 0.57 % Sn, 27.63 % Ti and 3.35 % Zn. Finally, the concentration trends of the critical raw materials (CRMs) (Blengini et al., 2020), were compared to the reported grade of mineral ores for virgin metals mining (Allegrini et al., 2014).

2.3. Statistical analysis

The differences between the 2 categories "feature phones" and "smartphones" were quantitatively evaluated performing a T-test with a hypothesis acceptance threshold $t_{crit} < 0.005$ (null hypothesis: the two categories are not different), comparing the differences between the average weight of each macro-component for the 2 categories. Moreover, the correlations existing between the different sets of macro-components in the 2 categories were investigated using Pearson correlation coefficient.

2.4. Economic analysis

The economic profitability of manual dismantling of the waste mobile phones was assessed through an itemized cost-benefit analysis. The costs were calculated considering the average EU cost of labour (27.7 €/h) and the lowest reported labour cost in a member state (i.e. 6.0 €/h in Bulgaria) (Eurostat, 2020b). This research was based on the assumption of keeping the management of the waste mobile phones (and therefore the related job places and the recovered secondary and critical raw materials) collected in EU inside the member states, according to the current Circular Economy policies and regulations. The time required to manually separate the different macro-components was accounted as 4 items per hour (this duration was defined as average value after recording the dismantling operations for an 8-hours shift in the WEEE treatment plant that supplied the items).

The collection (from the collection centres to the plant) and transportation (from the plant to the destinations of the separated materials and components) costs were not considered in the analysis, even if average values for EU can be derived from literature. The reason was that not all WEEE treatment plants in EU have the same catchment areas (distance from the collection centres to the plant) nor the destinations of the separated materials and components are located at a fixed distance from the plant.

The incomes were estimated considering the following actual market values: 5.000 €/t for PCBs, 130 €/t for plastic components, 180 €/t for other electronic components. A market value of 280 €/t was considered for steel scraps (Eurostat, 2020c). The details of the market values of plastic components and metals are provided in the Appendix (Table I) with the related references.

3. Results and discussion

3.1. Samples' origin

According to the compiled inventory (Appendix, Tables II and III, Figure I), the waste mobile phones considered in this work were put on the market in a 28-years period between 1989 and 2016. Feature phones were sold between 1989 and 2013 by 14 manufacturers: smartphones between 2006 and 2016 by 9 manufacturers (Appendix, Figure II). Five out of nine feature phones manufacturers produced 82 % of the collected items; within the inventoried 100 items, Nokia produced 47 % of the feature phones, whereas for the smartphones Samsung (33 % and Nokia (26 %) were the most common producers identified. The lifetime was equal to 15.1 ± 4.88 years for feature phones (minimum 5, maximum 29) and 6.37 ± 3.18 years for smartphones (minimum 2, maximum 12) (Appendix, Figure III). These results offer an interesting insight on the duration of the "effective lifetime" of mobile phones (probably implying several owners and/or extended shut off periods), which resulted much higher than the 2-3 years of lifetime reported by literature (Soo and Doolan, 2014) and intended as the duration of the possession of a mobile phone by a single owner. A recent study (Shaikh et al., 2020) identified storage as preferred option for obsolete mobile phones.

3.2. Mass balance

The average weight per item was 76.1 ± 20.9 g for feature phones and 80.4 ± 28.6 g for smartphones (Appendix, Tables II and III). The high standard deviation observed in the 2 categories was due to the differences observed among models put on the market in different years. A general declining trend was observed in the items' weight over the years (Figure 3, where the confidence intervals are not present in case of a single item inventoried for a specific year of production). Feature phones samples' weight ranged between a maximum of 151.58 g in 1989 to a minimum of 42.07 g in 2012 (-72%); smartphones samples weight varied between 117.5 g in 2007 and 51.56 in 2013 (-56 %).

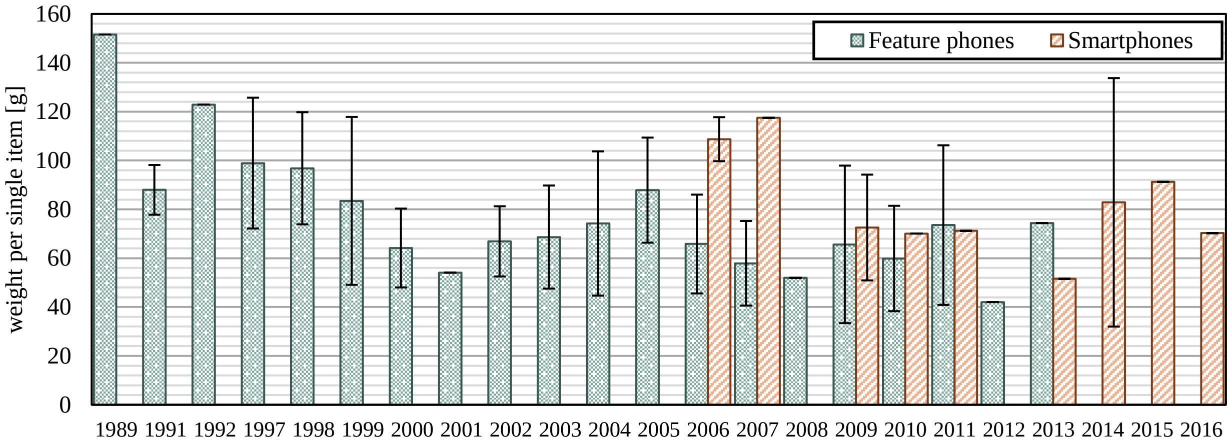


Figure 3. Trends over time of the weight per item of the considered waste mobile phones

From the overall mass balance (Figure 4) resulted that the main macro-component of waste mobile phones was plastic, representing 46 ± 7% wt in feature phones and 37 ± 8% wt in smartphones. The other components of feature phones were PCBs (29 ± 5 %), other electronic elements (17 ± 4 %) and metals (8 ± 6 %). Whereas smartphones' mass balance, other than plastic, consisted in 25 ± 11 % metal components, 21 ± 8 % PCBs and 17 ± 10 % other electronic components. These results were consistent with previous studies (Bachér et al., 2015; Fontana et al., 2019; Tan et al., 2017).

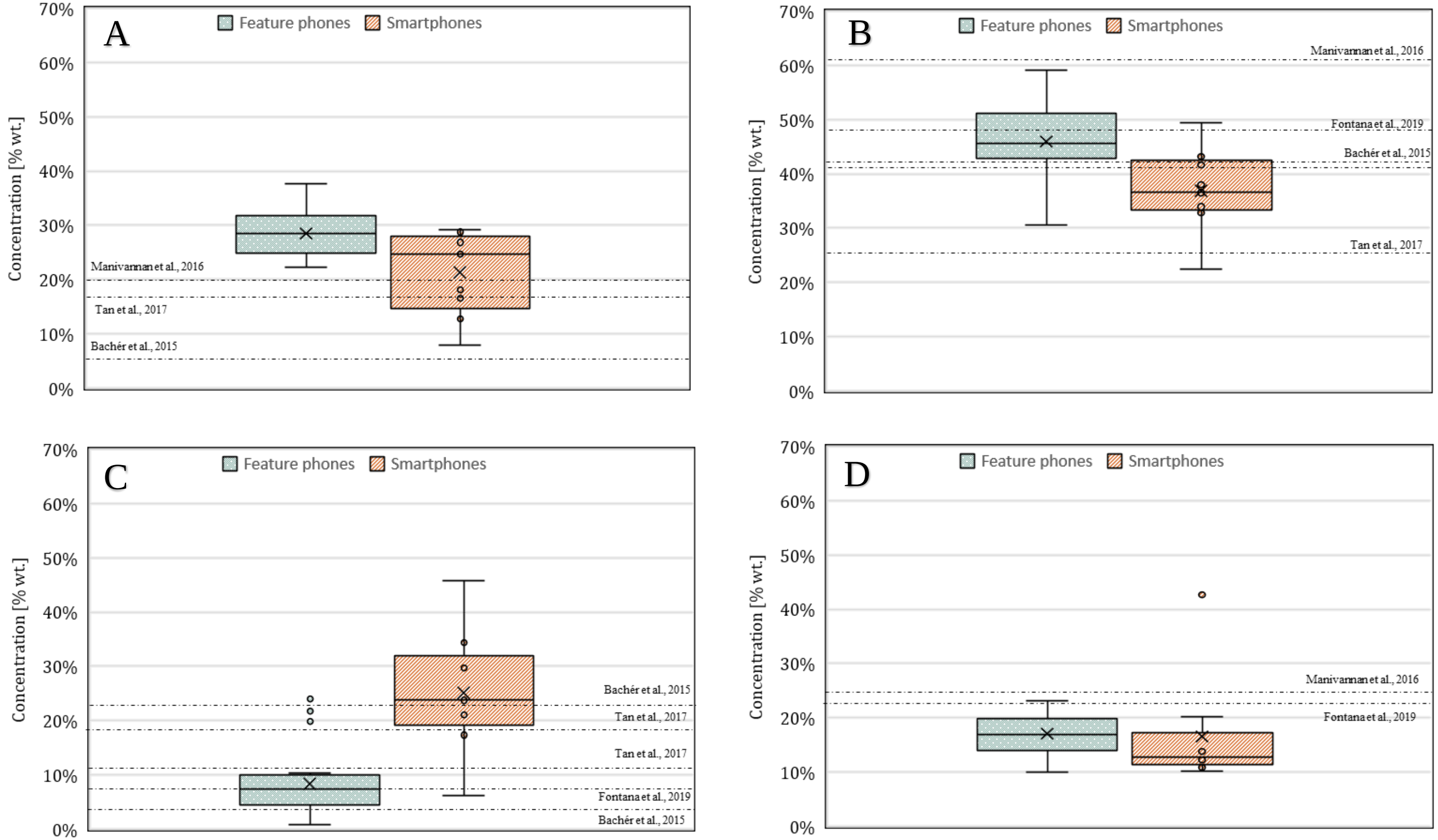
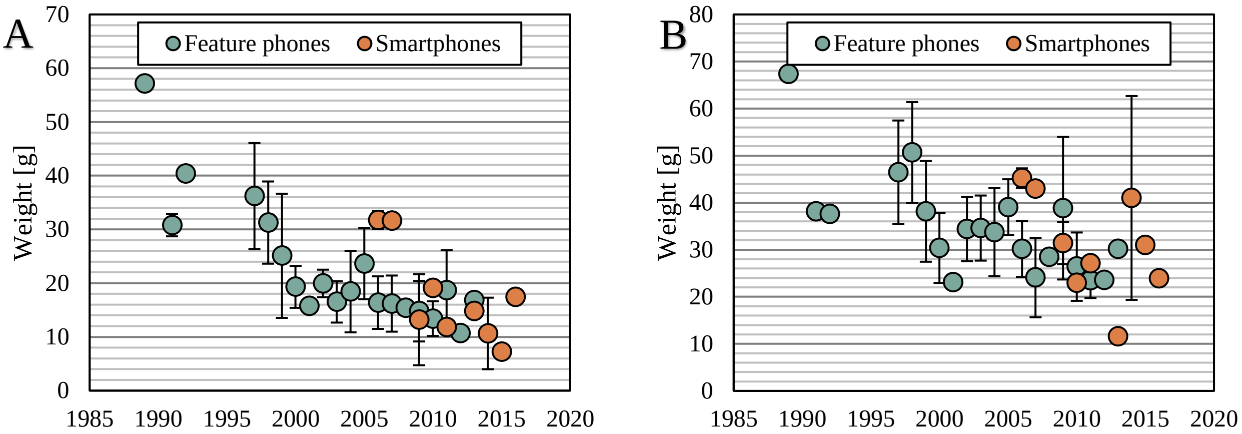


Figure 4. Composition of the studied waste feature phones and smartphones: (A) PCBs, (B) plastic components, (C) metal components and (D) other electronic components, compared to literature data

Considering the average macro-composition of the 2 data sets along the whole 28-years period, the main difference that stands out is the decrease of plastic (from 46 % wt. in feature phones to 37 % wt. in smartphones) in favour of an increase of metals (8 % in feature phones and 25 % in smartphones). Whereas the other components remained in a similar range: PCBs represent 29 % wt. of feature phones and 21 % wt. of smartphones, while other electronic parts had the same relative abundance (17% wt.) in feature phones and smartphones. The percentage of PCBs' weight in feature phones is considerably higher than literature data (where, however, the number of analysed samples was significantly lower than in this study). Smartphones' macro-composition, instead, is in trend with the findings of Tan et al., 2017, who analysed waste mobile phones produced between 2005 and 2011, comparable to the here-considered data set. Plastics sits perfectly in the wide concentration range set by literature data, from a minimum of 26 % wt. (Tan et al., 2017) to a maximum 61 % wt. (Bachér et al., 2015). Metals and other electronic components show results in accordance with previous studies, even if metals in smartphones are slightly higher.



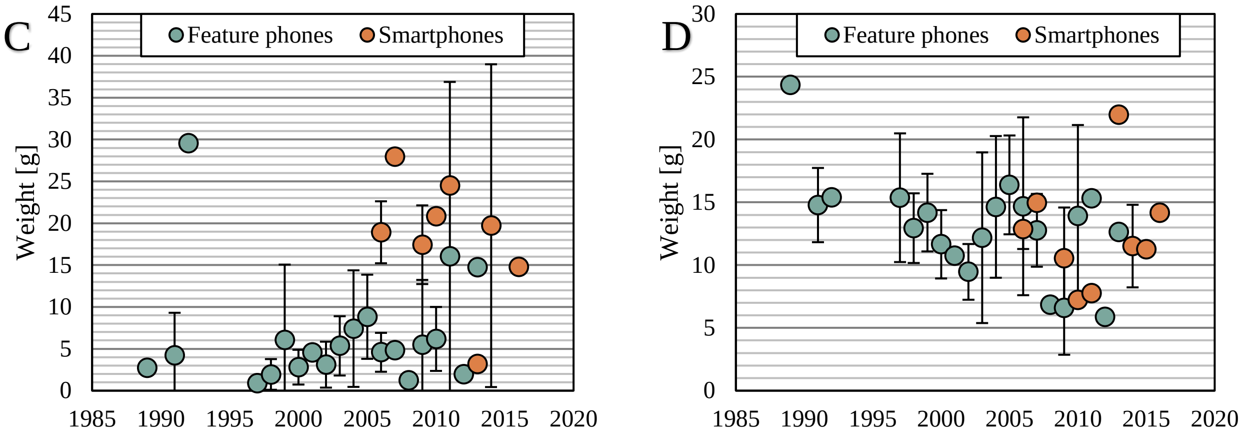
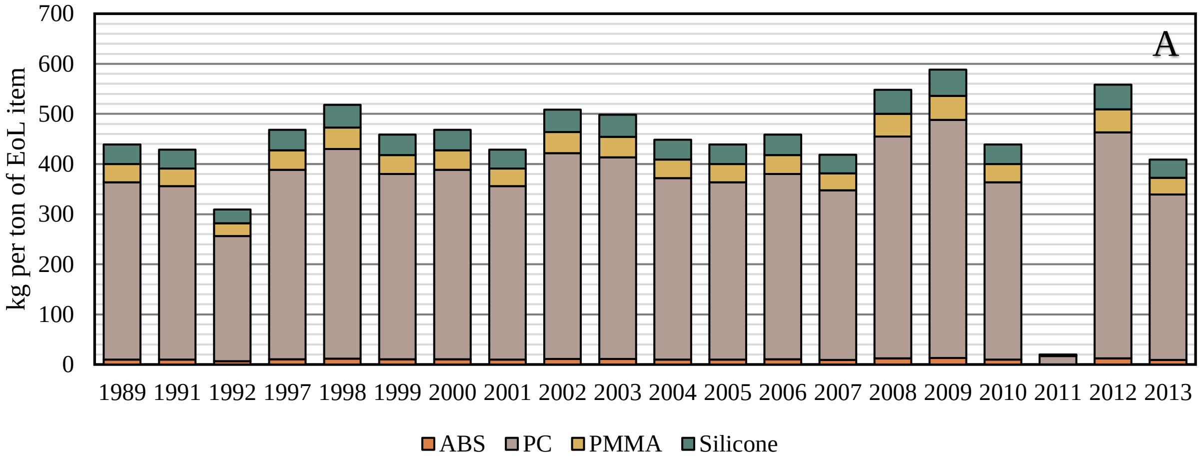
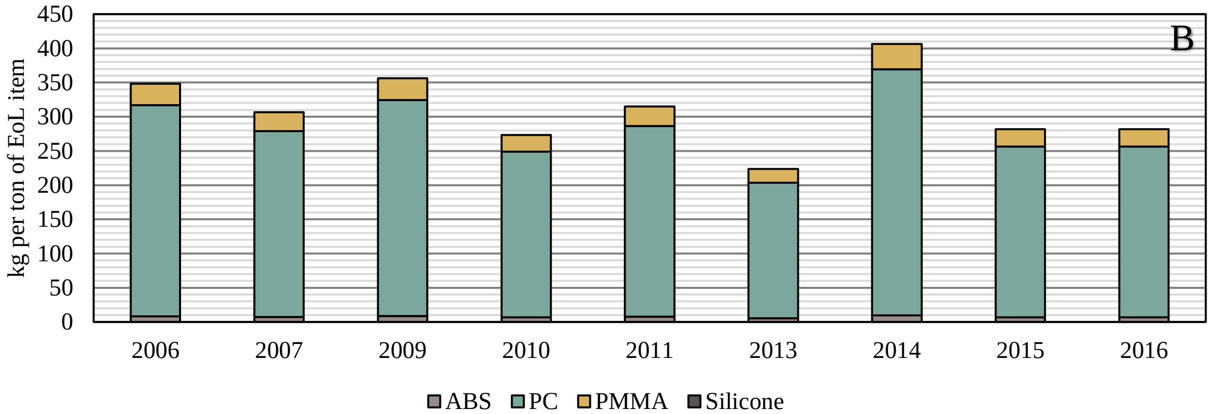


Figure 5. Temporal evolution of macro-components' mass [g] for (A) PCBs, (B) plastics, (C) metals and (D) other electronic components in the analysed feature phones and smartphones

Considering the temporal evolution of the items' weights over the studied period (1989-2016), a clear decreasing trend appears in the evolution of the weight of the single macro-components (PCB, plastics, metals and other electronics) (Figure 5). The changes in feature phones and smartphones macro-composition registered over time are linked to the observed general drop in the overall weight of the items. A clear decrease in the weight of PCBs (Figure 5A) and plastic components (Figure 5B) was observed in feature phones and in smartphones in the considered time period. The range of values recorded for PCBs from feature phones was maximum 57.16 g in 1989 and minimum 10.70 g in 2012 (-81 %), with an average weight of 22.84 ± 11.31 g; smartphones' PCBs have almost always been lighter, passing from 31.73 g in 2006 to 7.25 g in 2015 (-77 %), with an average weight of 17.50 ± 8.76 g. Plastic components dropped from 67.35 g in 1989 to 23.06 g in 2012 for feature phones (-66 %; average 34.94 ± 10.74 g) and from 45.22 g in 2006 and 11.57 g in 2013 for smartphones (-74 %; average 30.79 ± 10.91 g). The metallic components (Figure 5C) didn't show any particular time-related pattern; in feature phones (average 6.63 ± 6.71 g) stretched within 29.55 g in 1992 and 1.95 g in 2012, showing an abrupt increase to 14.76 g in 2013; in smartphones (average 21.00 ± 10.40 g) they varied from a minimum of 3.18 g in 2013 to a peak of 41.74 g in 2015. However, considering that in recent years smartphones became much more common than feature phones, it may be assumed that in overall the composition of mobile phones transitioned towards higher amounts of metallic components (+12 % in smartphones compared to feature phones). Other electronic components (Figure 5D) exhibited high variability in feature phones (average 13.03 ± 4.09 g), decreasing from 24.35 g in 1989 to 5.88 g in 2012 (-76 %); while for smartphones (average 12.48 ± 4.41 g), for which the minimum and maximum weight of other electronic components have been reported in two following years, 7.22 g in 2010 and 21.98 g in 2012, no specific decreasing nor increasing trend was observed. The results of the macro-characterisation performed in this study, combined with previous works focused on the characterisation of plastic (Fontana et al., 2019) and metallic components of mobile phones (Jing-ying et al., 2012; Jyothi et al., 2020; Kasper et al., 2011; Maragkos et al., 2013; Sahan et al., 2019; Xiu et al., 2015; Yamane et al., 2011), allowed to estimate how the composition of the analysed waste mobile phones evolved over the considered period of time (Figure 6).





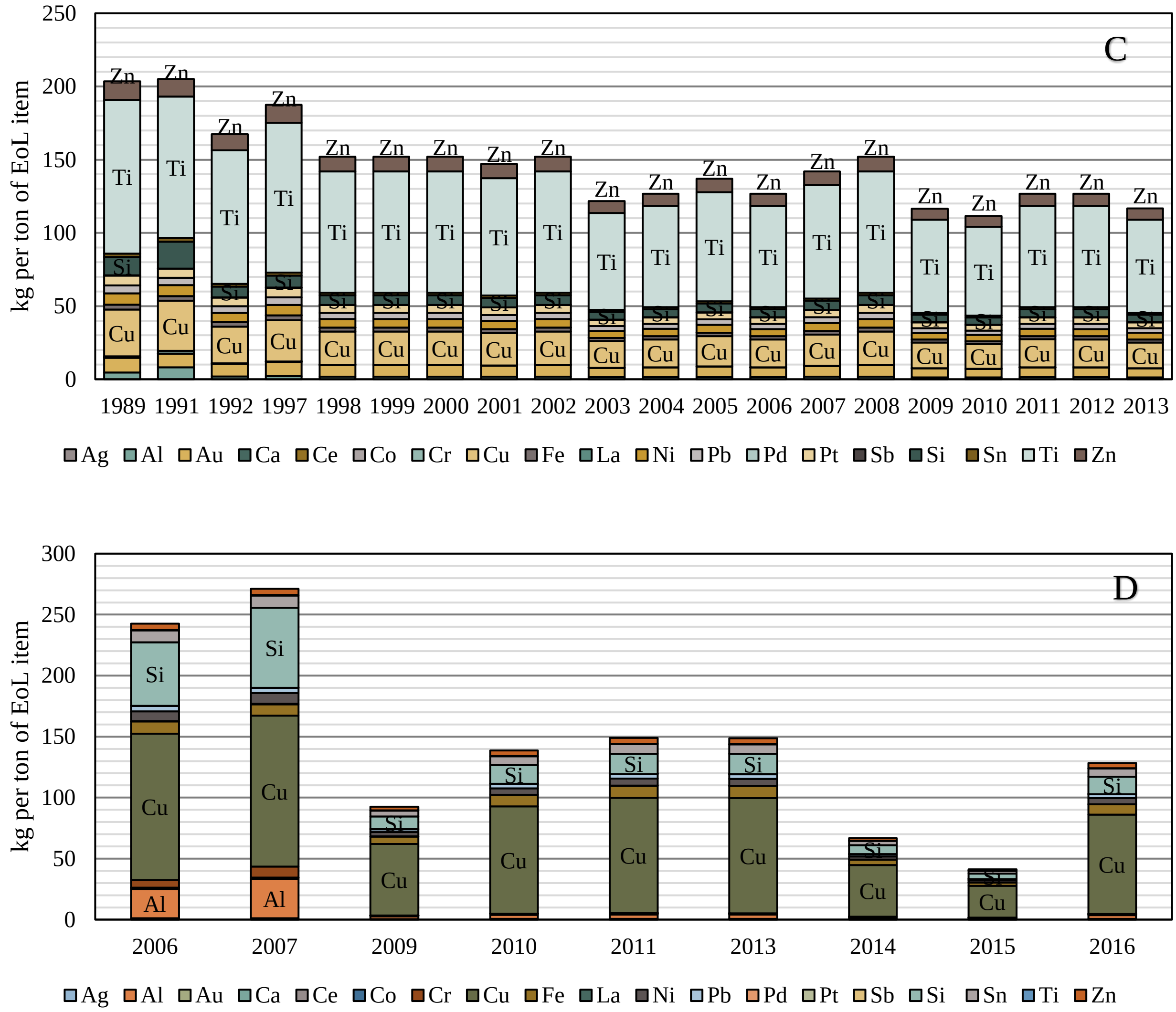


Figure 6. Characterisation of the macro-components: plastics (in (A) feature phones and (B) smartphones) and metals in metallic components and in PCBs (in (C) feature phones and (D) smartphones)

The main difference observed among the polymers contained in the 2 data sets was the absence of silicone in smartphones, as this material is characteristic of the keypads in feature phones. The other polymers showed similar trends, and PC was the most common. Conversely, the composition of metals exhibited major differences: the most common metals in feature phones were Ti, Cu, Si and Zn, while in smartphones the main metallic elements were Cu, Si and Al until 2008 and Cu, Si, Fe and Sn from 2009. The main trends observed in feature phones were the decreases in Si and Cu contents over the years, which are consistent with the decrease in PCBs weight (Figure 5A).

Considering CRMs, Co and Pd have been found only in smartphones (on average 20 mg/kg of Co and 53 mg/kg of Pd); Pt, Sb and Ti were present in both data sets, with higher concentration values in feature phones (on average 5.11 mg/kg of Pt in feature phones and 0.01 mg/kg in smartphones; 80.13 mg/kg of Ti in feature phones and 0.21 mg/kg in smartphones) . Concentrations of CRMs exceeded the grade of mineral ores for virgin metal extraction for Pd in smartphones, for Ti in feature phones and for Pt in both data sets. Specifically, smartphones' PCBs show an average concentration of Pd equal to 53 mg/kg, which is one order of magnitude higher than mineral ore concentration (2 - 7 mg/kg) (Robinson et al., 2011); while Pt concentrations (5107 mg/kg in feature phones and 5 mg/kg in smartphones) exceed mineral ore grades (2 - 4 mg/kg) (Robinson et al., 2011) and, eventually, Ti concentration in feature phones (on average 80,127 mg/kg) is above profitable mineral ores grade (25,000 mg/kg) (Kyocera SGS, 2021). Besides, other valuable elements that showed concentration values higher than mineral ore grade, both in feature phones and smartphones, were Au and Cu. Au mineral ore grade (5 - 30 mg/kg) (Kongolo and Mwema, 1998) is considerably below the 7119 mg/kg and 523 mg/kg respectively estimated in the PCBs of feature phones and of smartphones, while Cu concentrations in both samples sets (34,098 mg/kg in feature phones and 105,839 mg/kg in smartphones) exceed the 5,000 - 20,000 mg/kg characteristic of mineral ores (Schlesinger and Biswas, 2011).

3.3. Statistical analysis

The statistical analysis (Appendix, Table IV) returned a result below the critical value for each data distribution considered, therefore according to the results of the T test the macro- composition of the waste feature phones and the smartphones were different.

Pearson correlation coefficients (R^2) have been calculated between the total weight of each item and the dimension of its macro-components. PCBs and plastic, among all components, showed the highest correlation with the weight of the total sample, reaching R^2 0.796 for plastics and 0.660 for PCBs. PCBs' weight decreased over time, with a Pearson correlation coefficient between PCBs' weight and lifetime equal to 0.657, in agreement with the evolution of PCBs' design over the years reported by literature (Liu et al., 2019; Menad et al., 2013; Palmieri et al., 2014).

3.4. Economic analysis

The economic profitability of manual dismantling was analysed comparing the manual dismantling costs and the potential incomes related to the market values of potentially recyclable materials and recoverable macro-components. As the costs, manual dismantling scored 6.93 €/item, considering the average EU labour cost, and 1.50 €/item, considering the minimum EU labour cost. Despite the relatively high disparity in the resulting data, stemming from the intrinsic variability of the analysed items, the specific cost of manual dismantling per mass unit (1 kg) of waste devices displayed a growing trend over the years (Appendix, Figure IV).

Considering the incomes, the potential market value per item of the dismantled mobile phones decreased over the years as well as the weight of the devices. The estimate of the potential incomes from the sale of the materials and macro-components separated from the waste devices (Appendix, Figure V) allowed to evaluate the evolution of the specific market value of feature phones and smartphones (Appendix, Figure VI), calculated in 0.12 ± 0.06 €/item for feature phones (minimum 0.06 in 2012, maximum 0.30 in 1989) and 0.10 ±0.04 €/item for smartphones (minimum 0.05 in 2015, maximum 0.18 in 2007). The PCB was the most valuable component, representing from a minimum 87 % (in 2013) to a maximum 94 % (in 1989) of the value of a single item for feature phones (average 90 ± 2 %) and from a maximum 91% (in 2013) to a minimum 64% (in 2015) for smartphones (average 84 ± 9%). Thus, the observed PCBs' weight decrease (Figure 5A) implied a declining in the specific market values of the items throughout the considered period of time. This statement is supported by the fact that the most valuable components (Au and Pt in feature phones and Au, Ce, and Pd in smartphones) (Appendix Figure V) are part of the PCBs. The plastic components, despite representing almost 40 % wt. of the considered items (Figure 6A and B), did not entail significant revenues (Appendix, Figure VI), due to the low market value assigned to the "plastic mix" fraction. Conversely a higher exploitation of the plastic mix, based on the separation of the polymeric materials not containing brominated flame-retardants, which being recyclable entail higher economic value, could improve the economic performance of the EoL mobile phones recycle and recovery scenario.

The economic balance of manual dismantling appears initially (from the perspective of the considered period) profitable both for feature phones and smartphones (Appendix, Figure VIIA), nevertheless, both sample sets show a decreasing trend over the years, leading to a current situation of non-profitability due to the market value decrease of the waste items previously observed. Alongside, the maximum cost of labour necessary to achieve the economic profitability of manual dismantling (Appendix Figure VII B) declines over time falling below European standards (Eurostat, 2020b). The worst cases are represented by a maximum value of labour cost (i.e., necessary to guarantee the economic profitability of manual dismantling) equal to 10.40 €/h for feature phones (in 2012) and 16.76 €/h for smartphones (in 2013), not corresponding to European standards (Eurostat, 2020b). A recent study (Liu et al., 2020) referring to the Chinese context demonstrated the economic profitability of mobile phones' manual dismantling followed by the hydrometallurgical recycling of valuable metals.

4. Conclusions

This work presented a detailed characterisation of 100 waste mobile phones (i.e., the one-week inflow of waste mobile phones entering one of the largest WEEE treatment plants in Italy), showing how the relative percentages of their macro-components evolved over nearly 3 decades. Our study provided a snapshot of the composition of waste mobile phones in 2018, which is without any doubt different from what happened in the consequent years due to the prevalence of smartphones over feature phones on the market after 2006-2007. However, the Covid-19 pandemic had relevant effects on the global consumption patterns in 2020-2021, and consequently also on the amount and composition of the waste flows. Therefore, we consider 2018 data still reliable in the description of the pre-pandemic situation. While along the whole manufacturing period (1989-2016) of the considered 100 mobile phones the main component was plastic (46 %-wt. in feature phones and 37 %-wt. in smartphones), over the years PCBs' weight and plastic's content varied (respectively -80% and -70%), as well as metal components' amount (+12 %), especially for smartphones. The average cost of manual dismantling along the whole period was estimated as 6.93 € per item according to EU average labour costs and 1.50 € per item based on minimum EU labour costs.

In conclusion, on the grounds of the existing literature (Robinson, 2009; Cesaro et al., 2018; Man et al., 2013), from the points of view of the environmental impacts and health risks related to eventual incorrect management operations, manual dismantling happening in EU followed by the sale of separate materials and components is an option preferable to the diversion of waste intact items towards international routes and countries characterized by lower labour costs than Europe. However, the results of our study proved that in 2018 in Europe the manual dismantling of waste mobile phones was not economically profitable. A WEEE treatment plant could afford the manual dismantling of EoL mobile phones only if other profitable WEEE categories (i.e., white goods and large appliances) are managed in the same site. This situation will probably last for the actual decade. Current EU policies and regulations based on Circular Economy consider the application of eco-design principles to EEE essential to fulfil the ambitious recycling targets set for WEEE for 2030 and 2050. Specifically, the application of eco-design to mobile phones, aimed at decreasing the complexity of manual dismantling of waste items and at improving their recyclability (particularly of the plastic components), will be considered crucial in overcoming the above-mentioned bottlenecks in the next decades.

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