

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

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(Article begins on next page)

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

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7

8 **Highlights**

- 9 - 100 waste mobile phones were identified, dismantled, and characterized
- 10 - trends related to their macro-composition over 28 years were compared and discussed
- 11 - electronics and plastics components' weight decreased, while metals increased
- 12 - a cost-benefit analysis of manual dismantling was performed
- 13 - manual dismantling was not found economically profitable in the EU context

14

15 **Abstract**

16 This work presents a systematic characterization of 100 waste mobile phones (73 feature phones and
17 23 smartphones) produced between 1989 and 2016. All items were inventoried and the evolvement
18 of the relative abundances of their macro-components (mechanic and electro-mechanic parts,
19 electronics and others) and materials was investigated. The average lifetime was 15.1 years for feature
20 phones and 6.4 years for smartphones. The main component was plastic, on average 46%-wt. in
21 feature phones and 37%-wt. in smartphones; over the years electronics' and plastic's amounts

22 decreased (respectively 80 % and 70 %), while metal components' amount increased (12 %). A cost-
23 benefit analysis explored the profitability of the management of waste mobile phones through manual
24 dismantling followed by the sale of the separated components and materials. The average cost of
25 manual dismantling was estimated as 6.93 €/per item according to EU average labour costs and 1.50
26 €/per item based on minimum EU labour costs. According to the performed economic analysis, the
27 actual market prices for the potentially recoverable materials and components of waste mobile phones
28 were not able (particularly mixed plastics) to counterbalance the costs of manual dismantling
29 according to the European standard labour costs.

30

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

32

33 **1. Introduction**

34 Waste from electric and electronic equipment (WEEE) is one of the fastest growing waste streams
35 worldwide; its production soared from 44.4 Mt in 2014 to 53.6 Mt in 2019 and it is expected to reach
36 74.7 Mt by 2030 (Forti et al., 2020). WEEE management has always been a critical issue; in 2019 the
37 recycling rate topped at 17.4 % of globally generated e-waste, leaving behind almost 44.3 Mt of
38 residual waste dumped in landfills or improperly recycled (Forti et al., 2020). In the past decade
39 WEEE generation rate and recycling quota increased at different pace; the annual growth of WEEE
40 recycling from 2014 to 2019 was 0.4 Mt, while the generation rate increased almost 2 Mt each year
41 (Forti et al., 2020). The highest collection and recycling rates have been reported in Western (54 %)
42 and Northern (59 %) Europe in 2017 (Forti et al., 2020).

43 Among WEEE, small IT appliances as mobile phones (i.e., feature phones and smartphones) are
44 recently gaining attention. According to most recent statistics (Eurostat, 2020a) in 2017 mobile
45 phones represented less than 15 %-wt (equivalent to 0.55 Mt) of the total collected WEEE under the

46 category “IT and telecommunications equipment” (3.76 Mt) in EU-27. This is due to their light weight
47 compared to other larger WEEE. However, considering the number of waste items, mobile phones
48 stand out because of two key issues. Firstly, the fast rate of new items put on the market (according
49 to the United Nations, in 2017 Europe imported over 210 million mobile phones) (UN, 2017).
50 Secondly, the consumers’ tendency to consider obsolete their mobile phones much earlier than their
51 intended lifetime: after only 3 years in developing countries and 2 years in developed countries (Soo
52 and Doolan, 2014). WEEE generation shows direct correlation with gross domestic product (Arya
53 and Kumar, 2020; Torretta et al., 2013; Awasti et al., 2018): in the western world the average number
54 of obsolete mobile phones owned per capita is higher than 1. In details, in high/middle income
55 households (average purchasing power equal to 21,697 USD/y), the average number of owned mobile
56 phones is 1.2 per capita; in high income households (average purchase power equal to 51,581 USD/y),
57 the average number of owned phones reaches 1.4 per capita (Forti et al., 2020). The fast pace at which
58 mobile phones are dismissed, combined with their peculiar composition of valuable and hazardous
59 elements make their management a strategic issue. Small IT and communication waste appliances are
60 often traded in international routes (Robinson, 2009). Uncontrolled recycling activities could be
61 highly hazardous for human health and the environment (Cesaro et al., 2018), and they happen mostly
62 in developing and underdeveloped countries (Man et al., 2013). A recent study (Liu et al., 2021)
63 demonstrated that the key factors driving WEEE recycling are the incentives from the government
64 and the producers taking responsibility for recycling. Another research (Yang et al., 2021) calculated
65 that global WEEE recycling could provide 3 million job opportunities per year; the same authors also
66 estimated an environmental load (i.e., the cost required to offset the environmental impacts) equal to
67 1-9 USD/kg, proposing a WEEE emission trading system aimed at reducing the related carbon
68 emissions.

69 Electronics and ICT items are included in the key product value chains of the European Circular
70 Economy Action plan and of the European Green Deal launched in 2020. In a circular economy
71 perspective, waste mobile phones represent a valuable resource for urban mining, since precious

72 metals and critical raw materials showed relatively high concentrations in waste mobile phones
73 (among the others: Charles et al., 2020; Sahan et al., 2019; Tesfaye et al., 2017; Tunsu et al., 2015).
74 Besides, mobile phones composition is characterised by roughly 40 %-wt plastics, mainly
75 polycarbonate (PC), acrylonitrile-butadiene-styrene (ABS) and polymethylmethacrylate (PMMA) as
76 housing components, (e.g., covers, cases and frames), and PMMA and silicone for display windows
77 (Fontana et al., 2019). Specifically considering waste mobile phones' characterization, literature
78 mostly focus on the investigation of the composition of single material components, as plastics
79 (Martinho et al., 2012; Nnorom and Osibanjo, 2009; Palmieri et al., 2014; Sahajwalla and Gaikwad,
80 2018) or metals (Islam et al., 2020; Marra et al., 2018; Sahan et al., 2019; Tesfaye et al., 2017). When
81 a more general characterisation is involved, the experimental activity reported in literature is limited
82 to a narrow set of samples, from 2 (Bachér et al., 2015) to 10 (Tan et al., 2017) or 20 items (Fontana
83 et al., 2019).

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

94 Current waste mobile phones treatment technologies at industrial scale consist of: pre-treatment via
95 manual disassembly and shredding, followed by material separation based on different properties
96 (dimensions, density, magnetic and electrostatic behaviours, etc.) and finally material recovery
97 through acids extraction or purification of the metal concentrate (Gu et al., 2019). Disassembly is

98 usually performed manually, as the high variability of items' design hinders the profitability of
99 automatic disassembly (Bachér et al., 2015). Li-ion batteries may cause combustion hazard (Huang
100 et al., 2018), thus they are removed before manual disassembly according to the EU regulations; in
101 this case recycling has been reported to bring the highest environmental benefits (Gu et al., 2019).
102 Automatic shredding is usually involved in waste mobile phones pre-treatment to facilitate the
103 subsequent separations steps (Gu et al., 2019). The technical feasibility of mechanical pre-treatments
104 has already been investigated, and manual dismantling showed to ensure better quality in the
105 separated components compared to automatic separation (Bachér et al., 2015). Other studies
106 investigated the economic aspects of mobile phones' recycling (Sarath et al., 2015), and reuse and
107 recycling operations were compared (Geyer and Blass, 2010) based on datasets from UK in 2003 and
108 US in 2006, concluding that the economic profit stems from mobile phone reuse rather than recycling,
109 for which profitability could never be achieved even with minimized reverse logistic costs; however,
110 an exhaustive cost/benefit analysis was not performed. The disassembly of the LCD screen of
111 multiple mobile phones (Sawanishi et al., 2015), or of a whole single mobile phone was also
112 investigated (Sebo and Fedorcakova, 2014) to identify the optimal management strategy considering
113 the recycling of the camera and PCB, and the disposal of the remaining components. An estimate of
114 the secondary raw materials potentially recyclable from mobile phones (Gurita et al. 2016)
115 demonstrated positive environmental and economic outcomes if the collection rate is substantially
116 improved and if the recycling operations are focused on precious metals and critical materials.
117 To our knowledge, literature on waste mobile phones is still lacking a detailed cost/benefit analysis
118 of manual dismantling specifically aimed at optimizing secondary raw materials' recycling and
119 components' recovery, also considering how the composition of mobile phones changed over the
120 years.
121 Compared to existing literature, this work aims to answer 2 research questions (RQs): RQ1. how have
122 mobile phones' composition evolved along 28 years on 100 waste items, in a recycle-oriented
123 perspective? RQ2. is manual dismantling economically profitable according to actual EU labour costs

124 and market values of recyclable and recoverable components? The main goal of this work is to
125 understand the influence of waste mobile phones' composition on the economic profitability of their
126 pre-treatment based on manual dismantling followed by the separate sale of single components and
127 materials in a European context.

128

129 **2. Materials and methods**

130 **2.1. Samples origin**

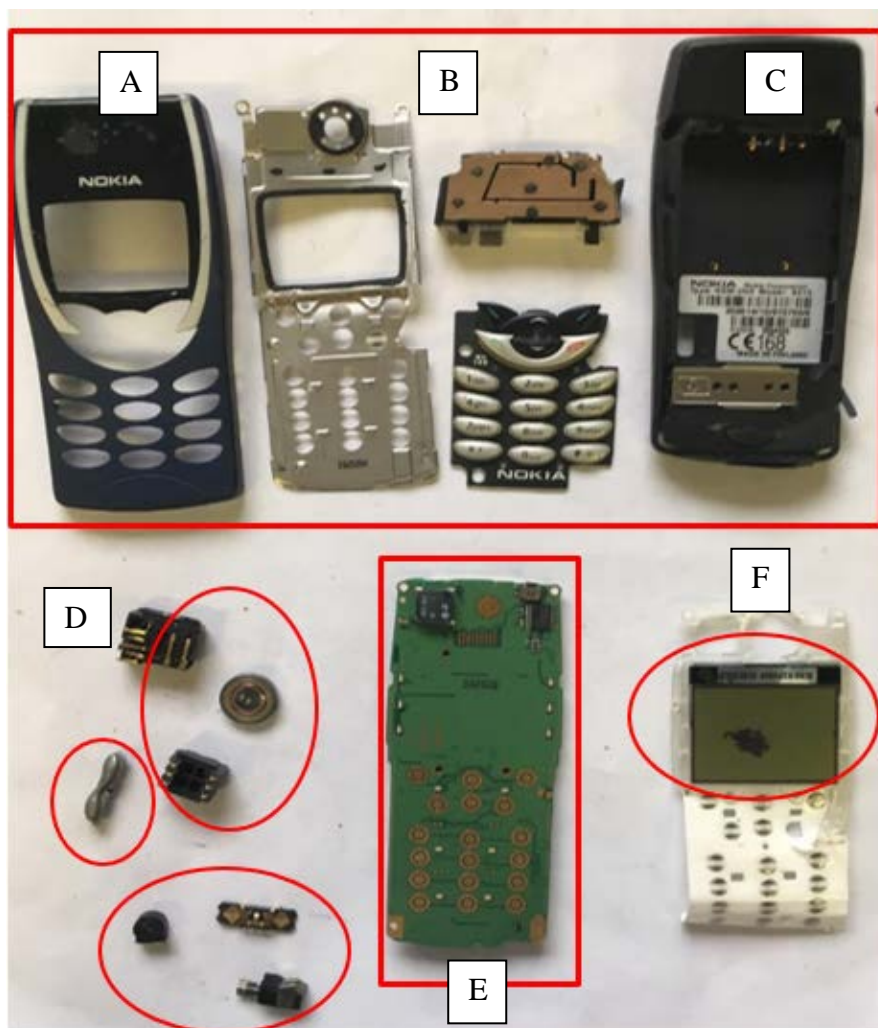
131 100 waste mobile phones (73 feature phones and 27 smartphones) were provided in 2018 by a WEEE
132 treatment plant near Turin, one of the largest in Italy. The waste mobile phones arrived at the
133 treatment plant deprived of the batteries, according to the Italian regulations. The size of the sample
134 (100 items) was equal to the inflow of waste mobile phones arrived at the plant in one week. The 100
135 items have been collected randomly within each of the two types of waste mobile phones, defining
136 in advance the relative abundances of feature phones (5.56 kg) and smartphones (2.17 kg) according
137 to the up-to-date input flows to the plant. The inflow of the WEEE treatment plant at the moment of
138 the sampling was made of 70-75 % feature phones and 25-30% smartphones (% referred to the
139 number of items, not to their weight).

140 **2.2. Samples' characterisation**

141 The first step was the setup of an inventory: the waste mobile phones were identified one by one,
142 searching brand, model and year of production on technical databases available online (as an example,
143 <https://puntocellulare.it/cercafonino/index.html>, *in Italian*). This information allowed to evaluate the
144 lifetime of the single items and the relative abundance of items belonging to specific brands and
145 models (without, of course, pretending to perform a market analysis). The lifetime was estimated as
146 the difference between the year of production of a single item and the year of collection from the
147 WEEE treatment plant (2018). Afterwards, the 100 items were manually dismantled into the

148 following macro-components (Figure 1): mechanical parts (cases, covers, keyboards and buttons),
149 electro-mechanical parts (microphones, speakers, displays and headpieces), electronics (printed
150 circuit board, PCB) and others (batteries, SIM and SD cards). The single macro-components have
151 been weighted through a PLJ42002F technical scale, and a mass balance was performed for each item
152 and included in the inventory.

153



154

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

159

160 The data related to the macro-composition (detailed in Figure 1) of the items commercialized in the
161 same year were merged to achieve an “average composition”, then different years were compared to
162 evaluate its temporal evolution. The detailed composition of the single dismantled items was
163 described according to literature (choosing studies spread between 2011 and 2020), with the
164 approximation of considering the same average composition for each component along the whole
165 period 1989-2016 for all the 100 items. In details, the plastic components of the feature phones were
166 acknowledged as: 2.2 % ABS, 80.5 % PC, 8.2 % PMMA and 8.8 % silicone (Fontana et al., 2019).
167 Since silicone was found exclusively in the keypads of the feature phones, the plastic components of
168 the waste smartphones were described as: 2.4 % ABS, 88.3 % PC and 9.0 % PMMA, excluding
169 silicone. For all items, the composition of the electro-mechanical parts was considered as: 2.00 g/kg
170 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
171 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
172 composition of the PCBs was calculated as average from different literature studies (Jing-ying et al.,
173 2012; Jyothi et al., 2020; Kasper et al., 2011; Maragkos et al., 2013; Sahan et al., 2019; Xiu et al.,
174 2015; Yamane et al., 2011): 0.58 % Al, 2.61 % Au, 0.07 % Ca, 7.62 % Cu, 0.90 % Fe, 1.95 % Ni,
175 1.39 % Pb, 1.76 % Pt, 2.21 % Si, 0.57 % Sn, 27.63 % Ti and 3.35 % Zn. Finally, the concentration
176 trends of the critical raw materials (CRMs) (Blengini et al., 2020), were compared to the reported
177 grade of mineral ores for virgin metals mining (Allegrini et al., 2014).

178

179 **2.3. Statistical analysis**

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

185

186 **2.4. Economic analysis**

187 The economic profitability of manual dismantling of the waste mobile phones was assessed through
188 an itemized cost-benefit analysis. The costs were calculated considering the average EU cost of labour
189 (27.7 €/h) and the lowest reported labour cost in a member state (i.e. 6.0 €/h in Bulgaria) (Eurostat,
190 2020b). This research was based on the assumption of keeping the management of the waste mobile
191 phones (and therefore the related job places and the recovered secondary and critical raw materials)
192 collected in EU inside the member states, according to the current Circular Economy policies and
193 regulations. The time required to manually separate the different macro-components was accounted
194 as 4 items per hour (this duration was defined as average value after recording the dismantling
195 operations for an 8-hours shift in the WEEE treatment plant that supplied the items).

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

202 The incomes were estimated considering the following actual market values: 5.000 €/t for PCBs, 130
203 €/t for plastic components, 180 €/t for other electronic components. A market value of 280 €/t was
204 considered for steel scraps (Eurostat, 2020c). The details of the market values of plastic components
205 and metals are provided in the Appendix (Table I) with the related references.

206

207 **3. Results and discussion**

208 **3.1. Samples' origin**

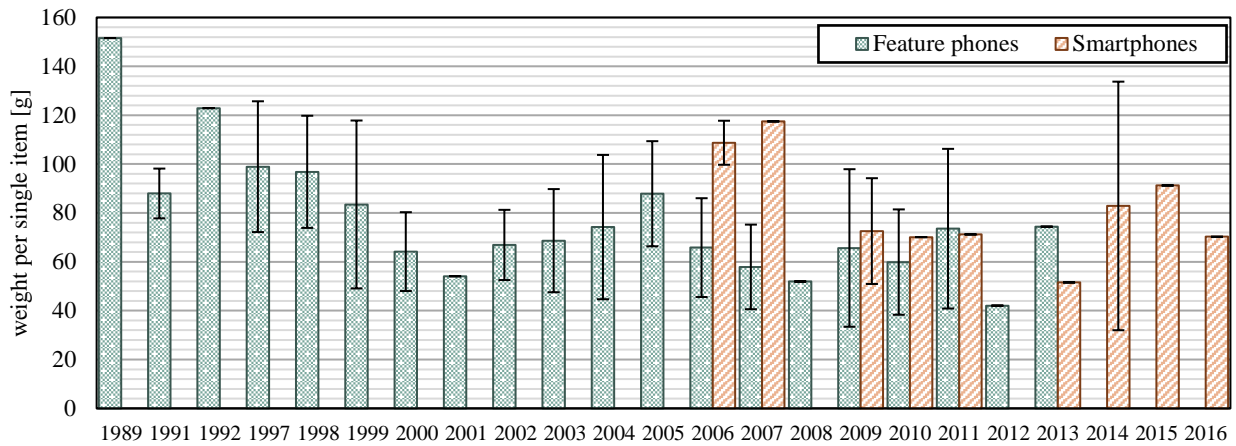
209 According to the compiled inventory (Appendix, Tables II and III, Figure I), the waste mobile phones
210 considered in this work were put on the market in a 28-years period between 1989 and 2016. Feature
211 phones were sold between 1989 and 2013 by 14 manufacturers: smartphones between 2006 and 2016
212 by 9 manufacturers (Appendix, Figure II). Five out of nine feature phones manufacturers produced
213 82 % of the collected items; within the inventoried 100 items, Nokia produced 47 % of the feature
214 phones, whereas for the smartphones Samsung (33 % and Nokia (26 %) were the most common
215 producers identified. The lifetime was equal to 15.1 ± 4.88 years for feature phones (minimum 5,
216 maximum 29) and 6.37 ± 3.18 years for smartphones (minimum 2, maximum 12) (Appendix, Figure
217 III). These results offer an interesting insight on the duration of the “effective lifetime” of mobile
218 phones (probably implying several owners and/or extended shut off periods), which resulted much
219 higher than the 2-3 years of lifetime reported by literature (Soo and Doolan, 2014) and intended as
220 the duration of the possession of a mobile phone by a single owner. A recent study (Shaikh et al.,
221 2020) identified storage as preferred option for obsolete mobile phones.

222

223 **3.2. Mass balance**

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

231

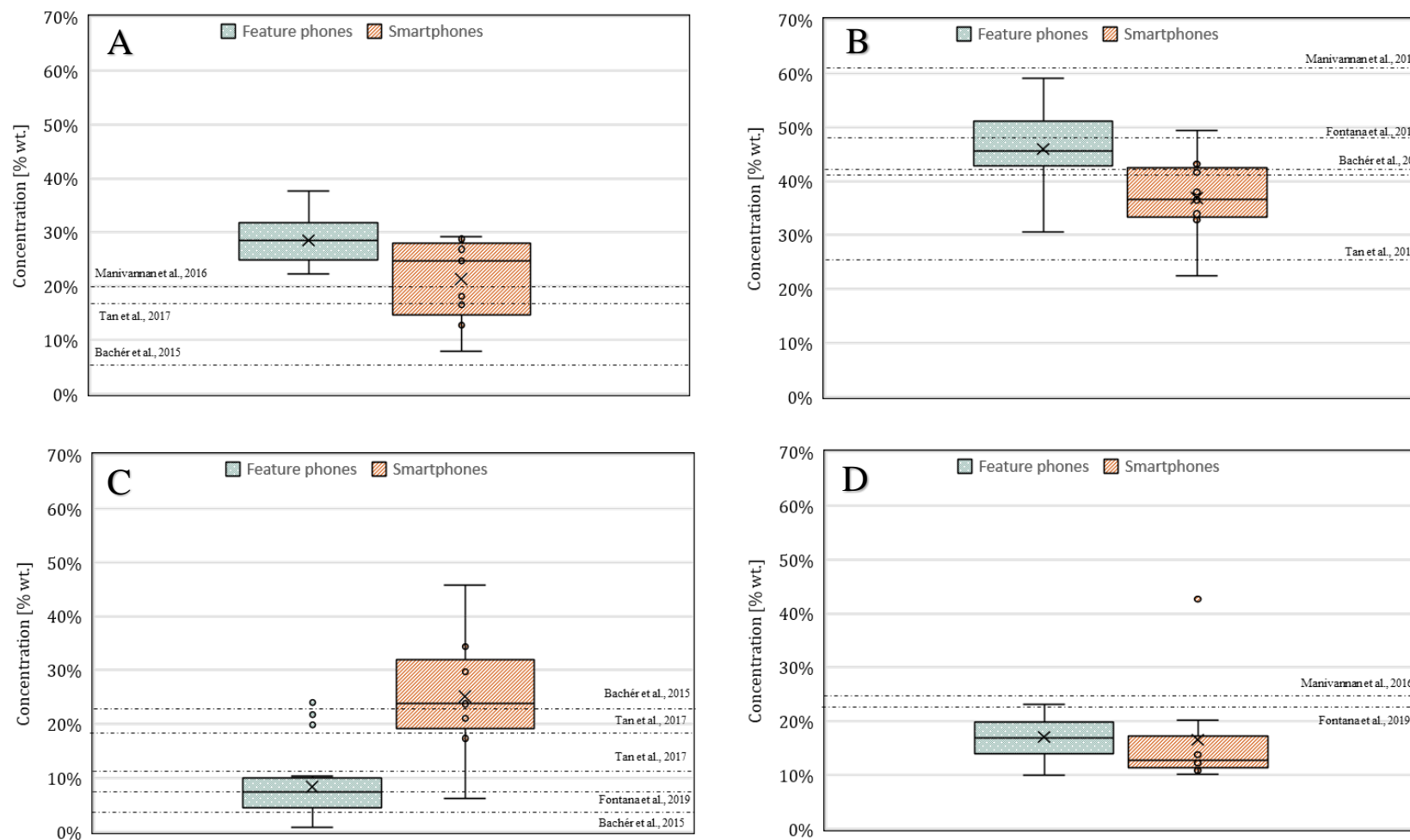


232

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

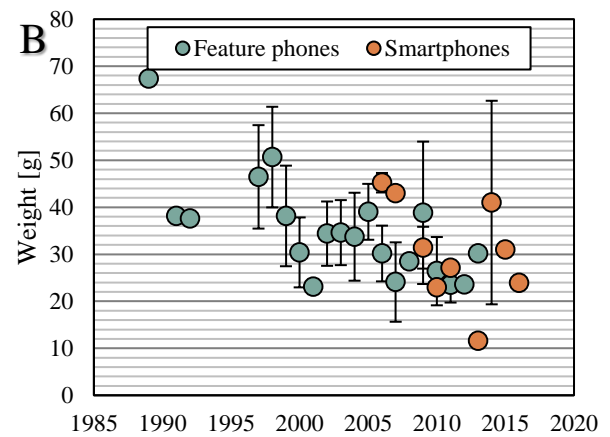
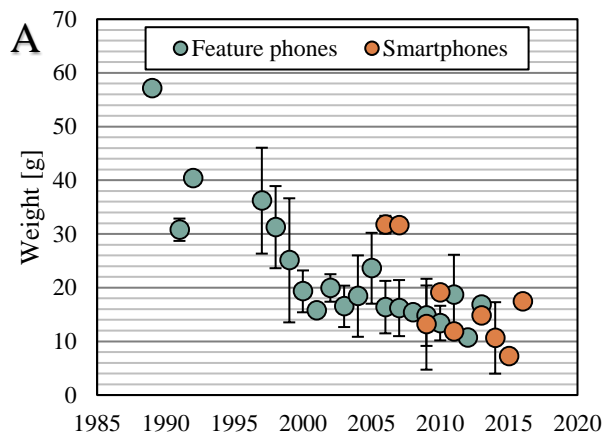
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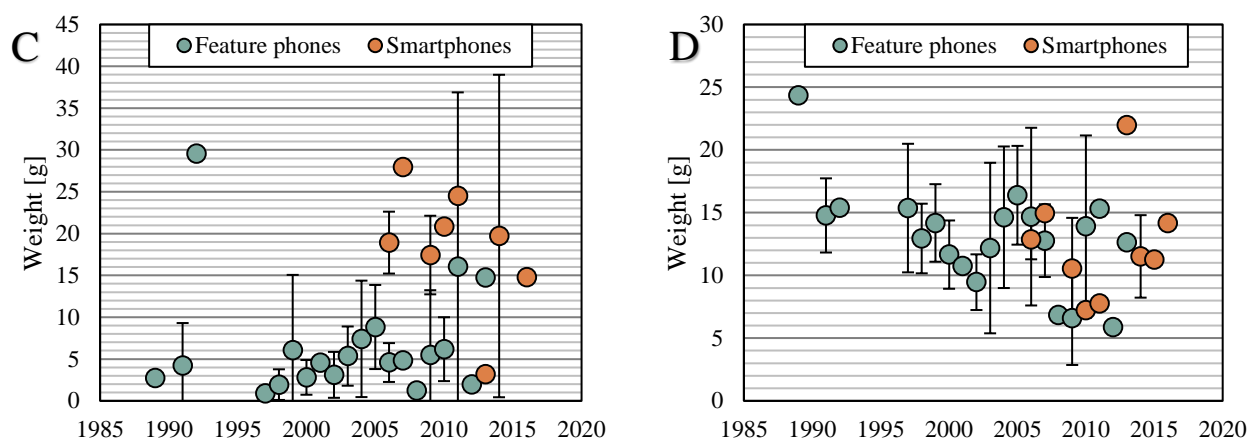
235 From the overall mass balance (Figure 4) resulted that the main macro-component of waste mobile
 236 phones was plastic, representing $46 \pm 7\%$ wt in feature phones and $37 \pm 8\%$ wt in smartphones. The
 237 other components of feature phones were PCBs ($29 \pm 5\%$), other electronic elements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



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

245 Considering the average macro-composition of the 2 data sets along the whole 28-years period, the
 246 main difference that stands out is the decrease of plastic (from 46 % wt. in feature phones to 37 %
 247 wt. in smartphones) in favour of an increase of metals (8 % in feature phones and 25 % in
 248 smartphones). Whereas the other components remained in a similar range: PCBs represent 29 % wt.
 249 of feature phones and 21 % wt. of smartphones, while other electronic parts had the same relative
 250 abundance (17% wt.) in feature phones and smartphones. The percentage of PCBs' weight in feature
 251 phones is considerably higher than literature data (where, however, the number of analysed samples
 252 was significantly lower than in this study). Smartphones' macro-composition, instead, is in trend with
 253 the findings of Tan et al., 2017, who analysed waste mobile phones produced between 2005 and 2011,
 254 comparable to the here-considered data set. Plastics sits perfectly in the wide concentration range set
 255 by literature data, from a minimum of 26 % wt. (Tan et al., 2017) to a maximum 61 % wt. (Bachér et
 256 al., 2015). Metals and other electronic components show results in accordance with previous studies,
 257 even if metals in smartphones are slightly higher.
 258



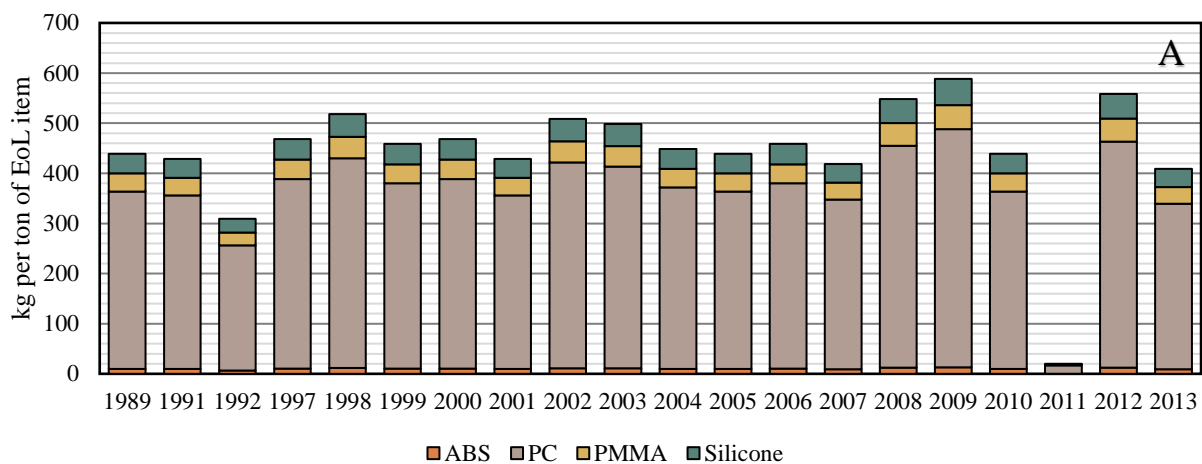


259 **Figure 5.** Temporal evolution of macro-components' mass [g] for (A) PCBs, (B) plastics, (C) metals
 260 and (D) other electronic components in the analysed feature phones and smartphones

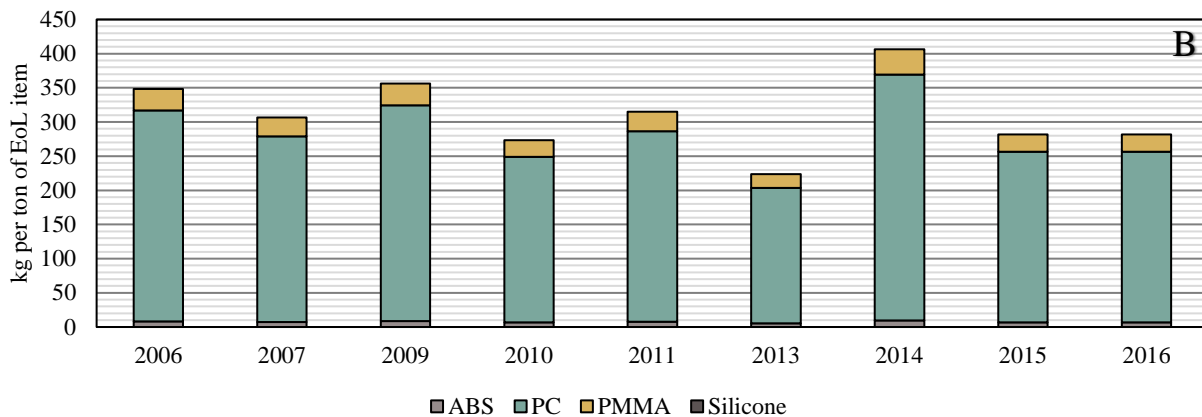
261

262 Considering the temporal evolution of the items' weights over the studied period (1989-2016), a clear
 263 decreasing trend appears in the evolution of the weight of the single macro-components (PCB,
 264 plastics, metals and other electronics) (Figure 5). The changes in feature phones and smartphones
 265 macro-composition registered over time are linked to the observed general drop in the overall weight
 266 of the items. A clear decrease in the weight of PCBs (Figure 5A) and plastic components (Figure 5B)
 267 was observed in feature phones and in smartphones in the considered time period. The range of values
 268 recorded for PCBs from feature phones was maximum 57.16 g in 1989 and minimum 10.70 g in 2012
 269 (-81 %), with an average weight of 22.84 ± 11.31 g; smartphones' PCBs have almost always been
 270 lighter, passing from 31.73 g in 2006 to 7.25 g in 2015 (-77 %), with an average weight of $17.50 \pm$
 271 8.76 g. Plastic components dropped from 67.35 g in 1989 to 23.06 g in 2012 for feature phones (-66
 272 %; average 34.94 ± 10.74 g) and from 45.22 g in 2006 and 11.57 g in 2013 for smartphones (-74 %;
 273 average 30.79 ± 10.91 g). The metallic components (Figure 5C) didn't show any particular time-
 274 related pattern; in feature phones (average 6.63 ± 6.71 g) stretched within 29.55 g in 1992 and 1.95 g
 275 in 2012, showing an abrupt increase to 14.76 g in 2013; in smartphones (average 21.00 ± 10.40 g)
 276 they varied from a minimum of 3.18 g in 2013 to a peak of 41.74 g in 2015. However, considering

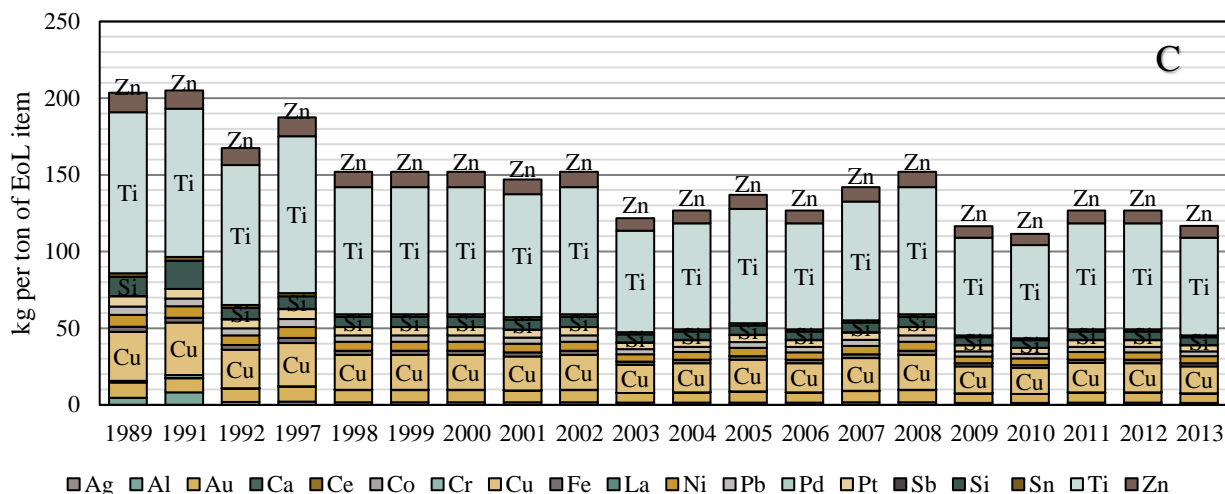
277 that in recent years smartphones became much more common than feature phones, it may be assumed
 278 that in overall the composition of mobile phones transitioned towards higher amounts of metallic
 279 components (+12 % in smartphones compared to feature phones). Other electronic components
 280 (Figure 5D) exhibited high variability in feature phones (average 13.03 ± 4.09 g), decreasing from
 281 24.35 g in 1989 to 5.88 g in 2012 (-76 %); while for smartphones (average 12.48 ± 4.41 g), for which
 282 the minimum and maximum weight of other electronic components have been reported in two
 283 following years, 7.22 g in 2010 and 21.98 g in 2012, no specific decreasing nor increasing trend was
 284 observed. The results of the macro-characterisation performed in this study, combined with previous
 285 works focused on the characterisation of plastic (Fontana et al., 2019) and metallic components of
 286 mobile phones (Jing-ying et al., 2012; Jyothi et al., 2020; Kasper et al., 2011; Maragkos et al., 2013;
 287 Sahan et al., 2019; Xiu et al., 2015; Yamane et al., 2011), allowed to estimate how the composition
 288 of the analysed waste mobile phones evolved over the considered period of time (Figure 6).



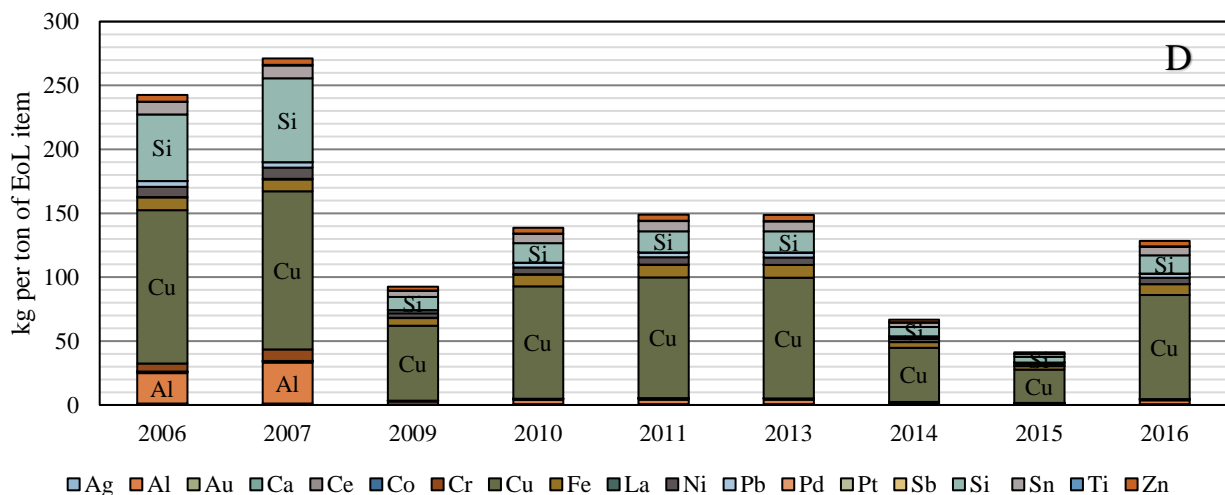
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290



291



292

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

296

297 The main difference observed among the polymers contained in the 2 data sets was the absence of
 298 silicone in smartphones, as this material is characteristic of the keypads in feature phones. The other
 299 polymers showed similar trends, and PC was the most common. Conversely, the composition of
 300 metals exhibited major differences: the most common metals in feature phones were Ti, Cu, Si and
 301 Zn, while in smartphones the main metallic elements were Cu, Si and Al until 2008 and Cu, Si, Fe

302 and Sn from 2009. The main trends observed in feature phones were the decreases in Si and Cu
303 contents over the years, which are consistent with the decrease in PCBs weight (Figure 5A).
304 Considering CRMs, Co and Pd have been found only in smartphones (on average 20 mg/kg of Co
305 and 53 mg/kg of Pd); Pt, Sb and Ti were present in both data sets, with higher concentration values
306 in feature phones (on average 5.11 mg/kg of Pt in feature phones and 0.01 mg/kg in smartphones;
307 80.13 mg/kg of Ti in feature phones and 0.21 mg/kg in smartphones) . Concentrations of CRMs
308 exceeded the grade of mineral ores for virgin metal extraction for Pd in smartphones, for Ti in feature
309 phones and for Pt in both data sets. Specifically, smartphones' PCBs show an average concentration
310 of Pd equal to 53 mg/kg, which is one order of magnitude higher than mineral ore concentration (2 -
311 7 mg/kg) (Robinson et al., 2011); while Pt concentrations (5107 mg/kg in feature phones and 5 mg/kg
312 in smartphones) exceed mineral ore grades (2 - 4 mg/kg) (Robinson et al., 2011) and, eventually, Ti
313 concentration in feature phones (on average 80,127 mg/kg) is above profitable mineral ores grade
314 (25,000 mg/kg) (Kyocera SGS, 2021). Besides, other valuable elements that showed concentration
315 values higher than mineral ore grade, both in feature phones and smartphones, were Au and Cu. Au
316 mineral ore grade (5 - 30 mg/kg) (Kongolo and Mwema, 1998) is considerably below the 7119 mg/kg
317 and 523 mg/kg respectively estimated in the PCBs of feature phones and of smartphones, while Cu
318 concentrations in both samples sets (34,098 mg/kg in feature phones and 105,839 mg/kg in
319 smartphones) exceed the 5,000 - 20,000 mg/kg characteristic of mineral ores (Schlesinger and
320 Biswas, 2011).

321

322 **3.3. Statistical analysis**

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

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

332

333 **3.4. Economic analysis**

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

341 Considering the incomes, the potential market value per item of the dismantled mobile phones
342 decreased over the years as well as the weight of the devices. The estimate of the potential incomes
343 from the sale of the materials and macro-components separated from the waste devices (Appendix,
344 Figure V) allowed to evaluate the evolution of the specific market value of feature phones and
345 smartphones (Appendix, Figure VI), calculated in 0.12 ± 0.06 €/item for feature phones (minimum
346 0.06 in 2012, maximum 0.30 in 1989) and 0.10 ± 0.04 €/item for smartphones (minimum 0.05 in 2015,
347 maximum 0.18 in 2007). The PCB was the most valuable component, representing from a minimum
348 87 % (in 2013) to a maximum 94 % (in 1989) of the value of a single item for feature phones (average
349 90 ± 2 %) and from a maximum 91% (in 2013) to a minimum 64% (in 2015) for smartphones (average
350 84 ± 9 %). Thus, the observed PCBs' weight decrease (Figure 5A) implied a declining in the specific

351 market values of the items throughout the considered period of time. This statement is supported by
352 the fact that the most valuable components (Au and Pt in feature phones and Au, Ce, and Pd in
353 smartphones) (Appendix Figure V) are part of the PCBs. The plastic components, despite representing
354 almost 40 % wt. of the considered items (Figure 6A and B), did not entail significant revenues
355 (Appendix, Figure VI), due to the low market value assigned to the “plastic mix” fraction. Conversely
356 a higher exploitation of the plastic mix, based on the separation of the polymeric materials not
357 containing brominated flame-retardants, which being recyclable entail higher economic value, could
358 improve the economic performance of the EoL mobile phones recycle and recovery scenario.

359 The economic balance of manual dismantling appears initially (from the perspective of the considered
360 period) profitable both for feature phones and smartphones (Appendix, Figure VIIA), nevertheless,
361 both sample sets show a decreasing trend over the years, leading to a current situation of non-
362 profitability due to the market value decrease of the waste items previously observed. Alongside, the
363 maximum cost of labour necessary to achieve the economic profitability of manual dismantling
364 (Appendix Figure VII B) declines over time falling below European standards (Eurostat, 2020b). The
365 worst cases are represented by a maximum value of labour cost (i.e., necessary to guarantee the
366 economic profitability of manual dismantling) equal to 10.40 €h for feature phones (in 2012) and
367 16.76 €h for smartphones (in 2013), not corresponding to European standards (Eurostat, 2020b). A
368 recent study (Liu et al., 2020) referring to the Chinese context demonstrated the economic
369 profitability of mobile phones’ manual dismantling followed by the hydrometallurgical recycling of
370 valuable metals.

371

372 **4. Conclusions**

373 This work presented a detailed characterisation of 100 waste mobile phones (i.e., the one-week inflow
374 of waste mobile phones entering one of the largest WEEE treatment plants in Italy), showing how the
375 relative percentages of their macro-components evolved over nearly 3 decades. Our study provided a

376 snapshot of the composition of waste mobile phones in 2018, which is without any doubt different
377 from what happened in the consequent years due to the prevalence of smartphones over feature
378 phones on the market after 2006-2007. However, the Covid-19 pandemic had relevant effects on the
379 global consumption patterns in 2020-2021, and consequently also on the amount and composition of
380 the waste flows. Therefore, we consider 2018 data still reliable in the description of the pre-pandemic
381 situation. While along the whole manufacturing period (1989-2016) of the considered 100 mobile
382 phones the main component was plastic (46 %-wt. in feature phones and 37 %-wt. in smartphones),
383 over the years PCBs' weight and plastic's content varied (respectively -80% and -70%), as well as
384 metal components' amount (+12 %), especially for smartphones. The average cost of manual
385 dismantling along the whole period was estimated as 6.93 €/per item according to EU average labour
386 costs and 1.50 €/per item based on minimum EU labour costs.

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

402

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