PCBA TO PCBA, A DEPOPULATION COMPARISON

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Abstract
In order to increase metal recovery from discarded printed circuit board assemblies, an additional preprocessing step where its electronic components are presorted before comminution and metallurgy is suggested. The first step in this process is depopulation where the electronic components are removed from the board. However, currently no practical apples to apples comparison has been performed. Therefore, six depopulation methods (both mechanical and thermal) were directly compared on both qualitative and quantitative indicators and evaluated using a multi-criteria analysis. The mechanical methods were faster less energy intensive than the thermal methods but produced lower quality products and had issues with scaling. Overall the best found method was using a pneumatic hammer due to its simplicity and effectiveness.

Keywords: *PCBA, depopulation, E-waste*

1. Introduction

Electronics are among the main drivers of our modern society and can be found everywhere from simple (e.g. dishwashers or traffic lights) to high-tech applications (e.g. MRIs or airplanes). However, this prominence has also led to a continuously growing stream of electronic waste (E-waste), which must be treated to achieve a circular economy by avoiding the loss of material and economic value, pollution of the environment and risks to human health. These problems are especially relevant for the printed circuit boards assemblies (PCBAs or PCBs for short) as they contain both valuable (e.g. gold and silver) and toxic elements (e.g. BFRs and arsenic) (Evangelopoulos et al., 2019; Huang et al., 2022). Roughly half of the weight of the PCBA is the “naked PCB” which is composed of epoxy, fiberglass and copper (van Beek, 2022; Romano, 2023). The “assembly” refers to the electronic components (ECs), such as chips and quartz resonators, that are placed on the board each with a specific material composition. For example, an inductor is mainly composed of iron with a copper spool while a plastic connector is mainly plastic with some copper/aluminium pins (van Beek et al., 2024). Therefore, making the whole PCBA a complex mixture of materials, frustrating the recycling of each individual material (Reuter et al., 2018).

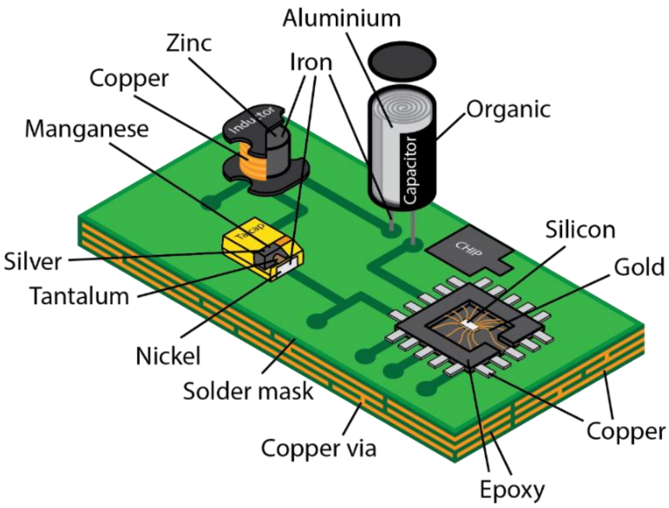

Figure 1. *A PCB with some electronic components and their main materials*

One suggested method in literature to improve the recycling of PCBAs is component-based presorting before comminution/metallurgy (Kopacek, 2016; Charles, et al., 2020; Abbadi et al., 2024). Here the ECs are removed from the board, a process called depopulation, sorted by type and finally sent to different recovery processes. This increases the concentration of materials, e.g. gold or tantalum, quite significantly as the ECs that don't contain said materials no longer dilute the mix making recovery easier, cheaper and more efficient.

In general there are two main methods an EC can be connected to the board. First it can be soldered onto the board, known as a Surface Mounted Device (SMD). Here solder paste and flux are placed on the board followed by the EC. Then the whole board is heating in a reflow oven to melt the solder flux mixture and locking the EC in place. The other type is called through hole components (THC), which is an older technique, where the ECs have connecting pins that poke through the board and are soldered on the back (either by hand soldering or wave soldering). Due to this entanglement, depopulating THCs requires significantly more force (especially if the pins are bent as well) than SMD (Yang et al., 2009).

PCB depopulation methods can be split into three different families: mechanical, thermal and chemical. In mechanical depopulation the connection (e.g. pins) between the EC and the board is broken through methods such as cutting, forceful impacts, grinding etc. freeing the ECs of the board (Ueada et al., 2021; Lee et al., 2012). Thermal depopulation, on the other hand, aims to melt the solder (e.g. residual industrial heat, infrared lights etc.) thus significantly reducing the force required for removal (often by gravity or brush) (Chen et al., 2013; Park et al., 2015). Lastly, the solder and/or connection can be dissolved using chemical methods, such as acids or hot solder baths, once again reducing the removal forces required (Zhang et al., 2015).

As can be seen, considerable research has previously been done on the topic of depopulation. However, these papers either focus on a specific depopulation method or only compare the methods in a theoretical sense (Maurice et al., 2021; Zhao et al., 2022). Therefore, this research tried to create an experimental apples to apples (PCBA to PCBA) comparison between different mechanical and thermal depopulation methods.

2. Methods

2.1. Sample

In order to be able to get a consistent comparison duplicates of the same PCB was used for all experiments (see *Figure 2***.** The PCB used during the experiment). This PCB was sourced from the company Famostar (partner in the Circular Circuits project) and is used in emergency lighting applications. It contains both THCs (e.g. connecting ports and aluminium electrolytic capacitors) and SMDs (e.g. chips and multilayer ceramic capacitors). This can thus show the effectiveness for both mounting methods.

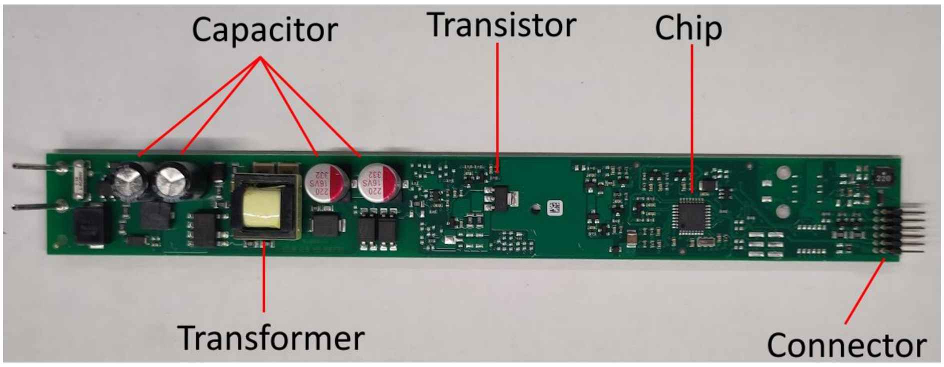

Figure 2. *The PCB used during the experiment*

2.2. Multi-criteria analysis

The chosen method for the comparison was a multi-criteria analysis as this allows both comparison on individual metrics, but also an overall conclusion. In total 7 different criteria were chosen in two different categories (quantitative and qualitative):

Quantitative

- Processing rate: how much time does it take to process one PCB (seconds per PCB), lower is better as this decreases processing costs
- Recovery rate: how many components get removed from the total (%), higher is better as it improves yields
- Energy consumption: how much energy per experiment is required (kWh per PCB), lower is better as it decreases processing costs
- Costs: what are the investment costs of a setup (euros), lower is better as it lowers investment costs

Qualitative

- Output quality: in what condition are the components after depopulation, higher is better as it improves sorting accuracy and reliability
- Safety: are there any safety concerns that have to be taken into account, higher is better as it improves employee wellbeing
- Scalability: can the method easily scale up, higher is better as it eases the adoption/scale up

As this is still a relative comparison a score of +1 was given for good performing methods, 0 for medium performance and −1 for bad performance. Lastly, not all of the factors were equally important and thus a weight factor was created with a strong focus on efficiency (processing rate, recovery rate and scalability) doubling their score.

2.3. Depopulation methods

2.3.1. Manual depopulation

The first method was manual depopulation where the solder was melted using a handheld heatgun (550 °C) and a screwdriver was employed for agitating the components of the board. This method is the simplest of all and was thus used as reference for the other methods. The SMDs were heated from the top, while the THCs were heated on the bottom side of the board to avoid overheating the ECs and giving a more precise heat. The energy/electricity consumption was measured using a Primera-line Brennenstuhl energy meter and the experiment was done within a fume hood in case the PCB caught flame due to the heat.

2.3.2. Pneumatic hammer

The pneumatic hammer, also known as air hammer, is an air driven hammer that allows fast forceful impacts. Therefore, it has the ability to break the connections between the ECs and the board. Here we used a Short barrel air hammer model AT-2050LBSG at 6 bar and an air consumption of 300 L/min. For this method two tests were performed:

- Clamping the PCB upside down in the vice and thus hitting the bottom to generate enough vibrations throughout the PCB to remove the ECs.
- Clamping the PCB normal side up in the vice and thus hitting the components directly.

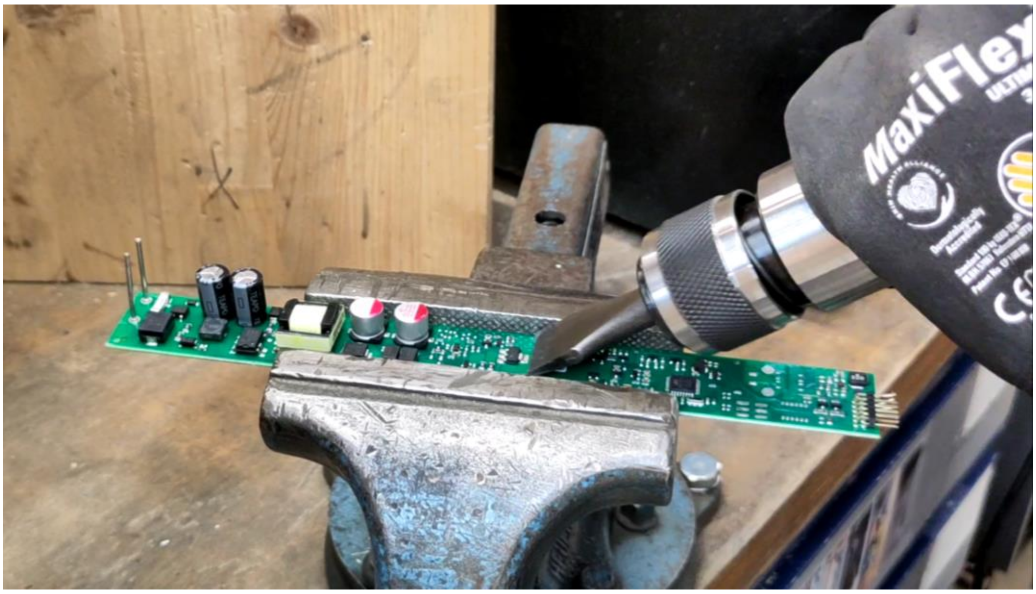

Figure 3. *The pneumatic hammer on the PCB*

For safety reasons a face shield, gloves and hearing protection were required as ECs would fly off violently after being hit. The energy was calculated by converting the processing time to air consumption and then to kWh.

2.3.3. Saw

The last mechanical method explored was the saw. Here a MLT-300 multitool of 300 W from Gamma was used to cut through the connections between the EC and PCB. A small setup (see Figure 4**.** The multitool saw) was created to be able to move the multitool consistently over the PCB. As this was an electric tool the energy consumption was again directly measured using the energy meter. Lastly, due to dust generation the experiment was done under a dust extractor and a mask was worn.

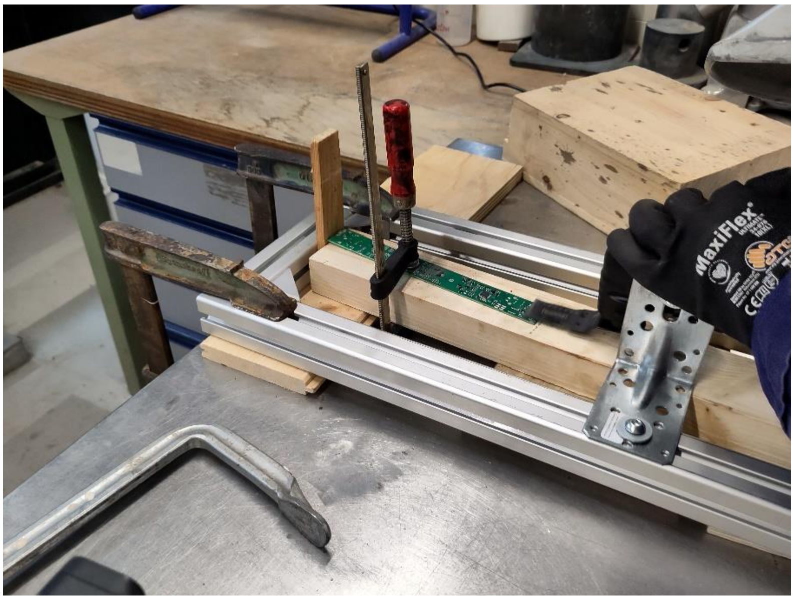

Figure 4. *The multitool saw*

2.3.4. Hot sand bath

The hot sand bath was the first thermal method that was explored due to the fast potential for thermal transfer. The hope was that this would limit the damage to the components as it was only heated for a short blast. For this experiment an electric sand bath of the model ST 82 was used and heated to 300 °C. Furthermore, a thermocouple was used to measure the PCB's temperature as well. The PCBs were placed at 2 cm depth in the sand (total depth 4 cm) and removed when the PCB hit 220 °C to be scraped off using a screwdriver. After cooling the sand was also sieved to check for any lost components. Lastly, the experiments took place in a fume hood due to potential thermal degradation and the energy consumption was measured for the operational time as it was assumed that such a setup would run continuously.

2.3.5. Oven

Multiple experimental runs were performed using a electric Wilten Wolten BV oven at 250 °C to melt the solder. First the optimal residence time was determined by placing the PCBs in the oven for multiple time intervals (5, 6, 7 and 8 minutes). The PCBs were taken out of the oven and scraped off using a screwdriver. The best result was then repeated three times to check for consistency. In the second set of experiments the optimal result was repeated but the scrape off was performed within the oven to reduce heating losses. Similar to the hot sand bath the energy requirements were only for the active part of the experiment and not the initial heating. Once again the oven was placed in a fume hood in case of off-gassing.

2.3.6. Reflow oven

As mentioned before, reflow ovens are often used in PCBA manufacturing for remelting the solder to lock the ECs in place. Therefore, it was also explored here using a Protoflow S/N2 reflow oven. However, as not the whole PCB fitted into the oven it had to be cut into pieces. Two main experiments were explored: hanging the PCB upside down and letting the components drop down in an aluminium tray; and taking the PCB out and forcefully hitting it using a screwdriver. In both cases the PCBs were preheated up to 160 °C for 100 seconds and finally heated up to 275 °C for 210 seconds. As this was at a different facility it was not possible to directly measure the energy consumption and was thus estimated using its maximum power draw (3500 W).

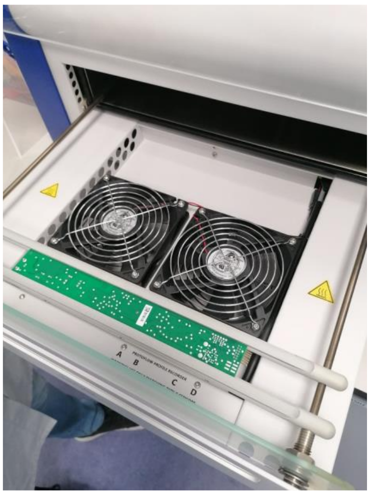

Figure 5. *The PCB in the reflow oven*

3. Results and discussion

First the results per depopulation method will be presented and discussed. This will be followed by the multi-criteria evaluation where the methods will be compared to each other.

3.1. Individual methods

3.1.1. Manual depopulation

As this was a manual process, the processing rate was also quite slow at 19:37, 30:00 and 21:35 minutes for each of the three runs. However, a very good recovery rate (100%) was achieved as good heat control could be employed. The measured energy consumption was also quite consistent at 0.2 kWh for each

PCB. As the setup is quite simple, low investment costs can be achieved as a heat gun can be found for around 40 euros.

Once again, output quality was very good due to the proper heat control which avoided overheating/melting the ECs and improved safety (although care still be taken due to the high temperatures). However, this advantage is has the very big drawback of very poor scalability as it is a manual process.

Table 1

Results of manual depopulation

Processing rate	Recovery rate	Energy consumption	Costs	Output quality	Safety	Scalability
1,177 s/PCBA	100%	0.2 kWh/PCBA	€40	Very good	Neutral	Very poor

3.1.2. Pneumatic hammer

As mentioned in section 2.3.2, two different experiments were performed. The first method of hitting the bottom of the board was a complete failure as it did not remove any of the ECs. Perhaps this could be achieved by finding the exact vibration that can create a standing wave in the board, however that would be such a finicky process that it is not scalable at all. Therefore, these results will not be continued.

The second process was a lot more successful where the hammer was clearly able to break the connecting pins of the THCs and the solder connection of the SMDs. This can especially be seen in the very high processing rate of 23 and 21 seconds respectively. Yet, not all ECs were successfully removed as can be seen in *Table 2*. In all cases the chips, transformers and capacitors were removed, but not all SMDs and connectors which results in a recovery rate of 93%. The energy consumption was calculated by taking the fastest run (20 s), converting this to air consumption (100 L) and then assuming a 70% efficient compressor under isothermal conditions for a total of 0.0065 kWh per PCB. Lastly, the costs were very low at only €20.

Table 2

Recovery rate of the pneumatic hammer

Experiment	Chips	Other SMD	Connectors	Transformers	Capacitors
Process 2 run 1	100%	99%	67%	100%	100%
Process 2 run 2	100%	98%	67%	100%	100%
Process 2 run 3	100%	92%	67%	100%	100%

Output quality was a bit of a mixed bag. Some components came of cleanly, while other were broken due to the high forces (see *Figure 6*. Broken inductor by the pneumatic hammer). This was especially the case for more brittle/ceramic ECs compared to the plastic ones. Therefore, output quality was determined as neither good nor bad. Safety, on the other hand, was very good as the main dangers are noise and ECs that fly off which both can be easily fixed by putting the depopulation method in a box. Scalability was deemed neutral as it is currently still quite a manual process but could be upscaled with some effort.

Figure 6. *Broken inductor by the pneumatic hammer*

Table 3

Results of the pneumatic hammer

Processing rate	Recovery rate	Energy consumption	Costs	Output quality	Safety	Scalability
20 s/PCBA	99%	0.0065 kWh/PCBA	€20	Neutral	Good	Neutral

3.1.3. Saw

Similarly to the pneumatic hammer, the saw was a very fast process (34 seconds) and had a very high recovery rate at 100%. Once again, the energy consumption and costs were very low at only 0.0028 kWh and €56 euros due to the simplicity of the setup. However, the output quality could at best be considered poor as the a slight misjudgement of the angle of the saw would result in damage to the ECs. The same holds for the safety as this process creates a lot of dust, especially if the saw hits the PCB itself. On the other hand, scalability is still neutral as each PCBA has to be treated separately instead of bulk processing.

Table 4

Results of the saw

Processing rate	Recovery rate	Energy consumptio n	Costs	Output quality	Safety	Scalability
34 s/PCBA	100%	0.0028 kWh/PCBA	€56	Poor	Poor	Neutral

3.1.4. Hot sand bath

First of all, it took a very long time (1:41 hours) for the sand bath to be heated to 300 °C due to the high thermal mass. As mentioned before, the PCB was placed into the sand at a depth of 2 cm and was heated until it reached 220 °C. For the two tests performed this took between 14:50 and 7:00 minutes and thus failed at the goal of fast heat transfer as originally thought. This could be due to the sand not being hot enough initially, yet increasing it further could also present damage to the ECs. The recovery rate was mixed, as can be seen in *Table 5*, where not all components were able to be removed by scraping them off. As this is a thermal method, energy consumption and costs for the experiment were also a lot higher at 0.33 kWh and €2,500 respectively. It should be noted that the costs can likely be lower with a simpler (not lab grade) setup.

Table 5. *Recovery rate of the hot sand bath*

Experiment	Chips	Other SMD	Connectors	Transformers	Capacitors
Run 1	100%	63%	0%	100%	100%
Run 2	83%	69%	0%	100%	100%

The quality of the components was good but had two important remarks. First of all, they were covered in sand and secondly all of the capacitors had burst due to the heat damaging their shape and creating a potential safety hazard. Therefore, the safety was only deemed poor. Scalability on the other hand was good as this could easily be scaled up by creating a bigger sand bath and shaking (e.g. a mixer) it to get the ECs off followed by a sieving step to remove the sand.

Table 6
Results of the hot sand bath

Processing rate	Recovery rate	Energy consumptio n	Costs	Output quality	Safety	Scalability
420 s/PCBA	69%	0.33 kWh/PCBA	€2,500.-	Good	Poor	Good

3.1.5. Oven

As mentioned before, three experimental runs were performed in the oven. First of all, the optimal residence time was determined and checked for consistency. Lastly, the depopulation was performed inside the oven as this residence time to reduce heat loss.

As can be seen in *Table 7*, the longer residence time of 8 minutes performed best, yet was not very consistent or produce high recovery rates. This improved by placing the PCB on its side in the oven and performing the depopulation there where a total recovery rate of 91% was achieved. During the 8 minute experiment a total of 0.4 kWh were used by the oven and such a device can be found for around 384 euros.

Table 7

Recovery rate of the oven

Experiment	Chips	Other SMD	Connectors	Transformers	Capacitors
5 min	67%	23%	0%	0%	50%
6 min	67%	8%	0%	100%	100%
7 min	83%	34%	0%	100%	100%
8 min run 1	100%	78%	0%	100%	100%
8 min run 2	83%	24%	0%	100%	100%
8 min run 3	67%	63%	0%	100%	100%

8 min in oven depop run 1	100%	87%	67%	100%	100%
8 min in oven depop run 2	100%	86%	33%	100%	100%
8 min in oven depop run 3	100%	75%	0%	100%	100%

The quality of the ECs were once again good as the oven was not set too high and thus little melting occurred, but with the footnote that the capacitors once again leaked/off gassed when removed decreasing safety to poor. Similar to the hot sand bath, the scalability is good, but set to very good as such heating devices already exist (Suny Group, 2025).

Table 8

Results of the oven

Processing rate	Recovery rate	Energy consumptio n	Costs	Output quality	Safety	Scalability
480 s/PCBA	87%	0.4 kWh/PCBA	€384	Good	Poor	Very good

3.1.6. Reflow oven

Two experimental runs were performed: hanging the PCB upside down in the reflow oven; and taking the PCB out and hitting it. In the first experiment only the capacitors fell off completely and the transformer partly. This showed that some mechanical forces are required which proved more effective during the second run. Here 67% of the chips, both capacitors and the transformer but only 4 of the 34 other SMDs came off. Thus the recovery rate was determined to be 50%, but it should be noted that not the whole PCB was tested in this method due to space limitations in the machine.

The energy consumption was similar to other thermal experiments at 0.30 kWh at a processing rate of 310 seconds. A specific recovery rate could not be determined in the current setup and was thus left out. A similar reflow oven (Protoflow S4 from LPKF) could be found for €5,750. Component quality was deemed good, yet the capacitors leaked/off-gassed again reducing safety to poor. Scalability was determined to be very good as once again, such devices already exist (AR&R, 2025).

Table 9

Results of the reflow oven

Processing rate	Recovery rate	Energy consumptio n	Costs	Output quality	Safety	Scalability
310 s/PCBA	50%	0.3 kWh/PCBA	€5,750	Good	Poor	Very good

3.2. Multi-criteria comparison

As mentioned in section 2.2, a multi-criteria comparison was created to compare the methods relatively to each other. Here a weight factor of 2 was also introduced to the main factors impacting throughput and implementation. The results of this comparison can be seen in *Table 10*. It is quite clear that the two mechanical depopulation methods (pneumatic hammer and saw) are most successful. This can mainly be attributed to their very high processing and recovery rate. Interestingly enough they also produce the worst quality of components which should thus be taken into account if this is of great importance (e.g. vision based recognition systems or reuse). It should be noted that without any weight factor the pneumatic hammer (score of 5) and the saw (score of 2) would still be determined the best.

The poor scalability of the two mechanical methods can best be attributed to the fact that bulk processing is not possible. Each individual PCBA has to be hammered/sawed one by one instead of treating multiple at the same time.

Of the thermal methods the oven was best due to its simplicity giving it the edge in costs but recovery rate as well. It could be argued that the costs for the hot sand bath are currently an overestimate and a cheaper system can be produced. However, this would still not give it the edge it required over the oven or the mechanical methods.

Table 10

comparison of all the methods for the MCC (green = +1, yellow = 0, red = –1)

Method	**Processing rate**	**Recovery rate**	**Energy consumption**	**Costs**	**Output quality**	**Safety**	**Scalability**	**Final score**
Weight factor	2	2	1	1	1	1	2	
Manual depopulation	1,177 s/PCBA	100%	0.2 kWh/PCBA	€40	Very good	Neutral	Very poor	**–1**
Pneumatic hammer	20 s/PCBA	99%	0.0065 kWh/PCBA	€20	Neutral	Good	Neutral	**7**
Saw	34 s/PCBA	100%	0.0028 kWh/PCBA	€56	Poor	Poor	Neutral	**4**
Hot sand bath	420 s/PCBA	69%	0.33 kWh/PCBA	€2,500	Good	Poor	Good	**0**
Oven	480 s/PCBA	87%	0.4 kWh/PCBA	€384	Good	Poor	Very good	**3**
Reflow oven	310 s/PCBA	50%	0.3 kWh/PCBA	€5,750	Good	Poor	Very good	**–2**

4. Conclusions

This paper aimed to create an apples to apples comparison of six different PCBA depopulation methods (manual depopulation, pneumatic hammer, saw, hot sand bath, oven and reflow oven). This was achieved by depopulating duplicates of the same PCBA using each of these methods and creating both quantitative and qualitative results for comparison. From the multi-criteria comparison is was determined that the pneumatic hammer is the most promising method due to its high throughput followed by the saw and oven. In general it can be stated that mechanical methods (pneumatic hammer and saw) produce safer, faster and cheaper results but produce lower quality components and are more difficult to scale up than thermal methods. Therefore, the choice of depopulation method depends on the purpose of depopulation and its follow-up steps (method of recycling, reuse, etc.).

5. Acknowledgements

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