UPSCALING of COLLABORATIVE DISASSEMBLY LINES for MOBILE PHONES – ECONOMIC and ENVIRONMENTAL CONSIDERATIONS

Rainer Pamminger[a,1], Sebastian Glaser[a,2] Roland Ambrosch[b,3], Mario Genner[b,4]

[a] *Institute of Engineering Design and Product Development, Vienna University of Technology, Austria*

[b] *CDP Center for Digital Production GmbH, Austria*

[1]rainer.pamminger@tuwien.ac.at [2]sebastian.glaser@tuwien.ac.at [3]roland.ambrosch@acdp.at [4]mario.genner@acdp.at

***Abstract* – To enable advanced mobile phone recycling and circular economy strategies like reuse of mobile phone components, a modular collaborative disassembly machinery demonstrator has been developed. The demonstrator consists of flexible usable dismantling modules, a collaborative robot and a human workspace. The remaining challenge is to scale the demonstrator from the prototype level up to line variants in series applications. This is achieved through simulation of different scenarios where cycle time, workload, economic- as well as environmental aspects are determined.**

The objective of the study is to define a virtualise disassembly line with blocks and algorithms in order to perform a simulation of different line variants and disassembly scenarios. With this quick evaluation next to the consideration of technical aspects, economic and environmental implications are simulated.

***Keywords* - upscaling, simulation, modular, collaborative, economic, circular environmental considerations**

I. Introduction

The current end-of-life strategy of electronics is focused mainly on recycling. The existing recycling technologies for electronics scrap focus on shredding devices into smaller fractions for recovery of prevailing valuable materials from integrated printed circuit boards. In this recycling and its metallurgic processes, low volume materials such as rare earths metals and still functioning valuable integrated circuits (processors, memories, controllers, etc.) meaning a lot of resources are lost..

In order to realise a more efficient use of resources the EC will push the shift from a linear to a circular economy. . Within a Circular Economy products and its components should be used as long as possible through strategies like reuse, remanufacturing or repair and if this is not feasible any more the materials should be recycled in an efficient way [1], [2]. In order to support the concept of a circular economy an economic feasible and environmental friendly disassembly of electronic products is key as it enables strategies like reuse or remanufacturing. Also additional legal requirements can be expected. The removal of the battery of smart phones is already mandatory [3] and more directives are on its way. First standards on have already been published on the European Commission [4].

The approach developed in the sustainablySMART project [5], implies a modular collaborative disassembly machinery to gain batteries and printed circuit boards with the integrated circuits from different types of mobile phones for further advanced end-of-life strategies.

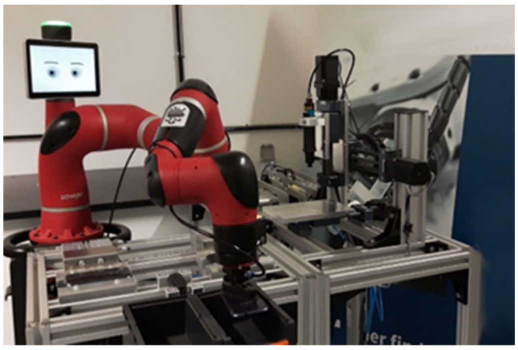

Figure 1: Disassembly machinery demonstrator with Sawyer-Robot. Source: sustainablySMART

A collaborative design, the interaction between robots and humans, makes it possible to combine disassembly steps in an effective and flexible manner. It is preferable when there are rapid changes in mobile phone models and the disassembly line have to be configured quickly, or when certain dismantling steps are too expensive to fully automate [6].

Today different mechanical designs of information technology devices like mobile phones or tablets exists on the market using different joining techniques like screws, clips and adhesives. Schischke et al. revealed very large differences in the complexity of the devices, quantified by a significant increase in the number of work steps required for dismantling [7]. The (analysed) performance of a whole disassembly line is essentially influenced by these mechanical designs. Every mobile phone variation and component has its own dismantling process which could be realised either manually or automatically.

When dismantling a mobile phone, the following steps need to be performed: Cover removal: opening the mobile phone either mechanically by loosening snap-fit fasteners (if it is a non-glued cover), or by detaching glued covers or screens via heating; Battery extraction: mechanically or via heat utilization; extraction of internal covers and PCBs: unscrewing and removal of electrical parts like vibration motors, speakers, microphones and cameras.

To fulfil these disassembly steps listed above, three modules were developed within the sustainablySMART project. A clamping module for mechanical extraction steps, a heating module to dissolve glue, and a unscrew module for the extraction of the PCBs.

The technical viability has been demonstrated by designing and realizing flexible dismantling modules being able to dismantle the different mobile phones.

Figure 2 illustrates the three basic dismantling modules to fulfil these disassembly steps listed above. A clamping module for mechanical extraction steps, a heating module to dissolve glue, and a unscrew module for the extraction of the PCBs. The disassembly line can consist of various arrangements of these modules beside collaborative robots and workspace for humans.

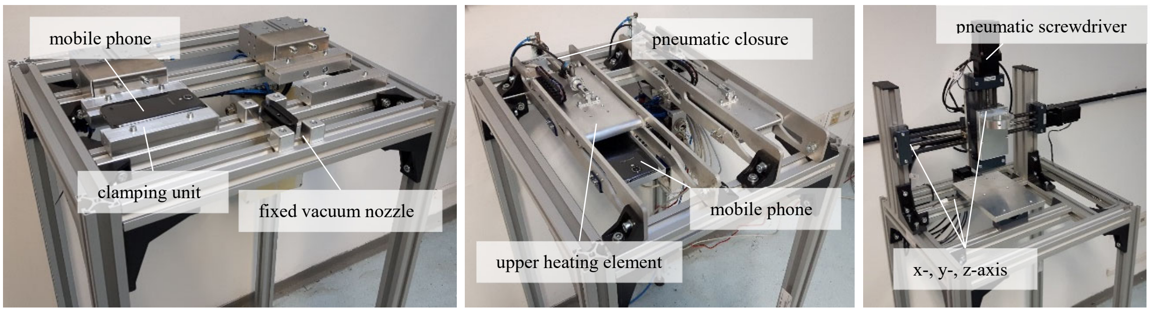

Figure 2: Dismantling Modules for a flexible mobile phone disassembly process: Clamping Module / Heating Module / Unscrew Module. Source: ProAutomation

1) *Clamping module:* The clamping module offers two clamping units. Such a clamping unit is similar to a bench vice, and holds a smartphone while for example the handling robot removes the back cover and extracts the battery. To increase the versatility, it also offers a fixed vacuum nozzle, which can grip phones that does not fit into the clamping unit.

2) *Heating module:* To detach glued covers, screens, or batteries, the heating module offers two heating units. A phone is pushed beside two elastic heating elements, and pneumatic closure ensures a good heat transfer.

3) *Unscrew module:* The unscrew module has a pneumatic screwdriver mounted on a linear x- and z-axis. The clamped phone moves via a third axis in the y-direction. With these setup internal covers and PCBs can be detached mechanically via unscrewing.

The next task is to scale the demonstrator from the prototype level up to series applications. This will be achieved through digital simulation.

II. Objectives

The objective of the study is to define a virtualise disassembly line with blocks and algorithms in order to perform a simulation of different line variants and disassembly scenarios. With this evaluation technical aspects as well as economic and environmental implications are simulated.

The focus for the modelling is on the finding of appropriate line setups for a collaborative disassembly process. The line consists of flexibly usable modules, collaborative robots and human workspaces. Depending on the arrangement of the separate modules, typical economic and environmental aspects like cycle time, workload, and process flow and energy consumption differ and are therefore simulated.

Questions to be answered are: How does the line setup look like to keep the costs low from an economic perspective, respectively how can such a line setup be found? How does a line setup look like regarding minimal environmental impacts? And how does the line look like if both economic and environmental aspects are considered?

III. Methods

This paper shows a method for an upscaling process of the collaborative disassembly line for mobile phones through simulation in respect to a line-view. While simulating operation periods using different market scenarios a lot of data are gained and analysed regarding peaks and surges of production efficiency.

Simulating industrial systems like production lines is a common method for testing scenarios and planning industrial systems. A virtual model representing as close as possible the real process which consist out of underlying algorithms is created and different experiments are carried out. Different simulation granularities enable to focus on different aspects. Since a real prototype of the dismantling modules was built, and their cycle times as well as their energy consumptions were measured in detail, the following work simulates disassembly line variants on a higher abstraction level. The modelled dismantling modules (e.g. unscrewing unit) are blocks, having inputs and outputs and internal algorithms which will be pre-defined. By using these blocks, serial, parallel and combined line arrangements will be simulated and compared. Upcoming bottlenecks and appropriate countermeasures (such as additional parallel dismantling modules) can be weighted by the throughput rate and the energy consumption.

The methodical approach for the environmental evaluation is built upon the ISO 14955 standard [8] regarding the energy measurements of machine tools. First these measurements are used as input for the line simulation to gain the "environmental results" for each simulated scenario, and additionally they are used to identify the most energy intensive process steps and the major consumers. Once these environmental weak points are detected, this can be used as a starting point for further improvement of the dismantling modules and the dismantling process. For example reducing the energy consumption by using more efficient dismantling technologies or changing the dismantling process.

A. *Upscaling through Simulation*

To encounter pros and contras of various collaborative disassembly line layouts a simulation is necessary. To achieve that, simulation tools like "FlexSIM / Visual Components" are used. The dismantling process is virtualised in three areas, so that an analysis of different line layouts can be realised flexible and statements about cycle time, workload and environmental impact can be made. These three sections are shown in Figure 3 below.

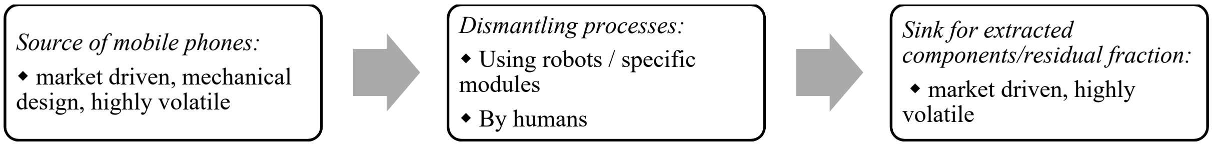

Figure 3: The three basic areas for simulation

One of the main uncertainties in the dismantling of phones is the market driven source of old, disposed mobile phones. Depending on the phone model and its mechanical design, different dismantling steps are needed and as a result different dismantling equipment (modules) is needed. Following the idea that smartphones are exchanged at least once every three years [9] the sales numbers of those years within Europe are used as an input.

This means the flexible line layout (robots, humans and changing module arrangement) is realised in dependence of the supplied mobile phones. Additionally, the workload of the human worker is analysed and possible cycle time optimizing redundancies of certain dismantling modules could be tested in dependence of the mechanical design of supplied phones. Furthermore, the cycle times of every station in contrast to the whole cycle time is analysed.

The relevant outputs of the dismantling process are the battery (pollutant), the printed circuit board and the residual fraction including displays and other small parts such as vibration units or speakers. Within the simulation two different scenarios are analysed: in the first scenario only the extraction of the pollutant (battery) is analysed and in the second one the dismantling of the phone. This approach is followed since legislation does require the separation of batteries before shredding the rest of the smartphone. The second scenario is analysed to enable reuse or advanced recycling to fulfil possible future requirement from an upcoming enlargement of the ecodesign directive (resource efficiency) [3]. Another advantage of this simulation is a better understanding of the availability of high quality fractions of different materials for the recyclers and its economic implications and the possibilities of new resale business cases.

Following this strategy and abstracting the dismantling line to blocks means that the simulation can be faster done and a longer duration can be evaluated. But the abstraction also means blurring the exact results (like for the cycle time). Nevertheless, the abstraction is done with respect to the measurements of the built-up prototypes (cycle times and energy consumptions), and knowing that the difference in cycle time and energy consumption is minor between different phone models.

B. Environmental Assessment

When assessing the environmental performance of a product, usually a so called Life Cycle Assessment acc. to the ISO 14040-44 framework is carried out [10]. A product generates emissions and consumes resources through its entire life. As a result, such an assessment must cover the product's full life cycle (raw materials, manufacturing, distribution, product use and product's end of life [11]. When identifying the environmental weak point of machine tools and also automated manufacturing lines, in most cases the energy consumption of the use phase will stick out, their typical profile is "use-intensive".

Therefore the ISO Standard 14955 addresses just the energy efficiency of machine tools during the use stage, i.e. the working life of the machine tool. Although the dismantling modules are not a typical machine tools like a milling machine or a turning lathe, it seems useful to follow these standard. Beside the environmental evaluation, also improvement potentials can be found and the energy efficiency of the disassembly machinery can be maximised for the planned industrial implementation. More potential benefits acc. ISO 14955 are: a higher energy efficiency cause cost reduction in machine tools operations, attraction of environmentally conscious investors, an increased competitiveness and increased knowledge about the product.

Going one step further, these environmental results serve as an additional input for the upscaling simulation as already mentioned before. This way, not only the most efficient line variant from an economical and technical point of view, but also from an environmental point of view can be identified. To get the relevant energy consumption data for the simulation input, the main procedure using the ISO 14955 Standard is summed up in 4 tasks below: defining the system boundaries, defining the generalised machine tool functions, mapping those functions to the components and parts and performing the measurements.

1) *System boundaries:* According to the ISO standard system boundaries and the relevant energy flows which will be measured have to be defined. In this study, two energy flows remain relevant, compressed air and electrical energy (heat- and air-exchange were neglected).

2) *Generalised machine tool functions:* According to the ISO 14955 a functional approach for describing the machine tool is used. The ISO standard suggests 6 standardized functions: machine operation, process conditioning, workpiece handling, tool-handling/die change, recyclables/waste handling and machine cooling/heating. Because the disassembly machinery defers quite a bit compared to a typical machine tool, only two out of 6 generalized machine tool functions stays relevant: machine operation and workpiece handling.

3) *Functional mapping:* Because the energy consumption per machine tool function is of interest, the components (and measurements) are assigned to these functions.

4) *Energy measurements:* There are two different ways to access energy consumption data, performing measurements or using data from datasheets. Generally speaking, declared energy consumptions in datasheets are often max or average ratings and do not match the actual situation.

In this study, all measurements were performed on-site at ProAutomation in Vienna. If necessary, multiple measurements were performed and the mean value was calculated. In some cases the power demand of the single components were determined from the module's power consumption. In addition to gather data from measurements, assumptions based on datasheets were taken.

IV. Results and Discussion

A. Selection of Simulation Abstraction

For the underlying process a prototype was built-up and measurements were taken regarding cycle time and energy consumption for two different phone types (Samsung S3 and S6). Those measurements showed that mobile phones with a different mechanical design have a slightly different cycle time since the battery was once pulled out by a robot and one pulled out by a human worker but in general the overall output was almost the same. The energy consumption of the robot and the dismantling stations is also not differing too much. The underlying reason is the built-up of phones and materials used.

Mobile phones are either structured from the display side or from the battery side, meaning that the head of screws are either orientated towards the back or towards the front of the phone. This is a big difference from the mechatronic point of view for the automation system but no difference in cycle time since the equipment for both variants is almost equal.

Regarding the different materials used mainly the glue or screws, which are holding the battery in place, are making a difference. On one hand batteries in three to four-year-old phones are either screwed to the phone or glued to the phone. In case the batteries are screwed an unscrewing station is used with a shorter cycle time and higher investment for one station and in case the batteries are glued a heating station is used with a longer cycle time and lower investments. Investing in two heating stations (which are running parallel for a higher throughput) results in the same costs as investing in one unscrewing station which leads to the fact that economical values are equal. Looking at the environmental impact it is clear that the heating stations needs significant more energy than an unscrewing station.

B. Basic Scenario for Point of Reference

The energy consumption needed to disassemble one mobile phone was calculated in a basic scenario. In this scenario the disassembly line layout is similar to the disassembly machinery demonstrator. The outcome serves as point of reference for the environmental simulation results.

In the basic scenario (Figure 4) a mobile phone similar to Samsung S6 is disassembled. The robot takes the phone and pushes it inside the heating unit. The heating module heats up the phone and the adhesive dissolves. Then the phone is clamped in the clamping module and the robot pulls off the back cover and extract the battery. In the last step all screws fixing the PCB get loosened, afterwards the phone is moved further to a worker who separates the PCB among other electronic parts. As it can be seen in Figure 2, the clamping- and heating module are designed for two phones each (two clamping and two heating mechanism) to achieve a higher through put. In the assessed basic scenario only one of each of these "stations" is used.

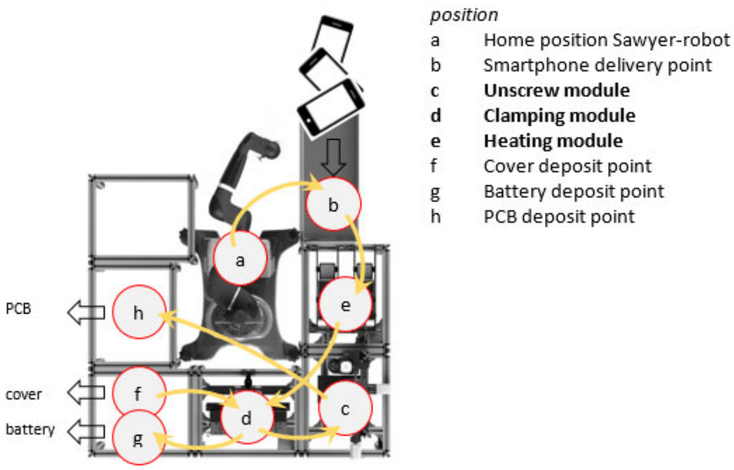

Figure 4: Basic scenario, necessary movements for mobile phone disassembly scenario

Figure 5 shows the average power demand of every operating state (OFF / Standby / Warm-up / Processing). It is obvious that the standby state compared to the processing state needs quite some power (standby > 50% of processing). In the assumed shift regime scenario with only 2 hours standby and 16 hours processing it does not effect the result per phone as it would in a scenario with a longer standby state.

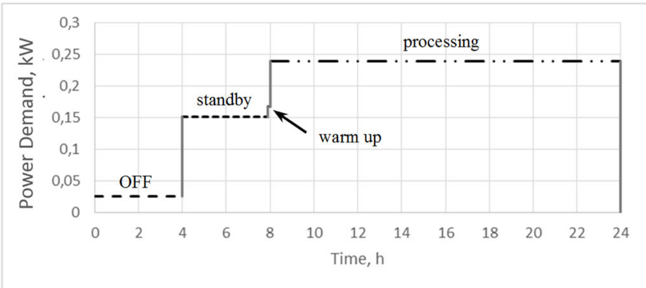

Figure 5: Shift regime scenario, (average) power demand of operating states

1*) Results - per type of energy*: The main type of energy used by the disassembly machinery is electricity as it can be seen in Figure 6, on the right side. But the unscrew module needs for almost half of its energy demand compressed air (48% compressed air in total, rest 52% electricity). This is caused by the demand of the pneumatic screwdriver, which needs about 86% of the total compressed air demand of the unscrew module. In the chosen shift regime scenario, about 400 phones become disassembled per 24h (145sec per phone, cycle time disassembly machinery). According to the shift regime including the energy consumption during the operating states OFF, Standby, and Warm-up the overall energy consumption to disassemble one phone adds up to 11,4Wh (without any attention to the data accuracy). With attention to the data accuracy and assumptions, the upper limit of energy demand per phone disassembly is in a range between 10Wh and 17Wh.

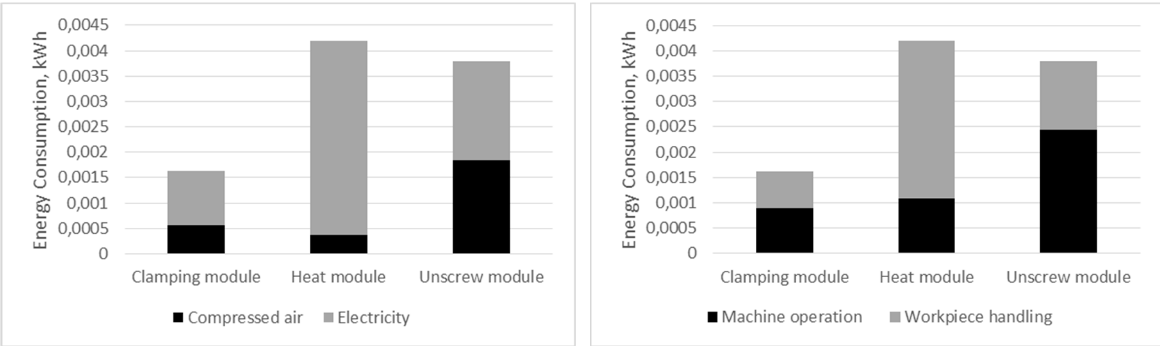

Figure 6: Energy consumption of modules processing one phone. Left: Types of energy / Right: Machine tool functions

2) *Results- per generalized machine tool functions acc. ISO 14955*: As suggested in the ISO 14955 Standard the energy consumption is identified per (generalized) machine tool function. The energy consumption of the two remaining generalised machine tool functions (workpiece handling, machine operation) are showed per module in Figure 6, on the left side. The heat module needs about 74% energy for workpiece handling, caused by complex movement required when clamping or removing a smartphone.

V. Conclusions

Within this paper the topic of upscaling disassembly lines and it's surrounding is described, leading to the necessity of simulations. Simulating different layouts and different market situations means simulating a high variety of inputs. Within this paper it is shown that different mobile phone types have to be evaluated and the huge variety of phone types have to be considered. To get an economical effective line layout the flexibility for future phones has to be guaranteed due to the fact that the marked situation is rapidly changing. Valuable inputs for the simulation are selling numbers of previous years since those numbers give indications of the upcoming market situation. With this knowledge the existing machine layouts and combinations of modules could be extended years before the recycling of the mobile phones or adapted to the changed circumstances. By using simulations, that developing stage is improved. Set-up times of automation equipment play a big role in the final simulation results and also have to be minimized in collaborative approaches.

Future work will have to focus on possible assessments that allow to evaluate results of simulations regarding economic and environmental results. For example, it is possible that one line layout delivers high throughput and high efficiency but low scores on environmental aspects like energy consumption coming from a higher use of electrical energy for the generation of heat or compressed air needed for the mobile phone disassembly steps.

As a next step, the simulation will get carried out in the upcoming moths. The templates for the blocks will be programmed, and the various scenarios will be build and analysed to gain in-depth knowledge about the economic and environmental aspects of disassembly line variants in real life series applications.

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