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Disassembly Layout in WEEE Recycling Process

Milan OPALIĆ[1], Milan KLJAJIN[2] **and**
Krešimir VUČKOVIĆ[1]

1) Fakultet strojarstva i brodogradnje, Sveučilište u Zagrebu (Faculty of mechanical engineering and Naval Architecture, University of Zagreb), Ivana Lučića 1, HR-10000 Zagreb,
Republic of Croatia

2) Strojarski fakultet u Slavonskom Brodu, Sveučilište J. J. Strossmayera u Osijeku (Faculty of Mechanical Engineering in Slavonski Brod, J. J. Strossmayer University of Osijek), Trg Ivane Brlić-Mažuranić 2, HR-35000 Slavonski Brod,
Republic of Croatia

kresimir.vuckovic@fsb.hr

Subject review

With increasing awareness of potentially harmful life-cycle environmental impacts, preserving natural resources, government regulations against disposal of toxic substances in landfills, and the consequent development of markets for recycled components and materials, more options are now available for the disposal of post-use electronic equipment (e.g. personal computers, computer monitors etc.). Disassembly is the first stage in the WEEE recycling process. Manual disassembly has proven to be the most efficient method. Automated systems find their implementation only when relatively uniform-type equipment or assemblies are disassembled. Layout changes can enhance disassembly speeds by efficient material movement. This paper presents a proposal of disassembly line layout configuration which has been designed for disassembly of electronic equipment, typically found in residential waste stream, commonly referred to as consumer electronics. This paper introduces also a new concept as a possible solution for the known problems in existing layouts that occur during disassembly process such as disassembly speed, lifting, contamination risk, cluttering of tools and overloading of the sorting operator.

Keywords
Dosassembly
Hazardous Materials
Layout
Recycling
Reuse

Ključne riječi
Opasni materijali
Ponovna uporaba
Postav
Rastavljanje
Recikliranje (opraba)

Postav za rastavljanje u procesu recikliranja otpadne električne i elektroničke opreme

Pregledni članak

Uz sve veću svijest o potencijalno štetnim utjecajima životnog kruga na okoliš, očuvanju prirodnih resursa, državnim propisima protiv odlaganje otrovnih tvari na odlagalištima i dosljednom razvoju tržišta recikliranih komponenti i materijala, sada je dostupno više opcija za dispoziciju ponovnog korištenja elektroničke opreme (npr. osobna računala, računalnih monitora i sl.). Rastavljanje je prva faza u procesu recikliranje otpadne električne i elektroničke opreme. Ručno rastavljanje se pokazalo najefikasnijom metodom. Automatizirani sustavi nalaze primjenu samo kada se rastavlja relativno jednolik tip opreme ili sklopova. Promjene postava mogu povećati brzinu rastavljanja pomoću efikasnog toka materijala. Ovaj članak prikazuje prijedlog postava konfiguracije linije za rastavljanje koja je dizajnirana za rastavljanje elektroničkih uređaja koji se tipično nalaze u segmentu stambenog otpada, a koji se obično nazivaju potrošačka elektronika. Ovaj članak također predstavlja novi koncept kao moguće rješenje u postojećim postavima za poznate probleme koji se javljaju tijekom procesa rastavljanja kao što je brzina rastavljanja, dizanje, rizik kontaminacije, buka alata i preopterećenja u operatora sortiranja.

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1. Introduction

Electronic equipment, in the broadest sense, refers to any product that relies on batteries and/or electricity for operation. In this paper the focus is on electronic equipment typically found in residential waste stream, commonly referred to as consumer electronics. This includes brown goods, small household appliances, home and office, data processing and telecommunication equipment. This paper does not deal with other equipment, such as white goods and commercial equipment, because the infrastructure for the disassembly and recycling of such equipment is already well established. Consumer electronics contain some hazardous materials such as lead, cadmium, mercury, antimony, arsenic, barium, beryllium and selenium, which is why the disposal of obsolete or broken consumer electronics is a serious and costly problem. Reuse and recycling have become crucial owing to the rapid advance in technology which leads to accelerated obsolescence, resulting in increased volume of consumer electronics for disposal. Landfill constraints require that new and better reuse and recycle methods should be found. The legislation on recycling and the drafts on electronic scrap regulations have the objective to recycle a maximum of material groups from scrap materials and to dispose of waste from recycling processes by using environmentally sound methods. Disassembly as the first stage in the recycling process provides means to efficiently remove components and assemblies containing hazardous materials, extract valuable components or metals, selectively destroy or recover proprietary parts, and avoid or reduce contamination in downstream volume reduction (shredding) and separation operations [1]. This paper introduces solutions for known problems in existing layouts that occur during the disassembly process such as disassembly speed, lifting, contamination risk, cluttering of tools and overloading of the sorting operator.

2. Disassembly process

The disassembly process can be defined as the systematic removal of the required parts from an assembly. There are two types of disassembly process: manual and automated. Manual disassembly has proved to be the most efficient method. There are two main limitations for the technical feasibility of automated disassembly. The first one is the high variety of products collected by recycling yards and the second one is the unfavorable design of products, since the disassembly option has not yet been taken into consideration during the design process [2].

EOL scanners, printers, display devices, personal computers, small household appliances, brown goods, white goods, telecommunication equipment, cellular phones, large electric motors and electronic systems are received by remanufactures. They range in weight from 0,1 to 2000 kg [3]. Disassembly process usually begins with an operator manually lifting and carrying the unit or part to be disassembled to a workbench from the sorting/staging area. Conventional tools driven pneumatically or electrically such as chisel, tongs, screwdrivers, etc are mainly used. Selectively disassembled parts are placed on a conveyor belt or in bins. Full bins are hand-carried to a sorting area by the operator. If the operator at the disassembly workstation does not sort items, specially trained operators in the sorting area perform sorting and separation of disassembled parts into sorting bins by visual inspection. Primarily valuable parts and hazardous components are removed intact and visually inspected for possible reuse (chips, memory, hard drives, etc.). The secondary output stream, for example, contains intact plastic and steel cases, printed circuit boards and hazardous waste, such as batteries and capacitors. The disassembly work is manual and, if possible, at least mechanized. It is done prior to shredding in order to:

- remove components containing hazardous materials
- selectively destroy or recover proprietary parts
- reduce contamination in downstream volume reduction (shredding) and separation operations
- extract valuable components or metals.

From an economic point of view the disassembly process should be carried out with minimum costs. The presence of nonreversible connections in complex components is one of the reasons why EOL disassembly is not carried out to its full extent, or parts might be more valuable intact. There is a trade-off between costs and benefits which results in an optimum disassembly depth that is different from complete disassembly (Figure 1).

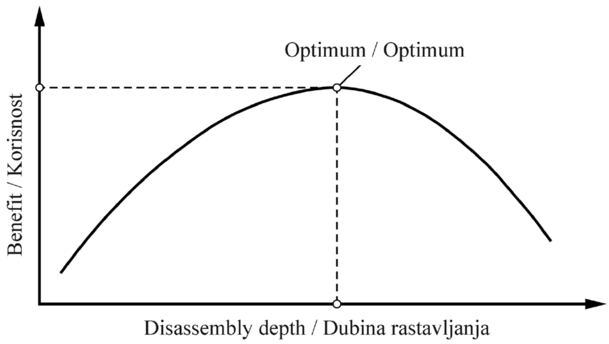

Figure 1. Optimum disassembly depth [4]

Slika 1. Optimalna dubina rastavljanja [4]

Disassembly depth higher than the optimum one requires excessive disassembly work and thus results in smaller benefit, as well as a smaller one that requires less disassembly work but recovers a smaller amount of valuable components and materials. For units containing hazardous materials the disassembly depth is defined by the government legislation which requires removal of all hazardous components and materials.

The economic benefit of recycling and remanufacturing facility is reduced when the recycler has to disassemble a heterogeneous stream of electronic equipment exhibiting variables such as fastener accessibility, condition of product, critical part location, and part identity. It is therefore recommended that recyclers explore the disassembly process for certain types of electronic equipment [5].

3. End-of-life options

The electronic equipment is assumed to have reached the end-of-life (EOL) status when it has served its useful life and/or is no longer functional or when technological obsolescence renders it unusable [6]. In the past, landfill was the usual method for the disposal of post-use electronic equipment (i.e., those re-used after being resold or donated). However, with the increasing awareness of potentially harmful life-cycle environmental impacts, dwindling natural resources, government regulations against disposal of toxic substances in landfills, and the consequent development of markets for recycled components and materials, more options are now available for the disposal of post-use electronic equipment (e.g. personal computers (PC), computer monitors etc.) [6]. The EOL options for electronic equipment are graphically depicted in Figure 2.

4. Current Layout Configurations

Various disassembly line layouts can be found at existing remanufacturing facilities. They can be divided in three different configurations [3] (Figure 3).

Into the first one, after receiving units from the receiving dock, the operator disassembles them on a workstation and puts the disassembled parts into their respective bins around the table. These workstations normally follow a parallel batch operation method, so that each operator independently receives a batch, then disassembles the unit and finally delivers the full bins to the collection/shipment area. The problem is

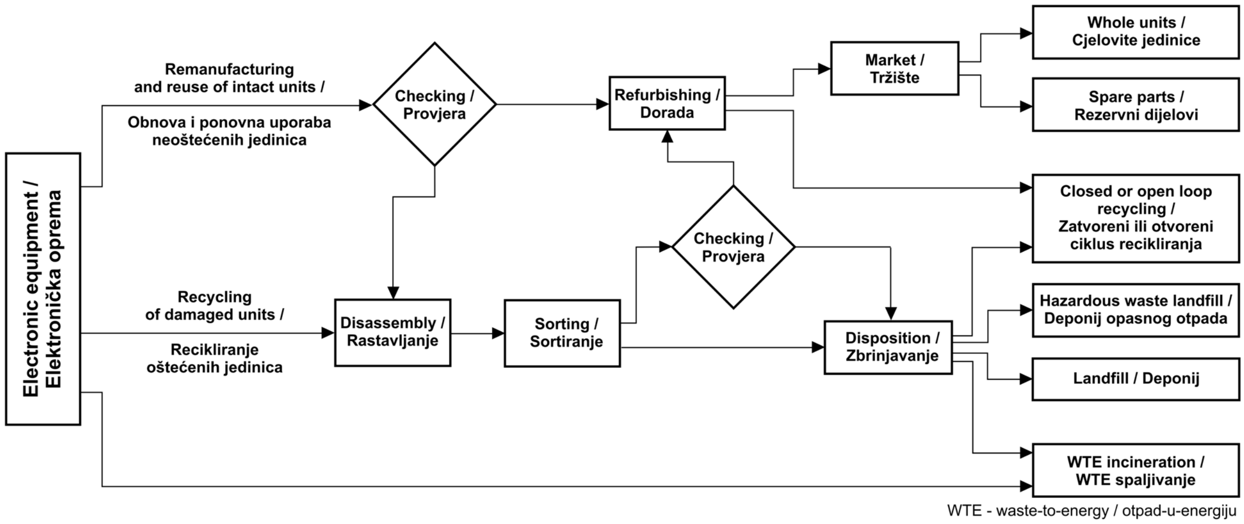

Figure 2. EOL options for electronic equipment

Slika 2. Mogućnosti zbrinjavanja dotrajale elektroničke opreme

Environmentally preferred EOL disposal options are reuse, recycling and remanufacturing. Reuse, often as result of reselling, involves continued use of electronic equipment for the purpose for which it was built, and is considered to occur within its originally intended useful life. Re-manufacturing is a viable option for electronic equipment that is no longer functional but could be refurbished (upgraded or restored to working conditions) at a cost lower than that of manufacturing new electronic equipment, to be sold again on domestic or foreign markets. Recycling involves recovering the individual materials from EOL electronic equipment, to be used in the production of new electronic equipment (closed-loop recycling) or in other products (open-loop recycling). Two other disposal options are waste-to-energy (WTE) incineration in incinerators or municipal WTE facilities and landfilling as the most undesirable option [6].

that the operator spends most of his time in material handling activities (receiving and delivering) rather than disassembly, and in lifting and placing units to be disassembled. In the second configuration, products arrive into the sorting and staging area on the conveyor. Products are then sorted and scheduled for disassembly, as opposed to the first configuration, where products are disassembled without any prior sorting. The disassembly operator receives products from a sorting area and delivers the disassembled parts to the sorting bin area. This is also a parallel operation where only a single operator is involved. The material handling time is less than that of the first configuration, because products arrive closer to the workstation for disassembly. The problem is that this configuration requires more effort in delivering disassembled parts to sorting bin areas every time the disassembly process is in progress. The operator also in this configuration lifts and places all units to be disassembled. The third configuration is similar to the second one except for the addition of a conveyor for disassembled parts. An operator disassembles units at

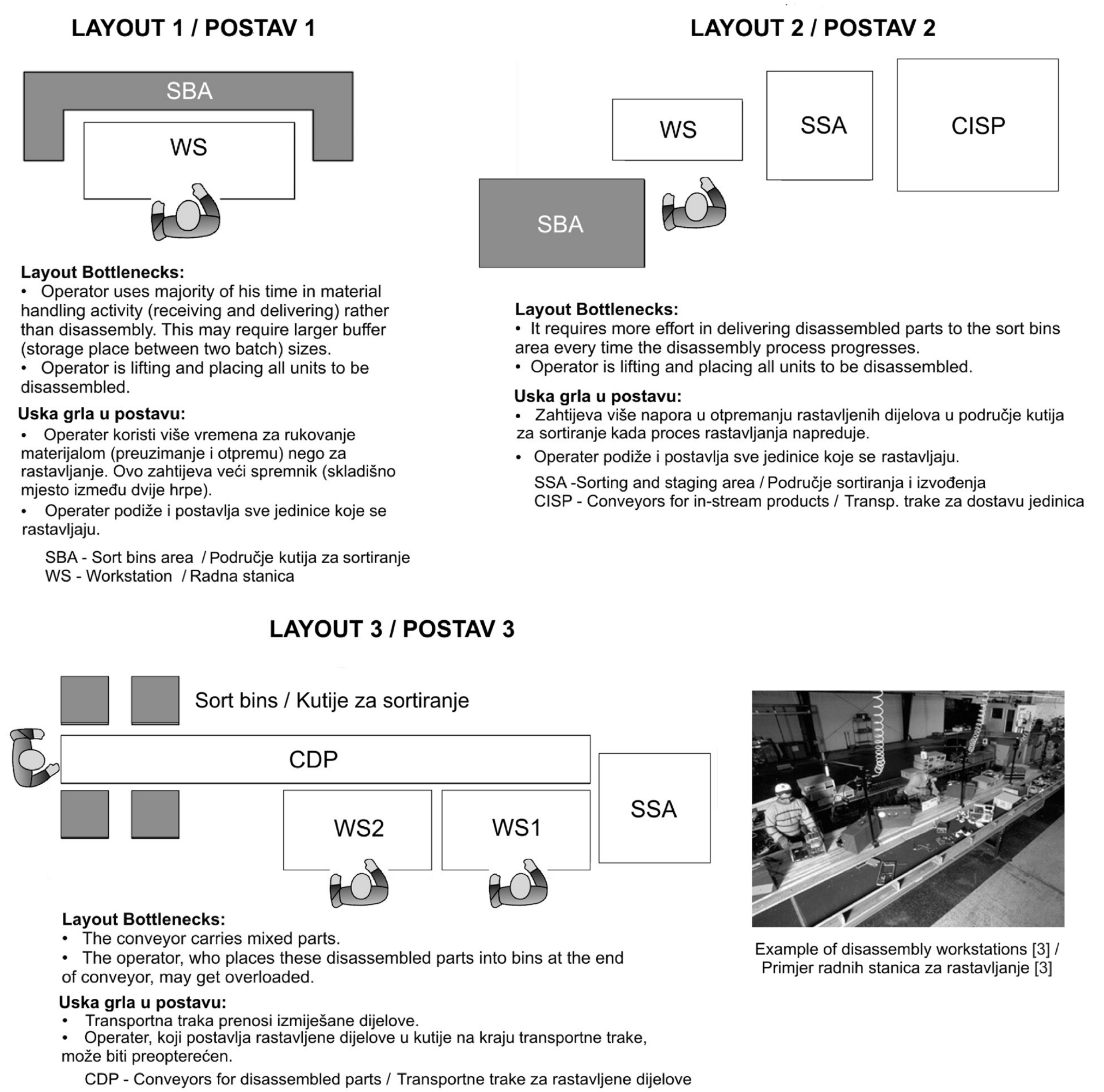

Figure 3. Three different configurations of existing disassembly layouts

Slika 3. Tri različite konfiguracije postojećih postava za rastavljanje

a workstation adjacent to the conveyor belt. As each piece is disassembled, it is placed on the belt. A skilled operator then sorts the disassembled parts into different bins at the end of the conveyor. This layout reduces lifting and lowers cost by increasing actual disassembly time by introducing a conveyor belt for disassembled parts. The problem is that the conveyor carries mixed parts to a sorting place. The operator, who places these disassembled parts into bins at the end of conveyor, may get overloaded. Improvements in the disassembly line layout should therefore:

- enable disassembly workers to disassemble the equipment without ergonomic stress or strain,
- allow the disassembled equipment to be sorted with great accuracy in a minimal amount of time,
- ensure that the distance the equipment travels during disassembly is kept to a minimum,
- allow that all items of similar type could be disassembled on a separate group of dedicated workstations so cluttering of tools at a single workstation is minimized [3].

5. Proposal of Disassembly Line Layout Concepts

Proposal of disassembly line layout configuration has been designed for disassembly of electronic equipment typically found in residential waste stream, commonly referred to as consumer electronics (Figure 4). This includes brown goods, computers, small domestic appliances and small office and telecommunication equipment. Prior to disassembly, electronic equipment is sorted at collection sites. Units that are considered to have the least commodity value (clocks, house telephones, etc.) are sent to an auto shredder for mechanical separation. Units that have potential value are sent for testing to be reused or refurbished for sale. Units that are returned from testing, because they did not pass it are, with the rest of the equipment, sorted by type and sent to disassembly facilities. The layout configuration is divided into two partially separated disassembly lines (they share an outgoing conveyor for disassembled parts and a sorting place) and is an improved and upgraded version of disassembly line proposed in [7]. The first line layout follows the disassembly process of the third layout configuration in Figure 3 and is designed for disassembly of electronic equipment, weighing from 0,1 to max. 25 kg (telephones, laptops, PCs, vacuum cleaners, microwave ovens, monitors, liquid crystal display (LCD) monitors etc). The second line follows the disassembly process of first layout configuration in Figure 3 and is designed for TV sets and computer monitors disassembling.

The disassembly process at the first disassembly line starts with a forklift carrying sorted items on a pallet from the receiving dock to a closed loop roller conveyer. The pallet is placed on the unloading platform that is on a level with the conveyer. Items are, then, manually unloaded from the pallet onto an 80 cm wide closed loop conveyor by an operator, and transported to disassembly workstations adjacent to the conveyor. In order to avoid cluttering of tools, the operator at the workstation selects the item on the closed loop conveyor similar to the previously disassembled one. The item is then unloaded to the workbench and disassembly can begin. All disassembly operations are performed manually. Tools that are not in use are stored in toolbox or laid on auxiliary table. After disassembling, easily identified larger parts such as plastic and steel cases are placed directly on the outgoing 60 cm wide belt conveyor. Smaller parts are sorted at disassembly working station into appropriate sorting bins. Sorting bins are in different colors and each color corresponds to a disassembled component type. Full

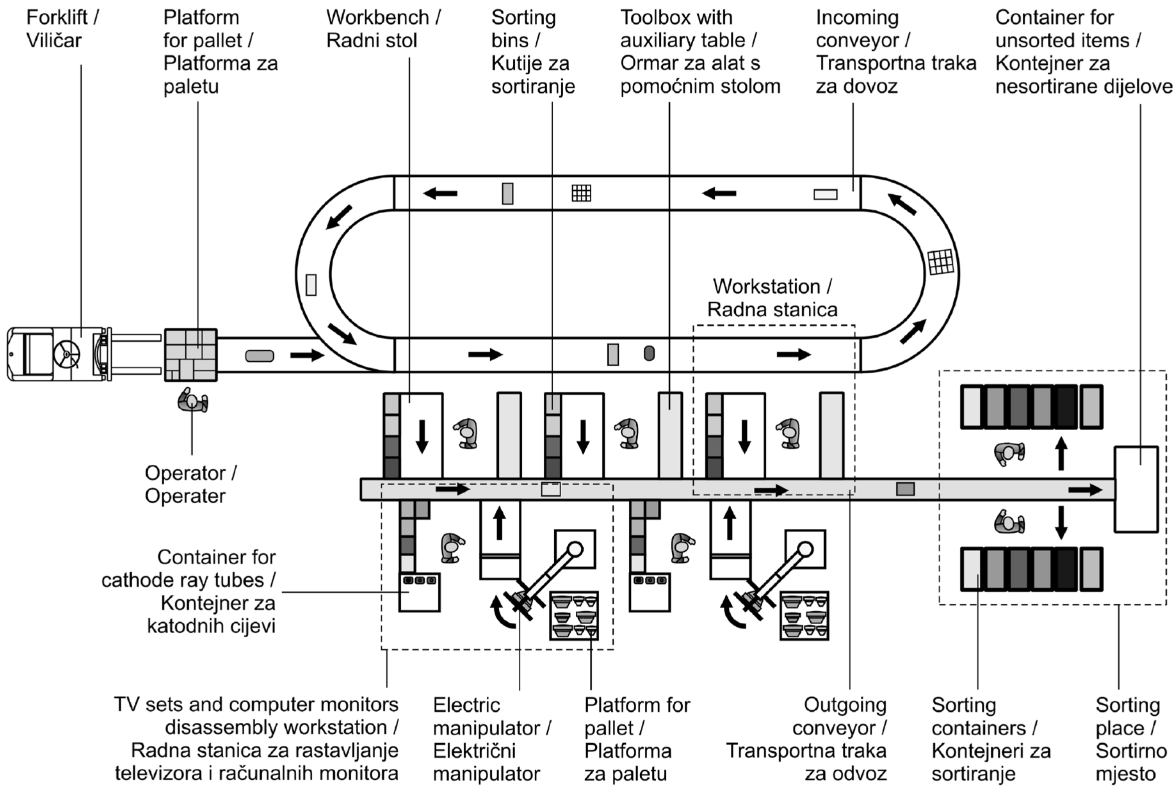

Figure 4. Disassembly line layout
Slika 4. Postav linije za rastavljanje

sorting bins are placed onto the outgoing belt conveyor and together with larger parts transported to the sorting place. The operator at the sorting place near the end of the outgoing conveyor sorts the disassembled parts in the appropriate containers.

At the second disassembly line, the disassembly process starts also with a forklift carrying TVs and monitors from the receiving dock to the unloading platform. Smaller items are manually lifted and carried to the workbench by the operator, while the electric manipulator adjacent to workbench is used for lifting heavier ones. The workbench is equipped with a special mechanism that allows rotation of unit providing easier access to the rear cabinet (Figure 5).

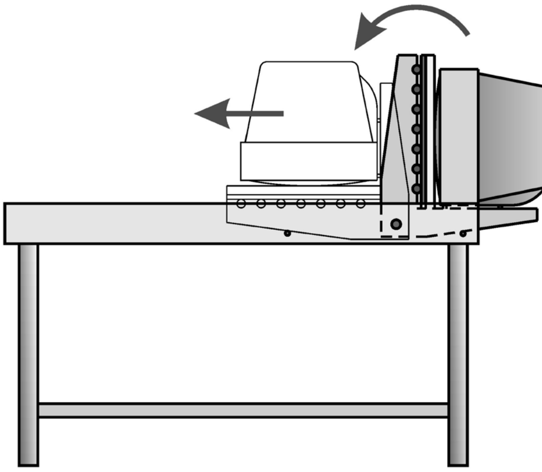

Figure 5. Workbench for disassembly of CRT units [4]
Slika 5. Radni stol za rastavljanje uređaja s katodnim cijevima [4]

The disassembling process is similar to the one described at the first disassembly line. Sorting is done at the already described sorting place. Because cathode ray tubes are easily broken and because they contain hazardous materials such as lead, phosphorus and beryllium [7] they are not placed onto the conveyor for disassembled parts but in a container adjacent to the workstation. Intact cathode ray tubes are sent to specialized facilities for further treatment. It is not recommended to break cathode ray tubes because when broken they are treated as hazardous waste and transportation costs are significantly increased. The gained volume reduction compared to intact cathode ray tubes is only 2-3 times [8].

In order to gain extra profit from remanufacturing recyclers have to specialize for certain types of electronic equipment because the disassembly, recovery, sorting and checking of the removed components from the large variety of electronic equipment is not economically justified. The concept of the specialized disassembly line for LCD monitors disassembly where each operator performs a separate disassembly step thus avoiding cluttering of tools at disassembly workbenches is proposed in Figure 6.

Disassembly begins with an operator manually unloading LCD monitor to be disassembled from a pallet to an 80 cm wide conveyor. The monitor is transported to a workbench adjacent to the conveyor where the operator removes the stand. The removed stand is placed on a conveyor and transported to the workstation where it is disassembled by the operator into power adapter, cables, plastic and steel parts. The rest of the monitor is placed on another conveyor and transported to a workbench where the operator removes the front cabinet. The removed

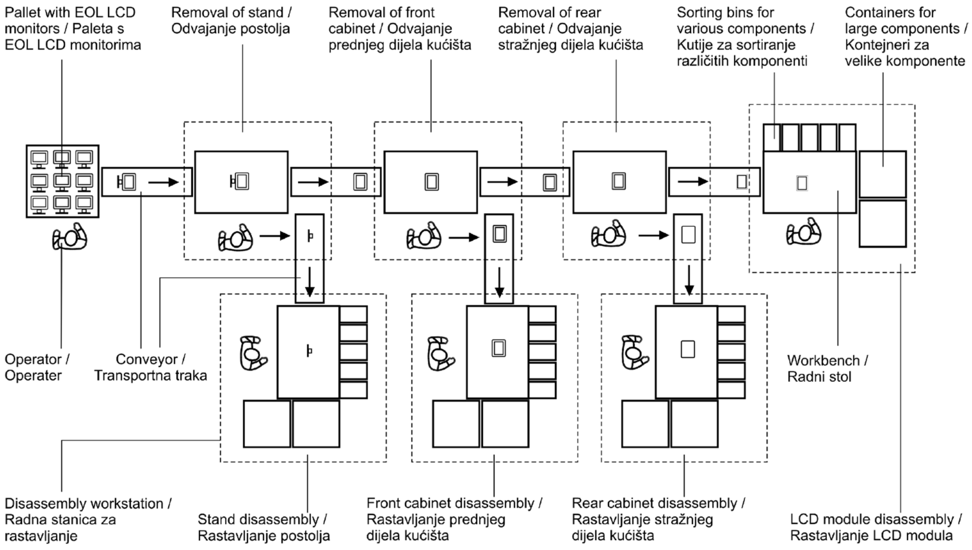

Figure 6. LCD monitors disassembly line concept
Slika 6. Koncept linije za rastavljanje LCD zaslona

front cabinet is placed on a conveyor and transported to the workstation where it is disassembled into printed circuit boards (PCB), cables and plastic parts. The rest of the monitor is, again, placed on another conveyor and transported to a workbench where the operator removes the LCD module from the rear cabinet. The rear cabinet is placed onto a conveyor and transported to a workstation where it is disassembled into PCBs, cables, plastic and steel parts and the LCD module is placed on another conveyor and transported to a workstation where it is disassembled to PCBs, plastic and metal parts, cold cathode fluorescent lamps (CCFL) and the LCD panel. The LCD panel can be further disassembled; however, they are usually shredded and glass is used as substitute for melting sand in specialized facilities for separation of base and noble metals or as substitute in production of products containing silicon for protection of walls against aggressive products while the foils and liquid crystals (LCs) are used as heating energy In order to recover indium, the upper and lower Indium-Tin-Oxide (ITO) glass from a flat panel must be separated and ITO electrode layer is removed by ultrasonic cleaning device [9]. Glass, foils and LCs are then recovered as previously mentioned. The removed PCBs and CCFLs are sent to specialized facilities for further treatment, while cables, plastic and steel parts are shredded, sorted and sold as raw materials.

6. Conclusions

Layout changes can enhance the disassembly process by efficient material movement. The new disassembly line layout concept introduces solutions for known problems in existing layouts. Focusing on the disassembly of electronic equipment found in residential waste stream and sorting it by type prior to disassembly enhances the disassembly speed because the operators disassemble similar equipment per time unit. The closed loop conveyor is introduced so that the operator could pick a certain type of unit which is the most similar with the last one disassembled. Because of all that, the cluttering of tools at each workstation is significantly lowered. Placing only easily identified disassembly parts directly onto the outgoing conveyor and sorting other ones at workstations into appropriate colored bins increases visual inspection and thus reduces the possibility of overloading the sorting operator. Lifting is reduced to a minimum by introducing hoists, platforms and conveyors while the workstations are placed adjacent to them. Introducing the partially separated disassembly line for this type of equipment reduces contamination risk of hazardous materials found in the equipment containing cathode ray tubes. The concept of specialized disassembly lines, as the one proposed for LCD monitors, enables recyclers to gain extra profit from remanufacturing.

The disassembly process can be further enhanced by implementing automatic operations for specific processes, such as punching out screws, or unscrewing screws. Manual sorting operations can be replaced with automatic vision recognition system but its effectiveness must be enhanced.

An automated disassembly process could consist of positioning of the monitor, clamping the monitor, opening the housing, unscrewing of circuit board, decoupling of cable connector and, at the end, handling of circuit boards. The material flow in the above described disassembly system, is physically carried out by means of a conveyor system and all drives, sensors and actuators are operated using a modern control system. Efficient utilization of this equipment requires a computer aided planning approach, which can be supported by a bundle of simulation tools [10].

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REFERENCES

[1] KOCH, P.; KASPER, R.: *Dismantling and Process Technology for Electronic Scrap and Discarded Electrical Appliances*, Aufbereitungs-Technik 37(1996), 211-220.

[2] FUGGER, E.; SCHWARZ, N.: *Disassembly and Recycling of Consumer Goods*, R´1999 Congress (Recovery, Recycling, Re-integration), Geneva, 1999.

[3] ..: *Demanufacturing of Electronic Equipment for Reuse and Recycling Technology and Demonstration Center (DEER2): Mission Need Statement*, National Defense Center for Environmental Excellence (NDCEE), Johnstown, 2000.

[4] KLJAJIN, M.; OPALIĆ, M.; PINTARIĆ, A.: *Recikliranje električnih i elektroničkih proizvoda (Recycling of Electrical and Electronic Products)*, Strojarski fakultet u Slavonskom Brodu, Slavonski Brod, 2006.

[5] HUNDAL, M.: *Design for Recycling and Remanufacturing*, International Design Conference - Design 2000, Dubrovnik, 2000.

[6] LEET, SM.; OVERLY, J.; KINCAID, L.; GEIBIG, J.: *Desktop Computer Displays: A Life-Cycle Assessment*, EPA/744-R-01-004a, 2001.

[7] OPALIĆ, M.; VUČKOVIĆ, K.; PANIĆ, N.: *Consumer electronics disassembly line layout*, Polimeri 25(2004)1-2, 20-22.

[8] MENAD, N.: *Cathode Ray Tube Recycling*, Resources, Conservation and Recycling, 26 (1999), 143-154.

[9] ...: *CRT Recycling Project*, Cascade Asset Management, LLC, Madison, 2002.

[10] LEE, CH.: *A Method for the Recycling of Scrap Liquid Crystal Display*, Knowledge Bridge 45(2004), 2-3.

[11] KERNBAUM, S.; FRANKE, C.; SELIGER, G.: *Flat Screen Monitor Disassembly and Testing for Remanufacturing*, Proceedings of 13th CIRP International Conference on Life Cycle Engineering, Leuven, 2006.