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Disassembly Factories for Electrical and Electronic Products To Recover Resources in Product and Material Cycles

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Cycle economy as a paradigm for industry in the 21st century depends on the economical and ecological treatment of limited resources. The objective is to achieve more use with fewer resources to increase the use-productivity of these resources. The European Union, aware of the adverse environmental impacts associated with electrical and electronic consumer goods in particular, has passed legislation regulating their appropriate end-of-life treatment. Adaptation processes, including essential disassembly and re-assembly operations, contribute significantly toward the economical fulfillment of these new legal requirements. Typically, the disassembly of used products is characterized by a high rate of manual operations, wide variety of product types, and unknown product properties. To cope with such demands, life cycle units or product accompanying information systems, are being developed and used for acquiring data about a specific product throughout its life cycle to aid in determining the level of product deterioration. Modular disassembly processes and tools have been developed and realized to enable the handling of multiple product variants. They are being implemented in prototypical hybrid disassembly systems for large- and small-size electrical and electronic consumer goods.

Introduction

Cycle economy as a paradigm for industry in the 21st century depends on the economical use of limited resources. Ecological limits must not be exceeded, and resources must be saved without lowering current standards of living. In short, more use must be obtained from products with fewer resources consumed in the process. Thus, increasing the use-productivity of resources is necessary (*1*). In Europe, current approaches for implementing a sustainable cycle economy by increasing the use-productivity are reflected by regulations such as the directive on Waste Electrical and Electronic Equipment (WEEE) (*6*), which will take effect in August 2004. The arising requirements can best be met by ensuring multiple use phases of products and components through adaptation processes (*5*), such as disassembly and re-assembly, to adapt a product for its respective new phase (*2*, *3*). Product accompanying information systems and disassembly processes by modular tools in hybrid disassembly cells contribute to effective and efficient adaptation (*4*).

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Environmental Impact of Electrical and Electronic Products and WEEE Requirements

Most industrial processes, including the electrical and electronics industry, have a major impact on the environment. During their life cycles, many electrical and electronic devices consume resources that are more or less scarce. Often, limited materials such as thallium, rubidium, and cesium are used, resulting in their rapid exploitation (*7*). Additionally, hazardous waste is generated throughout a product's life cycle, beginning with the raw material acquisition all the way up to end-of-life (EOL) treatment.

With respect to the pollution caused by this immoderate consumption of scarce resources and hazardous waste generation, the European Parliament passed the WEEE directive to regulate the separate collection and appropriate EOL treatment as well as designs for recycling of electrical and electronic goods (*6*). Under the new law, 10 major categories of materials used in electrical and electronic consumer goods must be recovered (see Figure 1). Here, the term recovery means the recycling of materials and the reuse of individual components or the complete product as well as energy recovery. In addition, WEEE specifies selective treatment processes for certain components—for example, the prior disassembly of printed circuit boards, batteries, or components containing hazardous materials such as flame retardants, asbestos, or mercury.

Manufacturers, therefore, must either recycle the materials used in their products for reprocessing in new production processes or reuse products or components to meet the specified recovery rates. However, there are intercessory aspects for pursuing material recycling. Studies indicate that state-of-the-art recycling processes are not yet capable of meeting the required recovery rates due to inadequate process efficiencies. Current cellular phone designs, for example, have been identified as not being able to meet the WEEE requirements, despite the application of complex recycling processes (*8*). Additionally, significant amounts of energy and raw materials are required to produce recycled products as compared to reuse. Reuse, therefore, represents the greenest EOL treatment option, contributing more to increased use-productivity of resources by enabling multiple usage phases.

Adaptation for Multiple Usage Phases

Products reach the end of their useful life as a result of various deteriorations. These deteriorations can be differentiated into physical changes—such as aging, breakage, corrosion, creep, deformation, fatigue, loss/displacement, and wear—and changing requirements, such as fashion trends or technical progress (*9*). These deteriorations cause restrictions or loss of product functionality, reduced environmental product performance, image loss, and even higher operation costs. Consequently, the end of a product's life is initiated when the product reaches the end of a usage phase. To enable additional usage phases, ensuring product or component reuse, a treatment is often necessary.

Processes aimed at transferring products or components to further usage phases are designated as adaptations (*10*), which include maintenance, repair, and remanufacturing. Their objective is to remove physical deteriorations or meet changing requirements by upgrading/downgrading, enlarging/reducing, rearranging, or modernizing a product (see Figure 2).

An adaptation process consists of several sub-processes. Material handling processes are needed for the supply and

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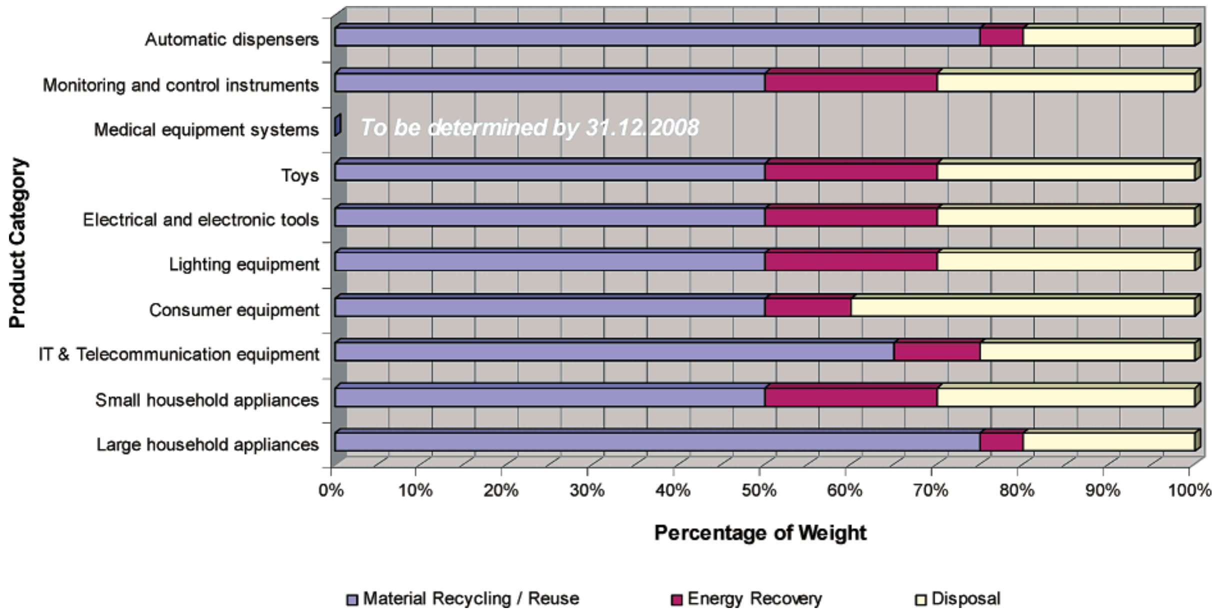

FIGURE 1. Required recovery and allowed disposal rates of electrical and electronic equipment by WEEE.

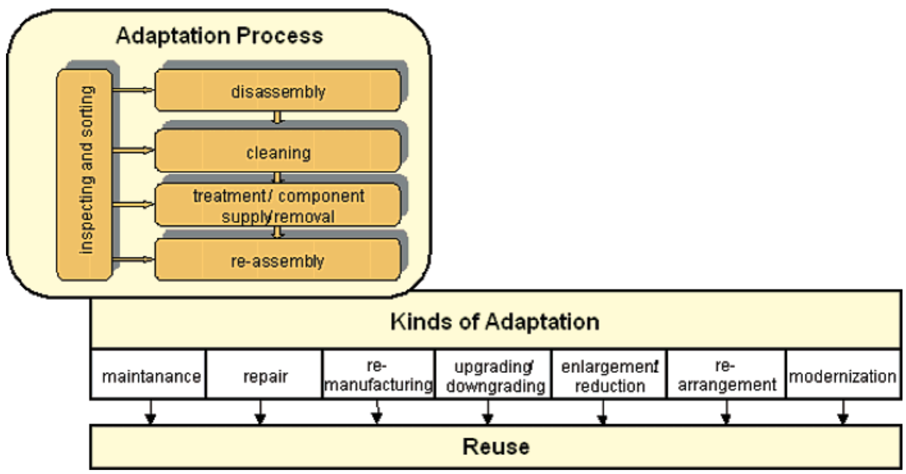

FIGURE 2. Types of adaptation and adaptation processes.

removal of components as well as treatment. Disassembly and reassembly are essential parts of an adaptation process. The disassembly process is characterized by the number of components to be disassembled, which varies according to the type of adaptation applied. For example, the disassembly of all product components is necessary when remanufacturing a product, whereas a product repair can be realized by disassembling only the deteriorated components. What manufacturing processes are applied depends on the existing deterioration. These processes are designated as treatment processes. Furthermore, cleaning processes are required for product adaptation, as are inspection and sorting as accompanying processes.

Obviously, the challenges for economical adaptation of used products (see Figure 3) result from the enormous number of product variants that exist on the market. Specific geometrical features, the number and type of components included, and the product structure characterize each product. To apply state-of-the-art adaptation processes, a multitude of different tools must be provided. Current adaptation processes are only conducted manually, so instructions, such as disassembly plans for the differing products, must be provided.

An economical adaptation also requires the treatment and disassembly of only those products that are deteriorated. Thus, knowledge of actual deteriorations and their extent must be provided prior to the adaptation process.

Life Cycle Unit: Information Provision for Adaptation Processes

Deteriorations in the form of physical changes are caused by biological, chemical, electrical, mechanical, radiation, or thermal mechanisms. Their extent is determined byproduct characteristics such as material or treatment, external influences such as temperature or dust, and type of usage. To conduct economical adaptation processes, knowledge about physical changes, product-specific characteristics such as components contained, and disassembly plans must be provided.

Microsystem technology offers new potentials for the development of innovative product accompanying information systems that acquire information by sensors and then process, store, and transfer data for evaluation. Additionally, actuators initiate disassembly processes (*11*). Figure 4 shows the life cycle unit (LCU) concept consisting of the four modules: sensor, marking, life cycle board (LCB), and actuator (*12*).

Sensors are integrated into products or components to acquire information on deteriorations such as aging, break-

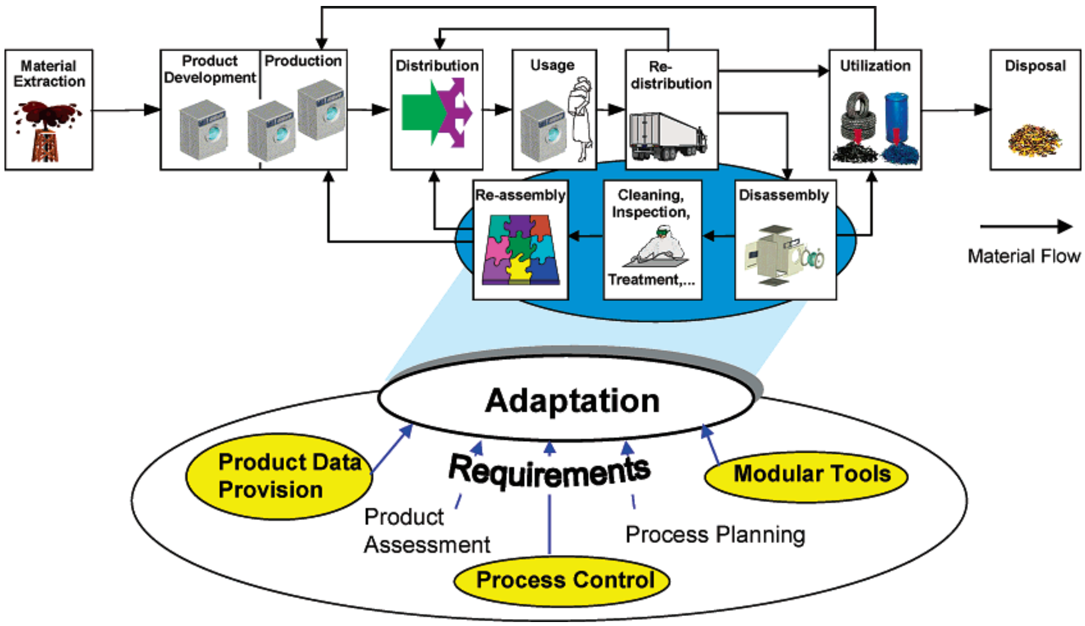

FIGURE 3. Requirements for multiple usage phases by adaptation.

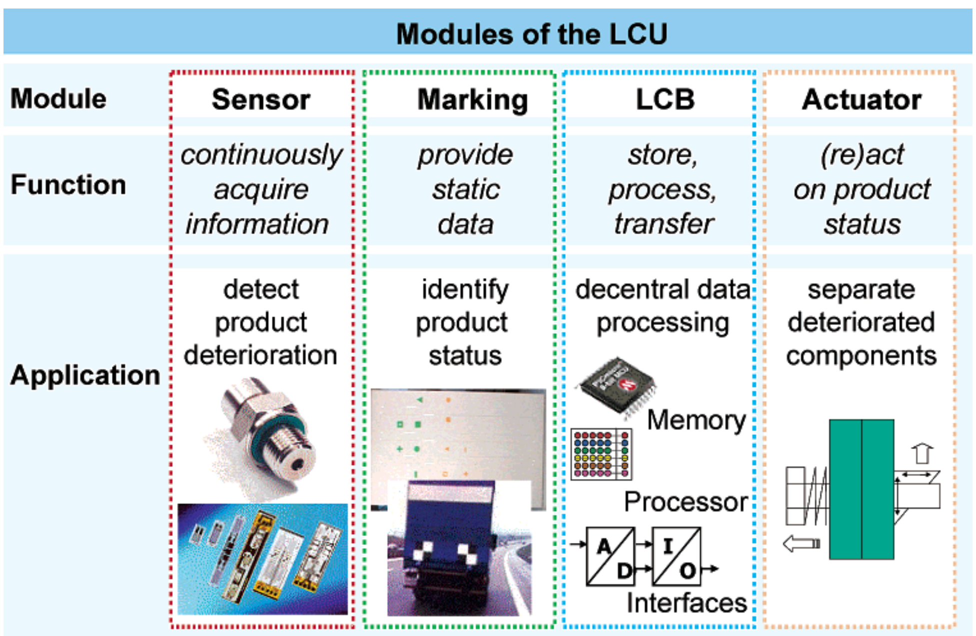

FIGURE 4. Modules of the life cycle unit (LCU).

age, corrosion creep, deformation, fatigue, and wear. Information is encoded in markings, bar codes, or transponders to support sensorial acquisition and decoding. The LCB (which consists of a processor, memory, and interface) is able to process, store, and transmit this information. The actuator module reacts on the acquired or stored information to compensate for the effects of deterioration.

Figure 5 shows the prototypical application of the LCU in a washing machine (*22*). The washing machine is equipped with sensors to acquire information on deteriorations of the depicted components. Parameters such as flow rate, voltage, current, temperature, and operating times are measured. Figure 5 also depicts the first prototype (top) of the LCU and its current development status (bottom left). In this concept, the information is read out by a personal digital assistant via infrared (IrDa) connection (bottom right). Here, not only is information on deterioration transmitted but also process-related information, such as a disassembly plan for the specific washing machine model. This concept focuses on local maintenance operations.

Flexible Disassembly Tools

Disassembly tools can be used for three major purposes: disassembling adaptable components, sorting material fractions, and separating hazardous materials. Fast access to the specific components is also necessary. The wide range of used products, the wide variety of joints within these products, and the unpredictable deteriorations of components and joints due to usage require flexible disassembly tools (*13*). Conventionally, many different ordinary assembly tools are used to disassemble products. However, ordinary assembly tools have not been designed for disassembly purposes. These tools use existing acting surfaces on joining elements to transmit forces and torques for the loosening or handling process. Acting surfaces must be detected and

FIGURE 5. Application of the LCU in a washing machine.

localized. The appropriate tool for loosening must be selected as well as positioned and oriented according to the acting surfaces.

Disassembly processes can be classified as nondestructive, partially destructive, and destructive. Destructive disassembly can be performed with a few flexible tools that create their own acting surfaces. To meet the high flexibility demands of disassembly processes, tools should be applied to a wide range of geometries. New end-effectors that create their own acting surfaces at the beginning of the loosening, handling, or fixing process have to be developed (*14*).

The approach of generating new acting surfaces for transmitting forces and torques has been implemented in the development of several prototypical disassembly tools (*11*). For example, a flexible tool for the loosening of screws has been developed and prototypically built. Screws are the most frequently applied joints in products, and they appear in a wide variety with regard to head shape and size. Additionally, screws are often worn or corroded at the end of the product's life cycle. Conventionally, screwing tools are used and adapted to the existent shape of the screw head by changing the screw bits. The torque for loosening the screw is transmitted through the existing acting surfaces of the specific screw head. Thus, a number of different tools are required, and frequent tool changes and modifications are necessary during disassembly processes, decreasing their efficiency and increasing the costs. The developed flexible unscrewing tool is characterized by its shape-independent end-effector. The end-effector is used by the tool to generate its own acting surface through a pneumatic driven internal impact mass with minimized reaction forces for the user or the operating robot (Figure 6).

The operation mode of the flexible unscrewing tool is depicted in Figure 7. The necessary acting surface is generated by a high-frequency impact mechanism with an energy of 15 J and a frequency 50 cycles/s.

The duration of the impact can be adjusted with a time switch. The necessary duration depends on the screw's size and hardness. After generating the acting surface, the screw is unscrewed by a pneumatic drive. A hydraulic rammer supports the unscrewing process by transferring rotatory impacts. Conventional bits can also be inserted in the high-speed clamping system instead of the sharp-edged end-effectors. Thus, the tool can be used as a normal air-powered screwdriver. For simple and safe applications, a special centering device has been developed that enables the worker to center the end-effector safely onto the screw head.

For fast adaptation of used products, modular and flexible disassembly and reassembly tools are needed. Tools for handling components and loosening joints are usually composed of units with similar functional structures. For example, a rotating motor is needed to transmit the loosening torque into a screw head as well as for driving the wheel of a cut grinder. To enable a reconfigurability, the units are designed as modules. The modules are characterized by uniform interfaces for energy and information flow and by fast exchangeability. Additionally, specific levels of performance must be considered with respect to different applications. As many different applications as possible with as few tools as possible. This can be achieved by reconfiguring the modules according to the specific disassembly task. Thus, tool flexibility increases while the overall costs decrease. Figure 8 shows a modular tool kit for disassembly tools.

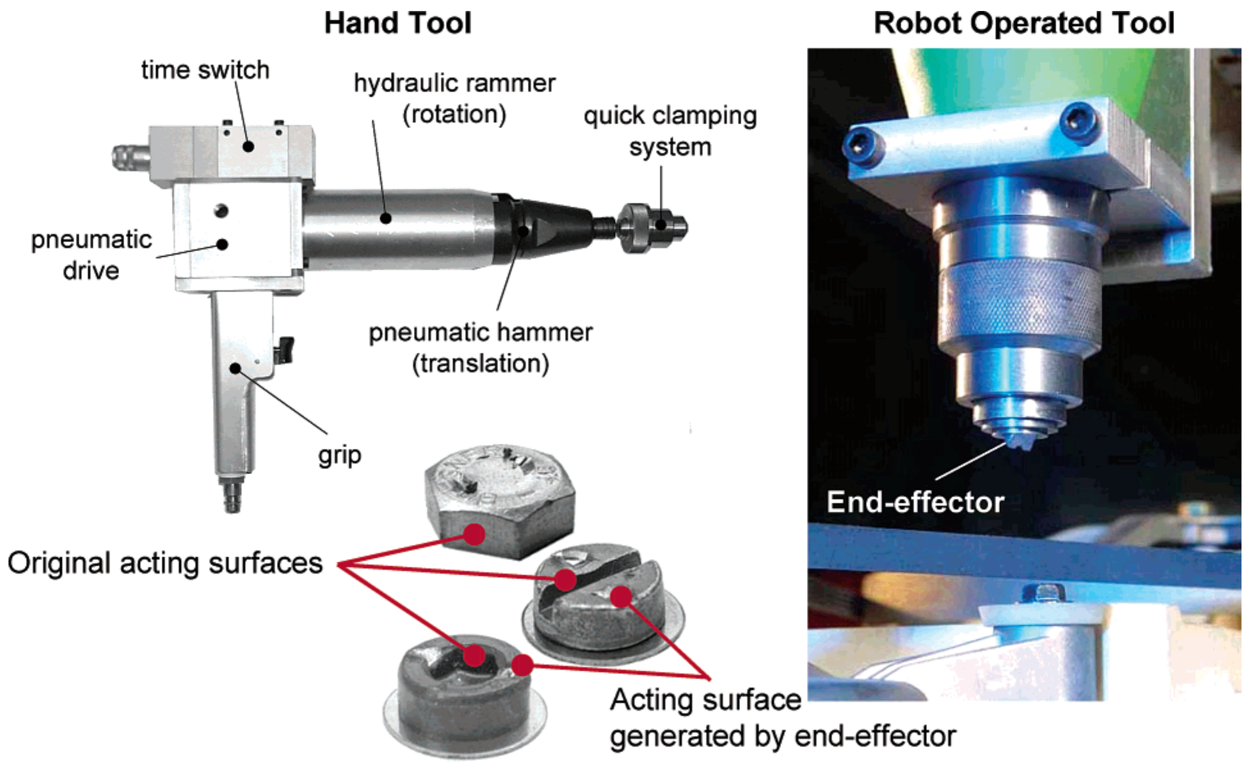

FIGURE 6. Flexible unscrewing tool (*11*).

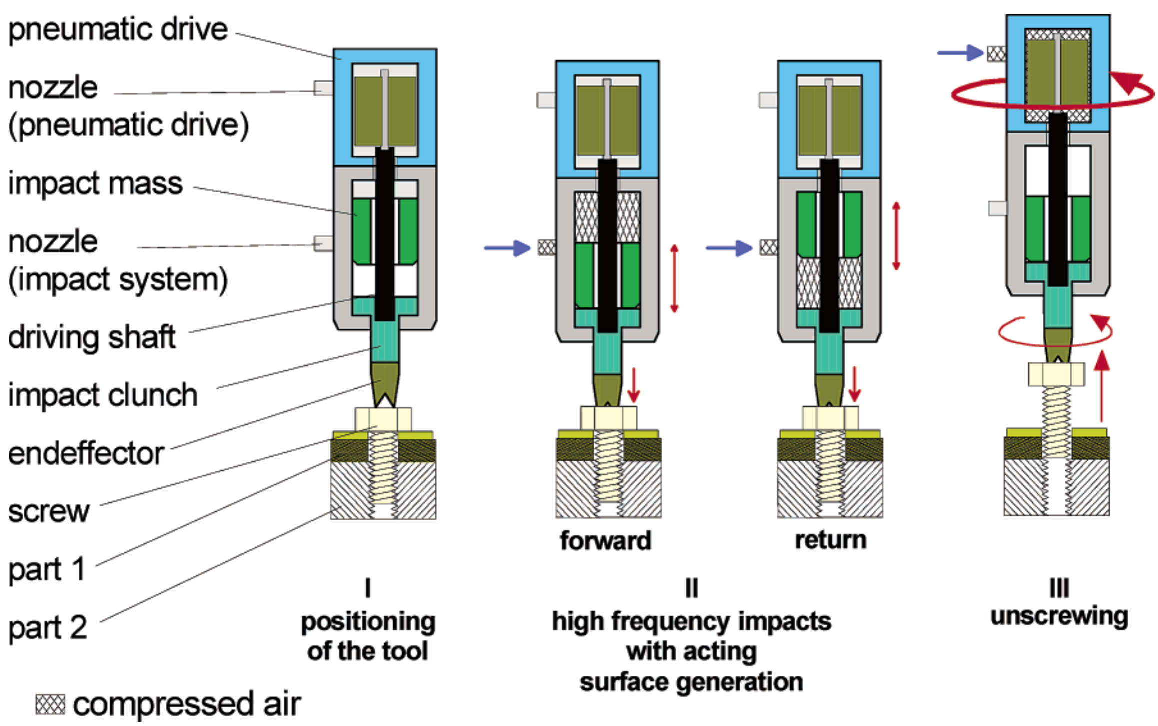

FIGURE 7. Operation sequences of the flexible unscrewing tool.

Case Studies

Disassembly Factory for Large Household Appliances. A prototypical disassembly factory for large electrical and electronic household appliances was developed. Figure 9 shows the annual number of products that fall into this category in Germany and the respective mass to be discarded. Nearly 600 000 t of waste metals, plastics, and electronic components such as printed circuit boards must be handled and treated every year.

Within a modular factory concept, manual and automated work stations are linked via a flexible transport system. Given the high flexibility demands of disassembly, this paper examines whether manual and automated work stations can be economically and reliably integrated into a flexible disassembly system. The chosen layout consists of a star-shaped structure with two bypasses at the front and the back. The front working area is for automated disassembly, and the back area is for manual operations supported by the LCU module marking. The system consists of three cooperating robots, arranged symmetrically along the mirror axis. The disassembly tools are integrated as modules in the disassembly system (Figure 10). Modules are a screwnail

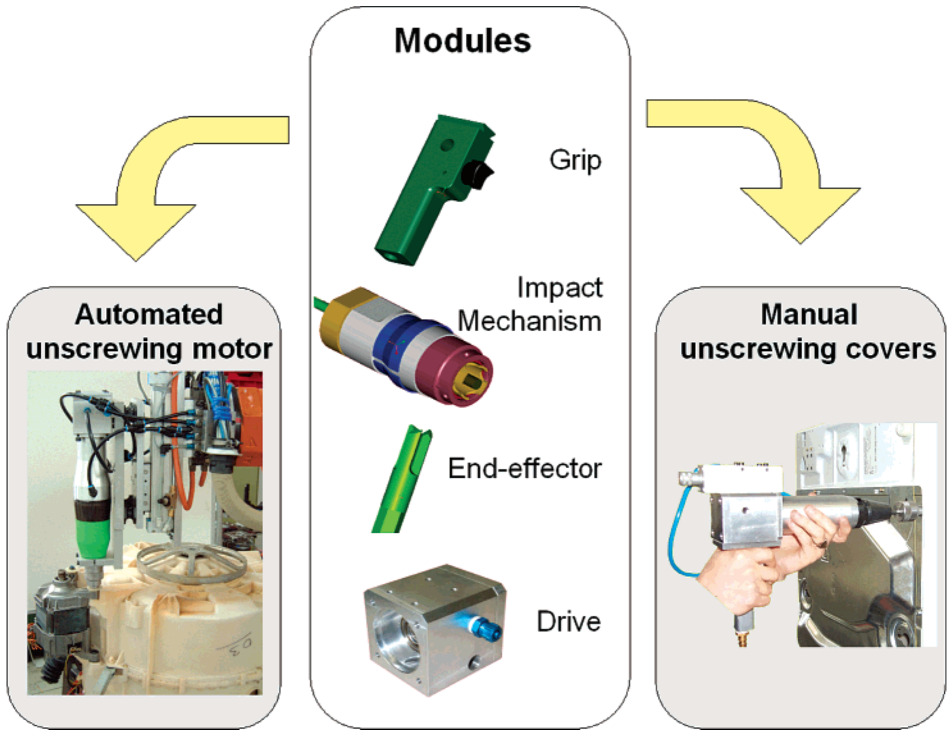

FIGURE 8. Modular and flexible unscrewing tool.

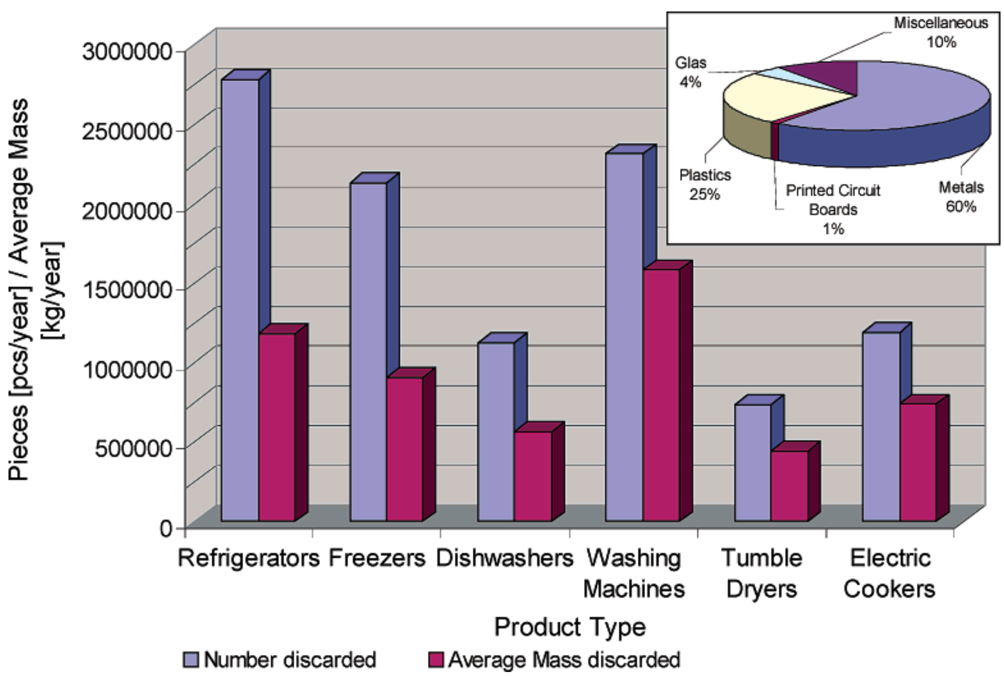

FIGURE 9. Pieces, mass, and material composition of large household appliances discarded annually in Germany (*15*, *16*).

gripper for plastic parts, a loosening tool for band clamp fittings, a scissor gripper for flexible parts, a screwnail gripper for heavy tumble systems, and an unscrewing tool.

Transferring product information to the control of the disassembly cell plays a major role. Necessary product information is transmitted to the control by the LCU. For example, disassembly plans that determine the components to be disassembled according to specific deteriorations can be specified. Additional databases are linked by an administrative information platform via the Inter- or Intranet, based on the Ethernet standards.

Disassembly Factory for Cellular Phones. The number of cellular phone users has grown dramatically worldwide. Today, there are more cellular subscribers than wireline phone subscribers (*17*), with estimates of more than 1.3 billion. At the same time, the number of obsolete cellular phones is constantly increasing. Currently, more than 500 million phones (*18*) are estimated to lie idle in closets and drawers, creating a stockpile that weighs more than 250 000 t. In Germany, the number of phones that are discarded annually with domestic waste to either be landfilled or incinerated is estimated to be 6.5 million, creating the potential for the release of heavy metals or halocarbon materials from batteries, printed wiring board, liquid crystal displays, plastic housings, wiring, and other materials (*19*, *20*). Once it takes effect in 2004, WEEE will cause a constant

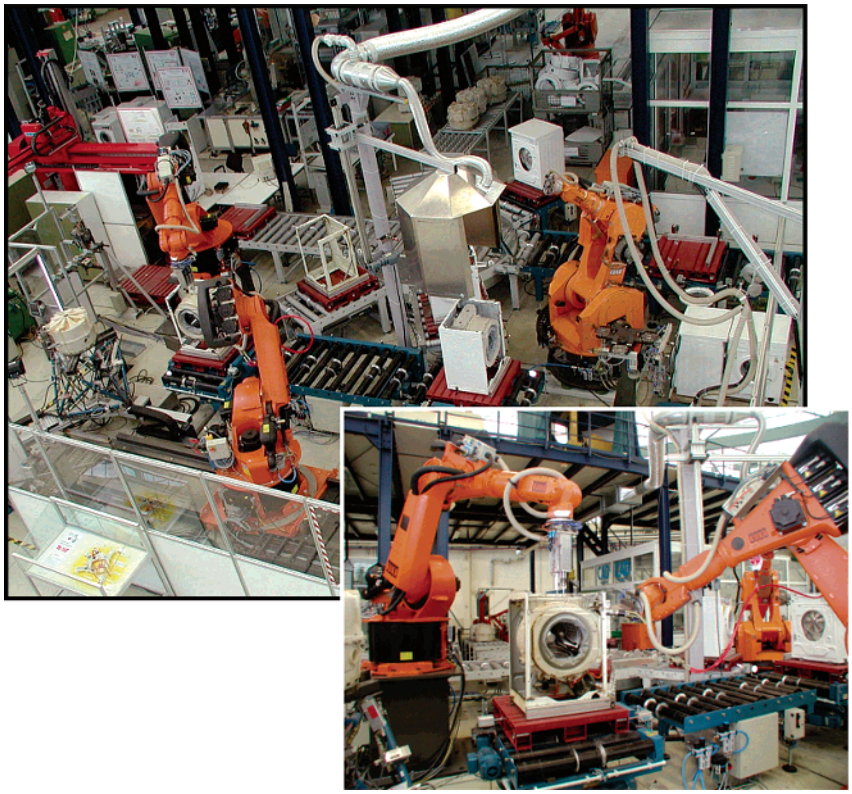

FIGURE 10. Prototypical disassembly factory for large household appliances.

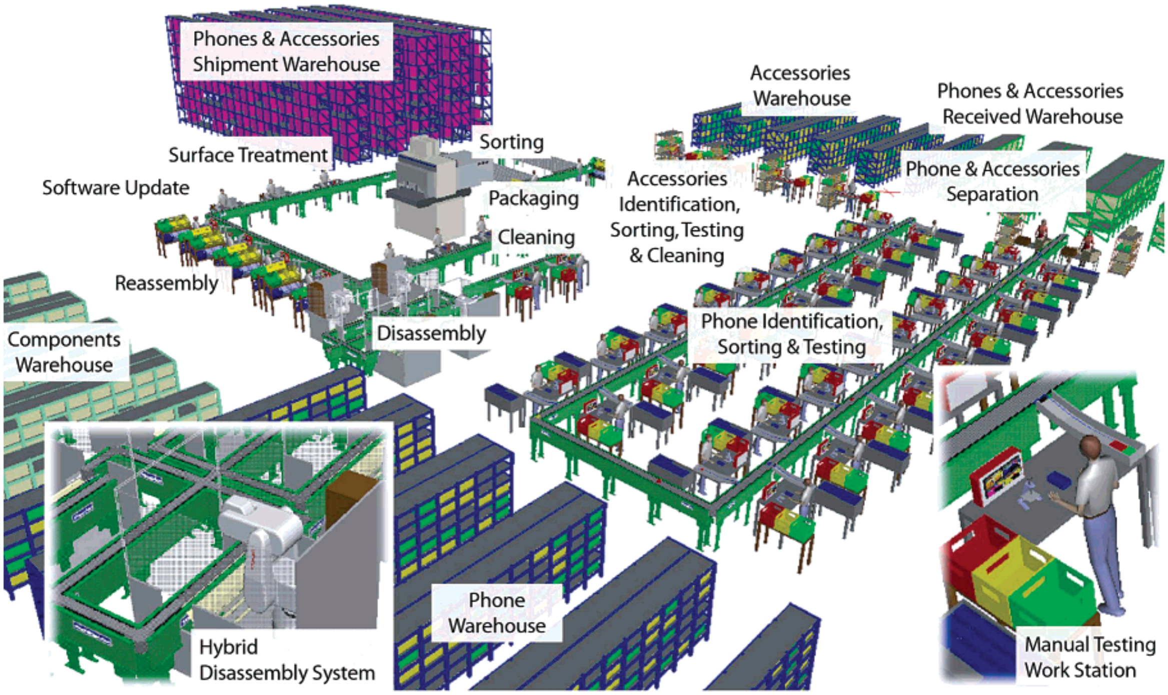

FIGURE 11. Virtual disassembly and adaptation factory for cellular phones (*21*).

reflow of up to 8 million cellular phones to be discarded only in Germany.

Additionally, cellular phones are characterized by an extremely high number of variants. Exacerbating these problems is the fact that cellular phone components are typically required to fit into a tight, enclosed space, which makes manual disassembly for component recovery and remanufacturing a challenging task.

To cope with the upcoming large volume of obsolete cellular phones, a disassembly and adaptation factory was virtually designed and graphically dynamically simulated with a discrete-event simulator (Figure 11).

Within this factory concept, cellular phones are sorted and tested, with older ones sent to external recycling. Phones that can be resold but need repair are disassembled, cleaned, and repaired to the extent necessary for achieving desired

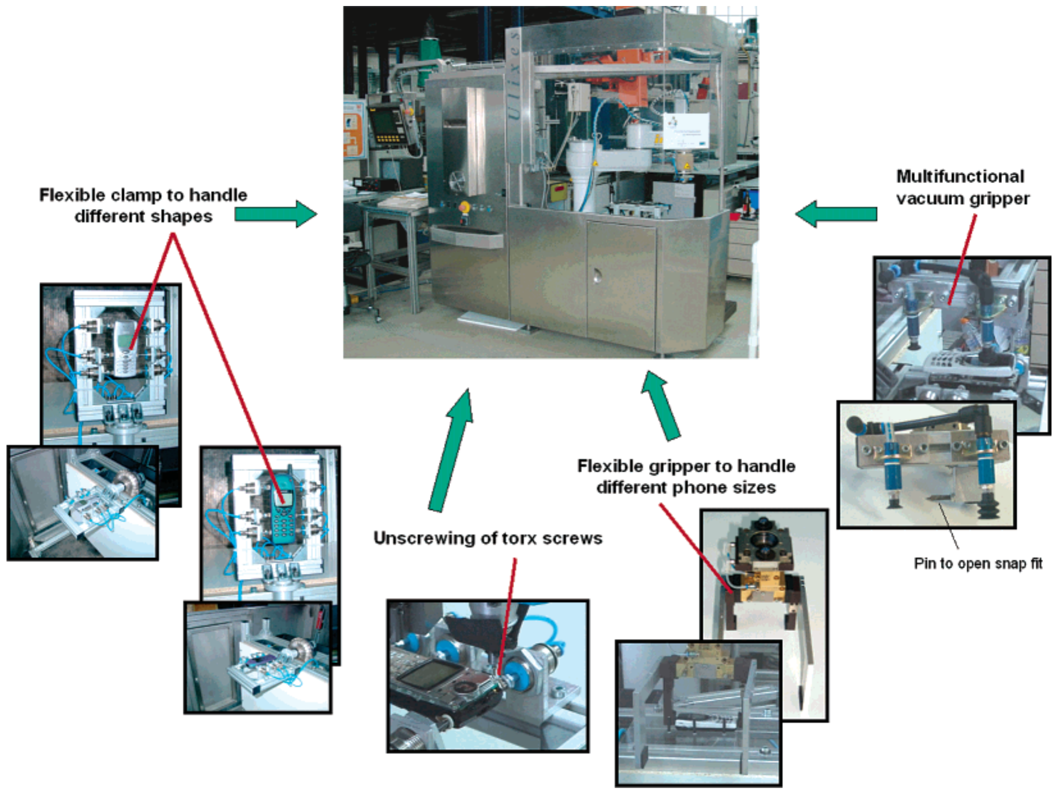

FIGURE 12. Hybrid disassembly system for cellular phones.

TABLE 1. Processing Times for Automated and Manual Disassembly of a Nokia 5110 Cell Phone

automated disassembly						manual disassembly
no.	tool no.	operation	primary process time (s)	secondary process time (s)	savings possible (s)	
1	1	identification of bar code	2			
2	2	pick and place in clamping device	5.42	9.32	2.5	
3	3	removal of housing cover	5.8	11.65	9.6	
4	4	unscrewing 4 × screw Torx 5 PWB	55.94	17.87	11.03	
5	5	rotation of clamp	2			
6	4	unscrewing 2 × screw Torx 5 of display PWB	25.85	4	4.16	
7	3	removal of display PWB	2.6	26.6	18.75	
8	4	unscrewing 1 × screw Torx 5 PWB	11.95	2.54	2.13	
9	3	removal of PWB	2.84	17.01	9.91	
total			164.55		34.95	98

[a] Tools: 1 = CCD vision system fix mounted; 2 = flexible gripper; 3 = vacuum gripper; 4 = screwing spindle; 5 = flexible clamp.

quality levels. Afterward, cleaning and software updating processes are applied. Following packaging, the phones enter the distribution stock.

A core part of the described factory concept is a hybrid disassembly system (Figure 12). Here, innovative tools such as a flexible clamping device that can handle cellular phones independently of their size and shape, a multifunctional vacuum gripper, and an unscrewing tool are integrated and operated by a robot.

In this system, the only manual operation is the removal of the main battery. The robot used is a 4-axis Scara, Adept Pack One brand. Of important note is that the system itself is a Reuse System, which was operated as a Food Robot for the mass production of sandwiches. The sensory equipment and the flexible tools that have been developed and implemented characterize the system.

Cellular phones are identified with a vision system. The International Mobile Equipment Identity (IMEI) number, which is listed as a 15-digit bar code, is detected with a CCD camera. This code uniquely describes the model and type of the specific phone.

A flexible gripper is used to pick cell phones independent of length and width. It places the phone in a flexible clamping device. Here, pneumatic cylinders are used to form the specific shape of the phone, and thus are able to grip independent of the provided phone geometry. The clamping device is attached to a pivot arm to ensure the time-efficient removal of nonridged parts, such as the key pad, by rotatory movement.

Cell phones with exchangeable front housing covers usually provide snap fits to attach the front housing to the back housing. A vacuum gripper with a specially shaped spike is used to open these snap fits and remove the front housing.

A commercial screwing spindle, operated in left-hand motion, is used to remove the screws. Most commonly, screws of the Torx 5 type are used. The tools described sit in a tool changing system as shown in Figure 12.

The disassembly process for a cell phone like the Nokia 5110 (Figure 13) is shown in Table 1. This phone is characterized by the high quantities sold. Belonging to a group of rather old models, it has 2 PWBs, one main and one for

FIGURE 13. Product structure of a Nokia 5110 cell phone.

the display, as well as several components that are separately connected to the housing.

As shown in Table 1, process times were recorded for automated disassembly, as well manual disassembly operations. Obviously, the processing times of the automated operations are about 170% of the manual ones. This is due to an inadequate system configuration that resulted from financial limitations. Most of the surplus results from the necessary tool changes. Integrating all the tools into one would lead to savings as shown in Table 1. Taking into account the high labor costs in European countries, automated disassembly would be able to economically compete with manual disassembly, despite the slightly longer operation times.

Conclusion

The adaptation of electrical and electronic products and components helps to reduce their environmental impact. Modular disassembly devices applied for product or component adaptation between different life cycle phases meet the requirements of continuously changing disassembly operations. The LCU concept provides access to status information throughout the life cycle of products and their components, thereby assisting in the planning, scheduling, and executing operations in disassembly and reassembly adaptation processes. Tool concepts with as many standardized modules as possible and as few application-specific elements as necessary save in setup and investment costs. Disassembly devices were integrated into disassembly factory concepts for large and small electrical and electronic consumer goods using both manual and automated modules.

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