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Design for Automatic End-of-Life Processes

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Structured Abstract

Purpose: This paper aims to explore how manufacturers can develop automatic end-of-life processes facilitated by product design methods, e.g. design for disassembly, recycling and remanufacturing. Another aim is to illustrate this kind of product and end-of-life process development while maintaining economic and environmental values. Here, the cases of toner cartridges and liquid crystal displays are the focus.

Design/methodology/approach: The research methodology for this paper began with a literature study within the fields of design for automatic recycling and remanufacturing. It also includes the research performed at two different industrial companies using automation in their end-of-life processes. These companies were visited and interviewed several times in order to understand their processes and what current problems they have in automation and product design.

Findings: Design implications on the end-of-life have been explored, and in particular, three general product trends are in conflict with automatic disassembly; 1) Products are getting more complex and more heterogeneous, 2) Products are getting sleeker and 3) Products are using more proprietary joints. In addition, the three industrial cases describe different problems in industry and how they can be tackled. Although many manufacturers have adapted the design principles of DFM and DFE, there is still much to improve when it comes to designing for the product's end-of-life processes. These kinds of adaptations should increase in importance over time as more and more products and components are remanufactured and/or material recycled. These kinds of adaptations will also encourage an increase of products passing through more resource efficient end-of-life options.

Practical implications: Manufacturers reading what design problems other companies are experiencing and what solutions can be found would facilitate their own businesses and willingness to start their own and/or improve their existing manufacturing business. This could then be in shape developing products for end-of-life processes which also would encourage them to start their own end-of-life process facilities.

Social Implications: From a societal perspective, an increase in remanufactured products being placed on the market can increase the awareness and confidence of the consumers in non-new products made from non-virgin materials. This will increase the market for second-life products and bring about economics of scale, which in turn will alleviate the problem of depletion of resources.

Originality/value: Most previous research in this area treats the different end-of-life processes separately; material recycling and product remanufacturing are but two examples. However, in this paper the focus is more on the overall view of end-of-life processes, along with examples of more specific and detailed end-of-life processes such as disassembly and cleaning.

Keywords: Disassembly, Assembly, Industrial Robotics, Design for Disassembly, Assembly, Snap-fit, Cleaning, Industrial Robotics, Recycling, Refurbishment, Industrial Robotics

1. Introduction

As resources become scarcer and prices of raw materials increase, reducing manufacturers' need to buy new materials and components to produce their products is made more beneficial. One way for companies to achieve this is by adapting to more circular flows of products and materials (Sundin & Bras, 2005). To do so, product end-of-life (EoL¹) processes, including product remanufacturing and material recycling, become more important. In addition, EoL processes are increasingly essential parts of manufacturers' business models to help protect their assets (Östlin et al., 2008) and become more environmentally and economically sustainable (Sundin and Bras, 2005). However, EoL processes are not always easy to perform efficiently by hand. Automation is a way for recyclers to reach preferable efficiency. In the same way that designers can adapt their products for manufacturing (DfM), they can also consider ways to facilitate EoL processes for their products (DfEoL), the focus of this paper.

1.1 Aim

This paper aims to explore how manufacturers can develop automatic end-of-life processes facilitated by product design methods, e.g. design for disassembly, recycling and remanufacturing. Another aim is to illustrate this kind of product and end-of-life process development while maintaining economic and environmental values. Here, the cases of toner cartridges and liquid crystal displays (LCDs) are the focus.

1.2 Research methodology

The research methodology consisted of a literature study within design for automatic disassembly, recycling and remanufacturing. In addition, empirical data from industries was added through the case studies of toner cartridge remanufacturing and recycling and component reuse of LCDs.

The toner cartridge case is based on research performed at a toner cartridge remanufacturer operating independently from the original equipment manufacturer (OEM). The industrial case is based on the authors' research at this company in a project called REKO², which has provided a solid understanding of the company's problems and solutions regarding its economic, environmental and work environmental performance (see also Sundin and Östlin (2005) and (Hermansson et al., 2007)). The methodology for collecting the empirical data consisted of practical work in the toner cartridge remanufacturing facility as well as interviews with directors, production managers and operators on the remanufacturing line.

The LCD case is based on a research project called HÅPLA³, which includes several electronic recyclers, e.g. Stena, Hans Andersson Metal, Kuusakoski and MRT Systems as well as electronic product manufacturer Samsung. The recyclers were visited and interviewed by the authors in order to gain knowledge about their operations. In addition, the companies have actively participated in the HÅPLA project (see also Elo and Sundin (2010 and 2011)).

¹ Generally, EoL refers to the stage when the product is no longer useful to the initial owner or purchaser.

² REKO is short for the research project "Sustainable Systems and Products for Reuse and Remanufacturing".

³ HÅPLA is short for the research project "Sustainable Recycling of Flat Panel Displays".

2. Product Life Cycle Perspective

When designing products with other aspects that go beyond the manufacturing stage, it is important to have a holistic system view and to adopt a life cycle perspective (see Figure 1). In this paper, the focus is on EoL processes and how these processes relate to the product life cycle, especially design.

Figure 1 The product life cycle (modified from (Lee, 2006)).

The EoL stage is the last stage of a product life cycle before looping back to the earlier stages, as shown in Figure 1. Furthermore, Figure 2 shows the different EoL sub-stages that a product will typically go through at the EoL stage.

Figure 2 Decomposition of the product end-of-life stage.

The EoL management of a product has to be at an optimal level and not restricted to only disposal or recycling in order to increase the recovery value and reduce the environmental impact. Problems with EoL today are mainly due to products not being designed to facilitate EoL processing; most products are expected to be disposed of. Hence, it is important that changes in concept and mind-set at the design forefront address the problem from its root, and at the same time solve current problems using state-of-the-art technology.

2.1 Automatic End-of-Life Processes

As can be seen in Figure 2, disassembly is a major sub-stage that many products must go through at their EoL stage in order to be remanufactured, recycled or properly disposed of. As defined in a previous study by Lee et al. (2008), there are two aspects to consider: improving the ease of disassembly through product research and development, and improving the current available disassembly automation technology. Easing disassembly from the design perspective has been studied by several researchers before, e.g. Johansson (1997) and Bogue (2007). This is an important element to consider during design because it will bring about benefits including simplification of products, lower assembly and manufacturing costs, reduced overheads, improved quality and reduced time-to-market (Boothroyd and Altling, 1992).

2.1.1 Motivations for Automated Disassembly

Disassembly can be automated to be more productive and reduce cost, so as to make it more economically viable to encourage a higher level of EoL management such as remanufacturing according to the waste hierarchy. In the WEEE⁴ sector, for example, recyclers are increasing the degree of automation due to increasing volume and labour cost (Santochi et al., 2002, Kopacek and Kopacek, 2006).

Another reason for automated disassembly is to reduce human contact with toxic and harmful substances detrimental to human health. These issues have also been pointed out by (Bogue, 2007) as a crucial factor when planning a disassembly process. This is evident in the disassembly of WEEE, which contained harmful substances such as mercury and beryllium. In addition, the toner used in toner cartridge remanufacturing could also be harmful to workers.

2.1.2 Limitations of Automated Disassembly

Ijomah and Chiodo (2010) have found disassembly as a bottleneck for a higher rate of recovery and as an important factor for the success of remanufacturing. Recyclers often do not separate components due to the high cost of disassembly, and remanufacturers often do not automate their disassembly processes due to low volume and rapidly changing product technology. A 100% manual EoL process will provide the remanufacturers/recyclers the greatest flexibility to change their process line in times of low volumes, such as during economic crisis, despite the limitations in productivity. This often requires a sustainable rate of return on investment and a minimum product volume for the process to be profitable. Hence, it also implies that automation will reduce the flexibility of the operations at the EoL as the processes are fixed and can be costly to change.

Given that the EoL industry can be volatile depending on the economic situation, it has more constraints and limits the development of technology. Furthermore, disassembly is inherently more difficult to automate as compared to assembly. Figure 3 shows the relevance and differences of assembly and disassembly in the product life cycle.

⁴ Refers to Waste Electrical and Electronic Equipment.

Figure 3 The relationship of assembly and disassembly in the product life cycle.

A big challenge to automate disassembly is that a disassembly process gets variable input, unlike an assembly process where input is fixed. This increases the uncertainties and makes it harder to design the automated processes. In the design of an automation process, the input requirements determine how robust and flexible the system has to be to deal with the uncertain input. According to Wittenberg (1992), for example, it is ideal to have a comprehensive, automatic identification system, together with component design for convenient and reliable automatic disassembling, as well as the provision of an automated means of disassembling to give the product designer the freedom to use any type of plastics material for any part of the product with the knowledge that it can be efficiently recovered for re-use or recycling. Instead of trying to reach this ideal, the designers could e.g. reduce the number of plastics to improve the EoL process. This has, according to (Bogue, 2007), been conducted in Japan for TVs; there, the types of plastics have been reduced from 13 (in 1984) to 2, hence reducing disassembly times from 140 to 78 seconds.

When a system must cater to more types of input, the functionality of the system needs to be increased along with the number of constraints in design, thus making the system more difficult and costly to implement. The industrial cases in this paper demonstrate how the variable inputs have been considered in the process of devising a common platform solution for automatic EoL processes.

2.2 Product Design Issues

When a product is not designed with EoL considerations in mind, difficulties occur at the EoL stage. One problem is when a product containing an embedded battery must be recycled, such as an electronic toothbrush; another is when hazardous materials need to be separated and disposed of properly and are costly and inefficient to manage. When there is legislation in place for the hazardous materials to be separated and there is no efficient way of removing the hazardous materials through disassembly, the whole product must be sent as hazardous material, resulting in more resources being used to treat non-hazardous material as hazardous material. For example, in some electronic products beryllium is not easily removed; hence, 1kg of material is sent in as hazardous material when it actually contains only 50g of hazardous material. The additional material could have been recycled or recovered for energy instead.

Furthermore, the trend of technology and product development is also in conflict with disassembly automation. Design implications on the EoL of electronic products have been discussed by e.g. (Lee et al., 2011), who state three general product trends that clash with automatic disassembly:

- 1) Products are becoming more complex and more heterogeneous
- 2) Products are becoming sleeker
- 3) Products are using more proprietary joints

2.3 Product Design Solutions

Many EoL issues stem from design; hence, it is most effective to incorporate the EoL management consideration into the forefront product design stage. The product developer has to adopt a system perspective in designing the product as a system solution. The considerations for the features that facilitate EoL processes are necessary. This is demonstrated in the case of single-use cameras by Kodak (Bogue, 2007) and Fujifilm (Sundin and Lindahl, 2008). In the case of remanufacturing, one important criteria is that the parts that are to be replaced in repair and remanufacturing must withstand the treatment of being assembled and disassembled several times (Sundin and Bras, 2005). Harjula et al. (1996) contend typical design changes according to DfA methods will be equally beneficial in simplifying disassembly at the EoL stage. This is for example valid when reducing the number of components and improving the ease of access in assembly. However, some DfA guidelines making assembly very fast, e.g. “one-way” snap-fits, are not always suitable for disassembly. In those cases, a “two-way” snap-fit would be better, as reported by (Forss and Terselius, 1994) and illustrated in Figure 4. Furthermore, Harjula et al. (1996) state that DfD changes that simplify the removal of critical items should also be considered. This will be beneficial to small electrical products, where the batteries need to be removed easily for proper disposal, and to preserve the value of the remaining materials for recovery purposes. There are also tools available for DfEoL and for aid in decision making at the EoL stage e.g. ELDA (Rose and Ishii, 1999) and DELII (Lee, 2008).

Figure 4 The upper two figures illustrate a snap-fit that allows for several assembly and disassembly sequences, while the lower two figures illustrate a snap-fit that does not allow for the parts to be disassembled.

Another possible future solution (when economically feasible) is Active Disassembly⁵ (AD), where the disassembly ability is designed into the materials from the beginning, which will provide an easier way to disassemble a product for EoL treatment (Willems et al., 2005). This will be a feasible solution for the disassembly of small embedded batteries from small electrical products and help to automate the EoL process (Carrell et al., 2011). However, this technology is currently too expensive, given the current state-of-the-art for widespread applications in mass consumer products. Moreover, a small amount of plastics can help in the smelting processes for recovery of metals.

3. Industrial Cases

In EoL processes like material recycling and remanufacturing, the level of automation is dependent on e.g. product volumes and the need for automated processes that are preferable from a work environment perspective. In some cases, the entire remanufacturing process is automated e.g. single-use camera remanufacturing (e.g. Sundin (2004)) while in other cases, only a few recycling/remanufacturing steps are automated. This section describes following two industrial cases of automated EoL processes and what product design issues there are:

- Remanufacturing of toner cartridges (automatic cleaning)
- Recycling and component reuse of LCDs (automatic disassembly)

3.1. The Toner Cartridge Case

Toner cartridges must be continuously refilled with new toner as they are used in printers and copy machines. Therefore, there is a good opportunity for remanufacturing companies to use a trade-in system to provide customers' printers with refilled toner cartridges. Many independent toner cartridge remanufacturers operate around the world, creating problems for OEMs as they lose market share to these remanufacturers. This competition can be seen as positive for the users, however, since they can obtain cheaper cartridges meeting their requirements (Sundin and Ostlin, 2005). The remanufacturing process at the company follows the sequence in Figure 5.

Figure 5 The remanufacturing process in the toner cartridge case.

3.1.1. End-of-Life Process Challenges

The cleaning process is dirty due to the toner remaining in the retrieved “empty” cartridges. Toner is very light and attaches to most things it comes into contact with; it also penetrates the most unreachable areas, making it very hard to isolate. Production line operators are often adversely affected by the toner, complaining about irritated eyes and throats. Today, operators at the company use highly-compressed air to remove the toner residues from the disassembled cartridges. The process of cleaning the empty cartridges with compressed air is also noisy, due to the ventilation and

⁵ AD has been studied since the late 1990s by e.g. CHIODO, J. D., BILLET, E. & HARRISON, D. (1998) Investigations of Generic Self Disassembly using Shape Memory Alloys. *IEEE International Symposium on Electronics and the Environment*.

compressed air flows needed to clean the cartridges. Since the toner cartridge remanufacturing is both dirty and noisy it affects a great deal of the operators' work in a negative way.

Due to the challenges in the remanufacturing process, a new automated cleaning process was found to be crucial for meeting the present and future needs of the company. In addition, the company remanufactures various types of toner cartridges, requiring the flexibility to change small volumes of cartridges in a short period of time, and making this an important task to achieve high flexibility for the remanufacturing process including cleaning.

With automation, higher production effectiveness can be reached, not only by a faster pace, but also because manual resources can be transferred to other production stages which are more complex and time consuming. In addition, the effect on the working environment through automated remanufacturing is enormous for the company; by reducing noise and toner powder in the working areas, the personnel become more satisfied in their work.

3.1.2. End-of-Life Process Solutions

The available cleaning machines are often made for high volumes, and when the correct volume in production is not achieved, nothing will be gained by investing in such machines. Another issue is that the machines are not flexible enough, and therefore difficult to implement in a smaller factory. For this reason, the company needed to develop its own automated cleaning machine, flexible to its particular needs, shown in Figure 6.

Figure 6:

Figure 6 The toner cartridge cleaning concept in operation mode (left) and in service mode showing the nozzles used for high-compressed air cleaning (right).

In order to make the remanufacturing process work well, the company has developed special fixtures for some of the steps in the remanufacturing process. For example, there was a universal carrier to put the cartridges in before the cleaning process as illustrated in Figure 7. A big problem when developing these carriers was that there were no measurements or similar information available from the OEMs.

Figure 7 The universal carrier developed to fit all toner cartridges to be cleaned in the cleaning step.

3.1.3. Product Design Issues

In the 1980s, the cartridge design allowed easy remanufacturing, whereas the present design makes it more difficult. In earlier designs, the manufacturers used clips to attach the components and parts together.

Since the OEMs and the independent remanufacturers are competing on the same market, the OEMs are trying to create as many obstacles as possible for independent remanufacturing. Hence, the OEMs are designing their cartridges in such a manner that makes them harder to remanufacture ((Sundin, 2004)(Sundin and Ostlin, 2005) and Williams and Shu (2000)). For example, the OEMs try to make the cartridges harder to disassemble by using more molding or melting processes to join the parts together (Sundin and Östlin, 2005). Some of these designs have since been abandoned due to high production costs. However, in many cases, the independent remanufacturers need to destroy the original cartridge in order to be able to refill the cartridges (see Figure 9). Furthermore, the independent remanufacturers need to design special tools for disassembling and reassembling the cartridges. In addition, the use of joining methods such as ultrasound welding and complex design geometries makes it nearly impossible to remanufacture without toner cartridge destruction. The conflict with OEMs is a big problem for independent remanufacturers.

3.1.4. Product Design Solutions

The cartridge design can be improved. There are, for example, OEMs that use special screws in their design that could be replaced with more common screw types (also found in other products Sundin et al. (2009)).

At the company, a special disassembly method has been developed to first open the cartridge with a saw, and then, after refilling it, reseal it with a self-designed clamp (Figure 8). In addition, some manufacturers integrate computer chips into the cartridges, which need to be reprogrammed by the remanufacturer for the remanufactured cartridges to properly function, adding time and cost to the remanufacturing process (Sundin and Östlin, 2005).

Figure 8 Toner cartridge destructively opened (left) and toner cartridge resealed with a clamp (right).

3.2 The Liquid Crystal Display Case

The HÅPLA project aims to make it possible to: lower the environmental effects of today's recycling of LCDs; fulfil today's legislation and environmental gains; increase profitability in the recycling industry; foster growth for suppliers of recycling equipment through new products; improve the work environment in the recycling industry; and lower the national costs due to LCDs. The project focus is on EEE⁶-like LCDs for monitors for desktop computers and screens in laptop computers and televisions, since currently the LCDs are the most commonly used (Fang-Mei and Ai-Chia, 2009).

The HÅPLA project involves the development of sustainable process techniques for recycling components and materials in LCDs including automatic, semi-automatic and manual disassembly processes. The project involves development of recycling processes for recycling materials in LCD panels (the part which contains the glass sheets in the LCD design, see Figure 11). The remanufacturing and recycling process is shown in Figure 9.

Figure 9 The recycling process for LCDs within the HÅPLA project.

Previous research about LCD recycling has been presented in for example the projects REFLATED (Holmes, 2010), ReLCD - Liquid Crystal Display Re-Use and Recycling (Ladanyi and Miklosi, 2006, Kopacek, 2010), and PRIME - Perfecting Research on Intelligent Material Exploitation (PRIME, 2011). The REFLATED project includes development of a semi-automated shredding process and a process for recovery of liquid crystal, indium and glass. The PRIME project also focuses on usage of a shredding process before extracting the materials of interest. Another project using shredding was conducted by Swico Recycling (2011), the aim of which was to investigate the gas emissions of mercury from the process. The HÅPLA and ReLCD project approaches are to remove mercury-containing components without using a shredding process before further recycling or, as in the HÅPLA project, reusing components. However, the HÅPLA project complements the ReLCD project by testing alternative technologies, creating new products from discarded LCD monitors and proposing guidelines for new environmental legislation and environmental labels.

⁶ Refers to electrical and electronic equipment

Another result from the HÅPLA project also resulted in the reuse of parts from LCD monitors to manufacture lamps for office areas and public rooms, for example. A modified version is to be used as a light source for photo and video shooting and have the ability to act as a flash. Figure 10 illustrates two products made from discarded LCD monitors which are available on today's market (Felix, 2011).

Figure 10 LED fitting made of discarded LCD monitor films and light guide (Felix, 2011).

3.2.1 End-of-life Process Challenges

Automated recycling of WEEE has been carried out for some time. The process often involves material shredders which grind the WEEE material into smaller fractions and then separate into materials of interest, e.g. copper, aluminium and plastics (Peeters et al., 2011). The challenge with using a shredding process is to remove mercury from the other materials. As shown in the project run by Swico recycling (2011) and in the report by Cryan et al. (2010), there are fractions of mercury missing after a shredding process, and the amount of mercury is hard to track down.

The recycling industry is facing tough challenges, both technical recycling problems and a lack of information about the incoming material, for example content, size and quantity (Lee, 2008, Elo and Sundin, 2010). All EEE producers must declare the content of their products according to the European Union directive (EU, 2003). However, the recyclers still have difficulties finding information about specific products in the waste stream. The technical challenges are related to a lack of information and the technical solutions needing to be robust to comply with the sub-stages, and to be flexible (Seliger et al., 2001, Feldmann et al., 1999). The technical challenges also include compromises of process equipment, such as fixtures and tools (Seliger et al., 2001). Since the incoming material contains a variation of materials, the process equipment and properties need to be adjusted to fit several different materials.

An automated recycling process for LCDs needs to be able to sort out all other materials. The process also needs to separate LCD monitors and televisions if the backlight units contain light-emitting diodes (LEDs) or cold cathode fluorescent lamps (CCFLs) containing mercury (Elo and Sundin, 2010). The amount of incoming material processed, together with the quality of the material processed, are two central variables the industry tries to continually improve upon to remain competitive.

3.2.2 Product Design Issues

Figure 11 illustrates an exploded view of the general design of an LCD monitor (A1-A4) and LCD module (B1-B4). The design is compact, and the components are stacked in a sandwich construction and held together by a metal frame (Ryan et al., 2011). To gain access to the mercury lamps, the entire monitor and module needs to be disassembled. In some cases, the lamps are accessible by disassembling the external casing and framework of the monitor. However, the mercury lamps are often hard to remove without breaking (Huisman et al., 2007). Automation is facilitated by the general exterior design of a rectangular shape with a flat screen. However, the wide range of sizes and variation of components makes it difficult to envision and plan an automatic disassembly process.

Figure 11 The left figure is an exploded view of an LCD monitor containing four parts: (A1) plastic front cover, (A2) LCD module, (A3) metal skeleton and (A4) back plastic cover. The right figure is an exploded view of a LCD module with seven parts: (B1) front metal frame, (B2) LCD panel, (B3) optical films, (B4) splint containing CCFLs or LEDs, (B5) light guide and (B6) light reflector (Elo and Sundin, 2011).

4. Discussion and Conclusion

Automation of EoL processes is an emerging area in the field of EoL management and is one of the key factors for the feasibility of sustainable EoL management. EoL is typically associated with disposal or recycling and is not managed in an integrated manner. It is more common at the EoL stage to have a general solution for salvaging what is valuable or convenient enough for recycling before sending for disposal. The industrial cases have focused on both proactively seeking a long-term solution by designing with an end in mind, and also reactively devising automation for EoL processes so that the lead time, cost and environmental health hazards can be reduced when handling LCDs on the market today.

This research highlights the concept of product life cycle thinking and introduces new ways of thinking to cooperate in the value chain. Both industrial cases show that, with the adoption of life

cycle thinking and innovation in product development, the EoL processes can be improved. This was accomplished through the automation of certain EoL processes at an appropriate level, and it brought about an increase in the value of the recovered materials or components and a reduction in the total amount of waste going to the landfill/incinerators. In both industrial cases, the environmental health conditions in the working space have also improved. The toner no longer spilled over and the mercury has been better contained. Technical solutions for both cases were proven to be feasible and are currently implemented in industry.

In the HÅPLA project, a holistic view for managing EoL products with automation of EoL processes has been adopted and implemented. The lead time for handling a used LCD has improved and the value of recovered materials has also increased. In addition, the amount of waste going to landfill has been reduced in weight percentage from 100% to 15% at the same time as components from used LCDs are reused in LED lamps for office use. This creates a new segment in the lighting industry and more work opportunities.

From a societal perspective, an increase in remanufactured products being placed on the market can increase the awareness and confidence of the consumers in non-new products made from non-virgin materials. This will increase the market for second-life products and bring about economics of scale, which in turn will alleviate the problem of depletion of resources.

In this paper, problems have been highlighted in automatic EoL processes deriving from current (often manual) processes and the product's design. Although many manufacturers have adapted the design principles of DfM and DfE, there is still much to improve when it comes to designing for the product's EoL processes. These kinds of suggested adaptations should increase in importance over time as more and more products and components are remanufactured and/or material recycled. These kinds of adaptations will also encourage an increase in products passing through more resource-efficient EoL options.

5. Future Research

In the on-going HÅPLA project, future research will include further development and implementation of the recycling and reuse processes in an efficient and environmentally beneficial manner. The expected result is to support environmental branding organisations with guidelines of how to design LCD monitors and televisions for disassembly, remanufacturing and re-use.

The work will be further extended by proposing and investigating other design solutions for EoL processes to improve environmental performance and recovered value of EoL products. In addition, the researchers within the HÅPLA project will facilitate new requirements for environmental labelling of LCDs to improve their ability to be disassembled. This will include e.g. time for disassembly and choice of materials used in LCDs.

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