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Identifying sustainable applications for printed electronics using the multi-perspective application selection approach

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ABSTRACT

Printed electronics are manufactured using additive methods and are envisioned as "green", low-cost, energy-efficient, and sustainable alternatives to present-day electronics. The present Multi-perspective Application Selection (MPAS) assessment aims to assess the current state of technology and evaluate the products in which applications of printed electronics would be feasible. The MPAS is a multi-stage tool apt for decision-making and identifying technologically feasible and environmentally sustainable applications of novel technologies.

The first step of the MPAS process involved the identification of all possible products in which printed electronics may replace conventional printed circuit boards (PCBs). For the same, 11 application categories of electrical and electronic equipment were considered. Then, by assessing the user acceptance criteria for each specific application category, unsuitable applications were filtered out from the study. Only those application categories with achievable user acceptance criteria were preselected as promising applications for printed electronics. The final evaluation step considered the technical and sustainability advantages of replacing PCBs with printed electronics in the specific products within the preselected application categories.

Thus, the MPAS yielded conventional low-voltage and low-frequency electronics applications with medium-low lifetimes (specifically clocks, toys, personal medical tests, radios, keyboards, mice, and calculators) as technically feasible and sustainable product applications for printed electronics. Furthermore, novel printed electronic products (such as smart posters, pamphlets, packaging, etc.) were also found to be suitable applications; however, management of the large quantities of waste generated from such applications is recognized as a concern.

1. Introduction

A growing interest in sustainable products and value chains has been slowly influencing the development of new products in the electronics sector. Printed electronics are a response to this interest as they aim to offer more environmentally friendly alternatives to conventional electronics (Välimäki et al., 2020). Traditional electronics rely on printed circuit boards (PCBs) for operations which offer high functionality through their etched copper tracks for conductivity on substrates made from glass-fibre and epoxy composites. However, these PCBs are energy-intensive to manufacture, which leads to substantial environmental impacts (Esfandyari et al., 2015). This high manufacturing impact of PCBs may become a significant contributor to global environmental problems considering that the demand for all electronics is booming along with the ever-growing need to communicate, connect and exchange information within the scope of Internet-of-Things (IoT) (Roselli et al., 2015; Wiklund et al., 2021). Hence, switching to lower impact and "green" printed electronics (Irimia-Vladu, 2014) offers the possibility of minimizing the future environmental impacts from electronics. Further optimizations of existing and conventional electronics systems are projected to be insufficient for supporting long-term sustainability (Moreau et al., 2021). Instead, innovation and a paradigm shift are required to establish a new technology system for electronics, such as printed electronics, that aligns with the sustainability goals of the world (Wernink and Strahl, 2015).

Printed electronics are envisioned to be "green" and offer low-cost, energy-efficient, and sustainable products with novel and innovative features such as circuit flexibility, lightweight, biodegradability, and benignity to the environment (Irimia-Vladu, 2014; Liu et al., 2014). By employing continuous and additive manufacturing processes, printed electronics are expected to minimize material and energy consumption in comparison to conventional PCBs (Glogic et al., 2021; Li et al., 2020). In contrast to the etched circuit designs of conventional PCBs, the circuit

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List of abbreviations

EoL	End-of-Life
EU	The European Union
IoT	The Internet-of-Things
IT	Information Technology
LCA	Life Cycle Assessment
LHA	Large Household Appliance
MPAS	Multi-perspective Application Selection
PCB	Printed Circuit Board
SHA	Small Household Appliance
WEEE	Waste of Electrical and Electronic Equipment

designs of printed electronics are generally printed using conventional printing techniques directly on the substrate using conductive inks, presently based on nanosilver. The conductive tracks created on the printed electronics eliminate the need for etching, i.e. applying and removing excess conductor material with hazardous chemicals in conventional PCBs (Glogic et al., 2021; Wiklund et al., 2021). Additionally, the substrates in PCBs are primarily comprised of glass-fibre and fossil-based epoxy, which are non-renewable, energy-intensive to manufacture, and cannot be recycled (Esfandyari et al., 2015; Premur et al., 2016). In contrast, printed electronics may be based on low-impact, renewable, biodegradable, biocompatible, and organic substrates such as paper, silk, chitin, and many more (Irimia-Vladu, 2014; Li et al., 2020). Furthermore, by eliminating the use of toxic materials, such as flame retardants (Liu et al., 2014), printed electronics are designed to minimize environmental damage at the End-of-Life (EoL). Thus, if the waste of electrical and electronics equipment (WEEE) based on printed electronics is mismanaged at the EoL, unlike the current WEEE, it will neither persist nor create toxicological issues in the environment (Shittu et al., 2021).

Nevertheless, the printed electronics technology is still at an early stage of development and is not market-ready. Presently, printed electronics are only feasible in low-density, low-frequency, and single-layered electronics (Liu et al., 2014) that do not require complex circuitry. Moreover, the degradable nature of substrates and other components will compromise the reliability of printed electronics circuits. Consequently, the lifespan of such printed circuits is also low as the conductive tracks are expected to degrade and are incapable of maintaining functionality over long periods like in the case of PCBs (Bonnassieux et al., 2021; Keskinen, 2012). Thus, printed electronics may be suitable in smaller devices, with short lifespans, and high volume market demands, i.e. for electronic products that are purchased often but quickly disposed of and generate large volumes of waste in a short time.

The shortcomings of printed electronics have, to a great extent, limited their applications to readily-disposable products with short use phases, such as smart packaging, healthcare products, and disposable sensors (Keskinen, 2012; Nassajfar et al., 2021). Simultaneously, the aforementioned advantages such as biocompatibility also offer avenues for biomedical applications within the body such as drug delivery systems, sensors, and monitors. Biodegradability and minimal use of toxic materials in electronics allow benign integration into life and the environment (Irimia-Vladu, 2014). This opens up the possibility for environmental sensing and monitoring applications during which the electronics may be "willingly" lost (site of use is also the site of disposal) or disposed to the environment without creating environmental concerns (Hakola et al., 2021). Furthermore, printed methods have been applied to fabricate radio frequency identification (RFID), organic light-emitting diodes (OLEDs), thin-film transistors (TFTs), resistive memory devices, solar/photovoltaic cells, diodes, actuators, thermo- and electrochromic displays, batteries, and sensors for measuring temperature, humidity and pH levels (Bonnassieux et al., 2021; Glogic et al., 2021; Hakola et al., 2021; Välimäki et al., 2020; Wiklund et al., 2021). As the technology develops further, printed electronics are envisaged to result in 'electronics everywhere' (Hakola et al., 2021). Some parts of printed electronics may be incorporated in not just electronic devices, but also non-electronic ones to enable some electronic 'add-on' functionality (Keskinen, 2012), for example, in packaging materials or clothing items (Kokare et al., 2021).

Many applications of printed electronics covered previously are novel and are intended to create new or 'add-on' functionalities. Such novel application fields, particularly those requiring short lifespans, are anticipated to be sustainable only through the use of printed electronics as the use of PCBs will only add to the nuisance of global e-waste. Considering the high environmental impacts of PCBs, exploring the potential of printed electronics to replace PCBs in certain conventional applications is necessary. The present assessment aims to adapt the Multi-Perspective Application Selection (MPAS) method (Piccinno et al., 2016) that was developed to explore sustainable application fields for one material (nanocellulose) with one functionality (reinforcing composite fibers). Here the MPAS has been applied to explore the electronic products in which printed electronics, given their present shortcomings, can replace PCBs. Future improvements in printing technologies and conductive inks are expected to boost the reliability and functionality of printed electronics (Glogic et al., 2021). However, this study assesses the present products for which it is possible to technically shift the manufacturing paradigm and thereby enhance the sustainability of appliances. Through the MPAS framework, technically feasible and sustainable applications of printed electronics in present-day electrical and electronic appliances have been identified and explained.

2. Multi-perspective application selection

The MPAS method was developed primarily to support researchers by helping them identify feasible applications of novel materials and products. A key feature of MPAS is the systematic evaluation of the techno-economic and environmental performance of the novel development in order to create a holistic view of the technology. Doing so widens the otherwise narrow view of researchers and allows the identification of applications that were not previously on their "radar". The MPAS may be considered a variation of the existing multi-criteria decision analysis (MCDA) methodology (He et al., 2019; Huang et al., 2011; Linkov et al., 2020; Malloy et al., 2016; Rycroft et al., 2019) that has been tuned specifically to select applications of novel materials and technologies. Undertaking a detailed comparison between MPAS and MCDA is beyond the scope of the present assessment, however there is valuable literature (Cegan et al., 2017; Kurth et al., 2017; Linkov et al., 2020) available that can facilliate such a comparison for interested readers. For marketing and further refinement of newly-developed materials and technologies, only by using their possessed qualities and properties, the complete spectrum of possible (as well as feasible) applications have to be recognized. Therefore, in such situations, an MPAS is relevant because, with this method, numerous possible applications can be screened during the early stages of development when little-to-no information is available (Piccinno et al., 2016).

Fig. 1 illustrates the application of the MPAS methods to the case of printed electronics and surmises the key steps. The process starts with exhaustively identifying a list of possible applications for the novel product or material. These possible applications are segmented further into application fields. This is followed by the evaluation of the user acceptance criteria that serves as the 1st prospective filter and weeds out unsuitable application categories from the assessment. A further evaluation of the techno-economic and environmental advantages from the adoption of printed electronics in the pre-selected applications is conducted. All the previously mentioned evaluations are scored as per the scheme described in Table 1. A total MPAS score is thus obtained for each possible application and only those applications are selected that have a higher MPAS score than the prescribed thresholds as depicted in

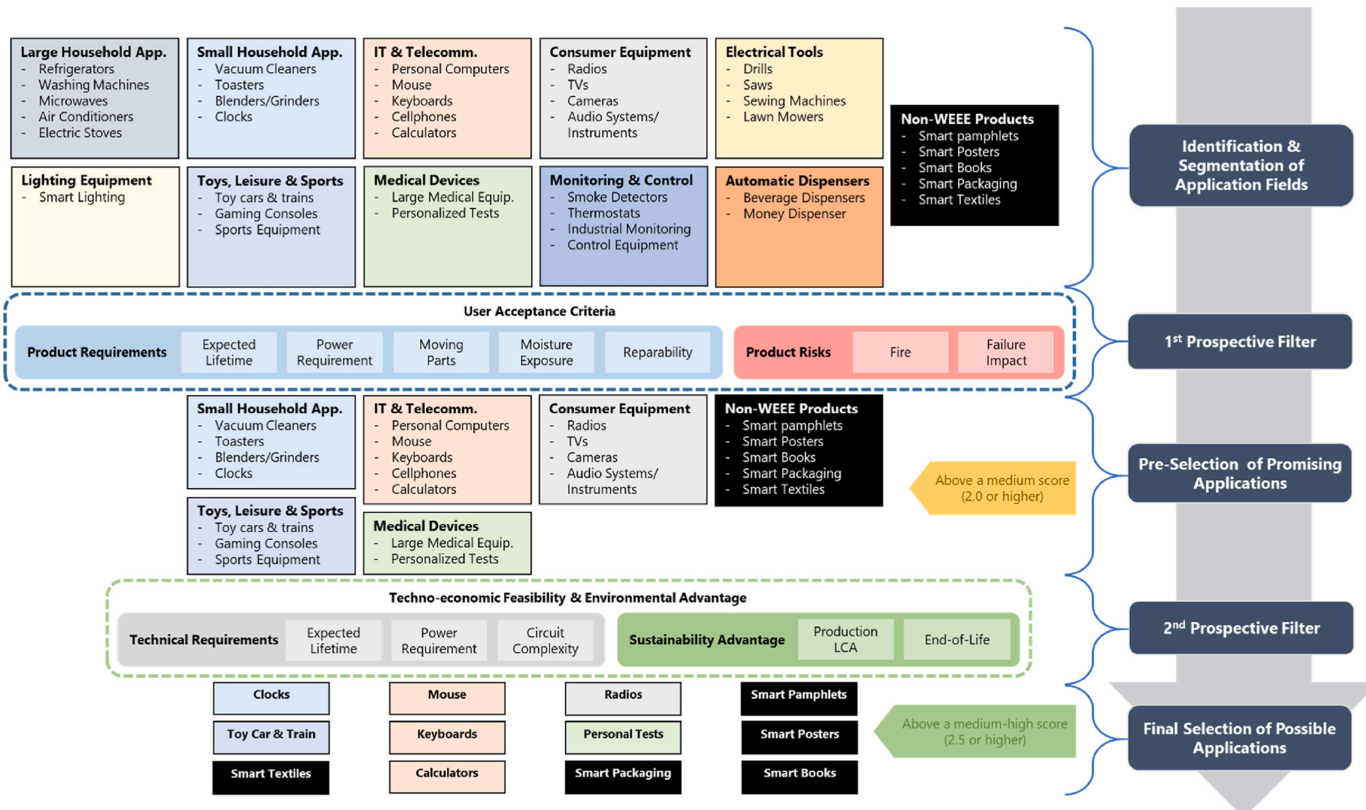

Fig. 1. Summary of MPAS method applied to identify suitable product applications for printed electronics.

Table 1
Guide for scoring: (a) the product requirement or risk in the user acceptance criteria; (b) fulfilment of technical product requirements or sustainability advantage; (c) the feasibility of printed electronics in an application category corresponding to the aggregated user acceptance criteria or the total MPAS score.

(a)		(b)		(c)	
Product Requirement/Risk	Score	Requirement Fulfilled	Score	Score	Feasibility in Application
High (H)	1	High (H)	3	≥2.75	High (H)
Medium-high (MH)	1.5	Medium-high (MH)	2.5	2.25 - 2.75	Medium-high (MH)
Medium (M)	2	Medium (M)	2	1.75 - 2.25	Medium (M)
Medium-low (ML)	2.5	Medium-low (ML)	1.5	1.25 - 1.75	Medium-low (ML)
Low (L)	3	Low (L)	1	<1.25	Low (L)

Fig. 1. Further chapters explain MPAS methodology in detail and explain how it has been applied to the case of printed electronics as depicted in Fig. 1.

3. Evaluation steps

3.1. Step 1: identification and segmentation of application fields

The first step for the MPAS method, as illustrated in Fig. 1, is the identification of possible applications for printed electronics. As this assessment considers the present potential of replacing PCBs with printed electronics in products, the possible products have been derived from and classified into application categories as per the 10 categories of electrical and electronic equipment listed in the WEEE directive (European Union, 2012). Table 2 lists all the application categories and the corresponding list of products considered in the assessment.

Apart from the electrical and electronic applications, there are other novel applications suitable for printed electronics that are beyond the scope of the WEEE directive; all these novel application products have been listed and classified into the 'Non-WEEE Products' application category in Table 2. Additionally, the list of products for each application category has been limited to include only those products in which replacement of PCBs is possible. For example, in the 'Lighting Equipment' category, the WEEE directive considers fluorescent lamps, which do not contain any PCBs for replacement and are therefore not pertinent to this assessment.

3.2. Step 2: user acceptance criteria

The second step of the MPAS involves the identification of 'user acceptance criteria': the fulfillment of these criteria is deemed as necessary by the users of a product. These criteria represent the

Table 2
Application categories and the corresponding list of products containing PCBs according to the WEEE directive (European Union, 2012) that are considered for replacement with printed electronics for the MPAS approach.

Application Categories	List of Products
Large Household Appliances (LHAs)	Refrigerators, Freezers, Washing Machines, Microwaves, Air Conditioners, Electric Stoves
Small Household Appliances (SHAs)	Vacuum Cleaners, Toasters, Blenders/Grinders, Clocks
IT & Telecomm. Equipment	Personal Computers, Mouse, Keyboards, Telephones and Cell phones, Calculators
Consumer Equipment	Radios, TVs, Cameras, Audio Systems, Instruments,
Lighting Equipment	Smart lighting
Electrical & Electronic Tools	Drills, Saws, Sewing Machines, Lawn Mowers
Toys, Leisure & Sports Equipment	Toy Cars and Trains, Gaming Consoles, Sport Equipment
Medical Devices	Large Medical Equipment, Personalized Tests
Monitoring & Control Instruments	Smoke Detectors, Thermostats, Industrial Monitoring and Control Equipment
Automatic Dispensers	Dispensers for Beverages, Money, Solids
Non-WEEE Applications	Novel applications such as interactive Posters and Pamphlets, Smart Books, Smart Packaging, and Smart Textiles

requirements of a product that have to be met to ensure proper functioning and they have been considered the 1st prospective filter in the MPAS as illustrated in Fig. 1. For electrical and electronic products, specific user acceptance criteria have been identified based on expert feedback. The criteria are then classified into product requirements and risks as described in Table 3. All the user acceptance criteria in Table 3 have been selected with the limitations of printed electronics in mind. Since printed electronics are still a novel technology, certain early-stage technology issues persist that directly prevent the fulfillment of user acceptance criteria in certain products.

As detailed in Table 3, user acceptance criteria are the demands in a specific product from an operational or technical perspective that enable proper functioning and minimize the risks of failure. For example, LHAs are expected to have long lifetimes, be reparable to ensure a long use phase, consume a lot of power, have many moving parts, and probably operate with water. If any of these product requirements are not fulfilled, there may be a risk of failure with impacts on the user. So to operate, all LHAs have certain benchmarks for user acceptance criteria. The first step of MPAS involves scoring the application categories based on the user acceptance criteria. This serves to determine which application categories have high product requirements as such application categories would be less receptive and adaptable to newer technologies (like printed electronics with their early-stage technology issues). Hence, the goal is to preselect application categories with less-demanding user acceptance criteria, which would be suitable for printed electronics.

To determine or rank the application categories based on their appropriateness for printed electronics, each category must be scored for the user acceptance criteria. However, as mentioned earlier, application categories with more demanding or higher (benchmark for) user acceptance criteria would be less likely to be receptive to printed electronics. Hence, the scoring is inversely related to the product requirement or risk, as depicted in Table 1(a). For example, the higher product requirements of LHAs are harder to fulfil and make them unsuitable for printed electronics; therefore, their user acceptance criteria score would be low.

The more demanding the above-stated user acceptance criteria for an application category, the lower the user acceptance score and the consequent feasibility of printed electronics. Each single-user acceptance criterion is scored between 1.0 and 3.0: according to Table 1(a), where a lower score corresponds to a higher product requirement or risk. A single and aggregated user acceptance criteria score, also termed as 'technical feasibility of application' (maximum of 3.0), is further

Table 3
Description of product requirements and risks that comprise the user acceptance criteria and their relevance to the replacement of PCBs with printed electronics.

User Acceptance Criteria	Description
Product Requirements	
Expected Lifetime	LHAs such as refrigerators and washing machines are expected to have long lifetimes of operations in comparison to SHAs such as toasters and blenders. This is a relevant criterion because the functionality of printed electronics deteriorates with time and therefore they are suitable for products with short lifetimes (Bonnassieux et al., 2021; Keskinen, 2012).
Power Requirement	The wattage or power consumption of a device depends on its function. Power requirement is relevant because higher power consumption implies more heat generation and consequently a higher fire risk. Again, LHAs like refrigerators require more electrical power for operation than SHAs. At present, the higher resistivity of the conductive tracks on printed electronics limits their application to low voltage and frequency applications (Liu et al., 2014).
Moving Parts	Motors are required in moving parts to create motion; these motors are prone to wear and tear and also create additional scope of heat generation. Additionally, the circuits used in moving parts require reinforcement against bending, torsion, or vibrations. Bio-based substrates used in printed electronics add functionalities like foldability and flexibility and cannot offer a board rigidity and strength comparable to conventional PCBs. So employing printed electronics may be challenging in a product like a printer, which has a moving part required for printing.
Water/Moisture Exposure	Exposure to moisture can be detrimental to circuits if they are not designed to operate in humid conditions. Moreover, certain products such as washing machines are expected to store and operate with water. In such cases, the circuits need a waterproof coating so that accidental exposure does not hamper the functioning of the product. Water spills or even operations in environments with high moisture can expedite the degradation of the bio-based substrates in printed electronics and be detrimental to their functionality.
Reparability	Products with longer lifetimes are (also legally) expected to be repairable and undergo repair or maintenance cycles to ensure proper functioning (Sajn, 2022). Presently, mounting of components on printed electronics is achieved through conductive adhesives; these glued-on parts cannot be removed without damaging the circuits and will therefore impede replacement or reparability.
Product Risks	
Fire Risks	Heat and fire sources in an appliance warrant the need for flame retardants in the circuit boards and surrounding components. Dry bio-based substrates used in printed electronics are flammable and can be fire hazards in the wrong applications. For example, the fire risks associated with LHAs (that require more power for operation) are also higher than those from SHAs; so the application of printed electronics may be less risky in the latter.
Failure Impact	Typically, the impact of a failure is correlated to the importance of a device's operation; for example, failure impact due to the breakdown of a crucial medical device will likely be detrimental to human health. The low reliability of printed electronics makes them unsuitable for use in applications where failure impact may be high.

calculated for each application category by taking an equally weighted mean of all product requirement and risk scores. As per Table 1(c), the feasibility of printed electronics in a specific application category is determined based on the aggregated user acceptance criteria score. Based on expert feedback, only those application categories offering a medium score of above 2.0 were preselected for the next step of the MPAS. In this manner, the user acceptance criteria filter out those application categories that are unsuitable for printed electronics.

3.3. Step 3: technical requirements

After filtering based on the user acceptance criteria, only a few application categories are shortlisted. The respective products from the preselected application categories will be assessed on whether or not the technical requirements of a specific product can be met by printed electronics. In Fig. 1, the assessment of technical requirements is a part of the 2nd prospective filter in this MPAS.

Although the user acceptance criteria were assessed for each application category, within the preselected application categories, individual products may have varying demands and requirements for operations. For example, both toasters and clocks, despite having different functions and technical requirements, are classified as SHAs. However, to apply the user acceptance criteria filter, the product requirements were generalized at the level of application categories to preselect the most feasible application categories for the printed electronics. Once the suitable application categories have been identified, it is necessary to validate whether or not printed electronics can fulfil the specific technical requirements at a product level, i.e. for individual products within the preselected applications categories. The technical requirements considered relevant for each product within the preselected application categories have been listed and described in Table 4.

The descriptions in Table 4 question the extent to which the respective technical requirements can be fulfilled by replacing PCBs with printed electronics in a specific product. The fulfilment of technical requirements by the replacement of PCBs in a particular product can be scored according to the scheme in Table 1(b). It is important to note that the scoring methodology for the fulfilment of technical requirements in Table 1(b) is the reverse of the scoring of the user acceptance criteria in Table 1(a), i.e. 'high' fulfilment of technical requirements is awarded a 'high' score of 3.0 whereas 'high' user acceptance criteria receive a 'low' score of 1.0. This is because the higher user acceptance criteria imply that the benchmark for the application category is higher and thus replacement of existing PCBs is unsuitable. In contrast, higher fulfilment of technical requirements in a specific product implies that the adoption of printed electronics is suitable.

3.4. Step 4: sustainability advantage

Apart from meeting technical requirements, printed electronics are also positioned as sustainable alternatives to PCBs. Therefore, the sustainability advantage perspective has also been incorporated into the 2nd prospective filter MPAS process (Fig. 1) as described in Table 5. To account for the sustainability advantages over the entire life cycle, both the production life cycle assessment (LCA) and the EoL perspectives have been considered with equal weighting in the scoring. The use phase of the life cycle of printed electronics has been ignored because the application would likely be in low voltage appliances and their lifespan is anticipated to be short. Hence, the energy consumption or maintenance requirements during the use phase are expected to be negligible.

In literature (Glogic et al., 2021; Kanth et al., 2012; Kokare et al., 2021; Li et al., 2020; Nassajfar et al., 2021; Sudheshwar et al., 2023), for the same application, printed electronics outperform conventional PCBs in the context of environmental impacts during the production processes. The lower production impacts of printed electronics may be primarily attributed to the lower material use during additive manufacturing and the replacement of high-impact epoxy and glass-fibre substrates (Esfandyari et al., 2015; Sudheshwar et al., 2023) with novel and low-impact bio-based substrates. Therefore, in this MPAS assessment, all the products that have been considered for the replacement of PCBs with printed electronics have been awarded a 'high' score of 3.0, following the scale in Table 1(b). This high production LCA score applies to all products because regardless of the specific product, within the same functionality constraints, printed electronics will always have lower environmental impacts from production than their PCB counterparts. Thus, irrespective of whether PCBs are replaced in a clock or a calculator, there is a high advantage from the production LCA perspective because printed electronics can offer the same functionality with a lower environmental impact.

For the scoring of the EoL, the collection rates (Horta Arduin et al., 2020) of the respective application categories have been calculated using Eurostat data from 2017 for the European Union (EU) as seen in Table 6 (European Commission, 2021). Only application categories that were preselected and not filtered out based on their user acceptance criteria score have been listed in Table 6. As explained in Table 5, it is desirable to collect more waste for recycling materials. Therefore, the EoL score is mapped to the estimated collection rate. The highest collection rate was found to be 58%, and the corresponding application categories (and their products) were awarded a high EoL score using Table 1(b) as reference. As the estimated collection rate decreases in Table 6, so does the corresponding EoL score.

3.5. Step 5: evaluation of MPAS score

The MPAS score serves in the final selection of electrical and

Table 4
The technical requirement considerations for printed electronics if they replace PCBs in products.

Technical Requirements	Description
Expected Lifetime	With the known degradation periods of the circuit functions of printed electronics, can the expected lifetime for the specific product be achieved?
Power Requirement	Some products may require more power than others within the same application category; to what extent can printed electronics fulfill the power requirements of the product?
Circuit Complexity	At present, printed electronics can only replace simple, single-layer PCBs, whereas complex circuits may be laid out over multiple layers in PCB; to what extent can the desired circuit functions be achieved on a single-layer printed electronic?

Table 5
The description of the parameters considered to assess the sustainability advantages of printed electronics.

Sustainability Advantage	Description
Production Life Cycle Assessment (LCA)	Printed electronics are proposed as more sustainable alternatives to PCBs and many LCAs in literature (Glogic et al., 2021; Kanth et al., 2012; Kokare et al., 2021; Li et al., 2020; Nassajfar et al., 2021; Sudheshwar et al., 2023) report that environmental impact from the production of printed electronics is lower than that from the production of PCBs.
End-of-life (EoL)	To minimize the overall impact during the life cycle of printed electronics, proper collection and recycling at the EoL are necessary to ensure the recovery of valuable metals with high sourcing impacts (Hummen and Sudheshwar, 2023; Keskinen, 2012; Kunnari et al., 2009).

Table 6
The End-of-Life Score is determined for each application category based on the collection rate estimated with Eurostat data (European Commission, 2021).

Application Category	Collected [t]	Put on Market [t]	Collection Rate [%]	End-of-Life Score
Small Household Appliances (SHAs)	435,583	998,949	44%	Medium-high (MH)
IT & Telecomm. Equipment	674,869	1153812	58%	High (H)
Consumer Equipment	597,367	1022696	58%	High (H)
Toys, Leisure & Sports Equipment	24,863	289,534	9%	Low (L)
Medical Devices	15,121	121,935	12%	Medium-low (ML)

electronic products in which the application of printed electronics is suitable. The application categories were first pre-selected with the user acceptance criteria, and the individual products within the selected application categories were scored based on the meeting of technical requirements and the sustainability advantages from the replacement of PCBs with printed electronics. Finally, the scores for user acceptance criteria, technical requirements, and the sustainability advantage are aggregated into a total MPAS score ranging between 1.0 and 3.0 using an equally weighted mean. Based on expert feedback, only those specific products, with an MPAS score higher than 2.5 (or medium-high) are finally proposed as possible applications for printed electronics.

4. Results

4.1. User acceptance criteria

Table 7 scores the technical feasibility of each application category for printed electronics based on the product requirements and risks under the user acceptance criteria. Only those application categories that receive a technical feasibility score greater than 2.0 (medium) are pre-selected for further evaluation.

LHAs are expected to have high product requirements as well as product risks, therefore they receive a low technical feasibility score and would be unsuitable for the application of printed electronics. Similarly, the lighting equipment category also scores low technical feasibility: although product requirements are not as high as for LHAs, the operation of lighting equipment is generates heat and there are fire and failure risks associated with short-circuits. Power tools also score low and do not make it through the pre-selection because they have high energy requirements and rely on a lot of moving parts. These product requirements of power tools raise the associated fire risks, and their proximity to the human body during failure may lead to bodily harm and thus a high failure impact. Monitoring and control instruments are also not preselected: although the product requirements may not be high, product risks are high because product failure may have severe impacts, especially for safety applications such as smoke detectors. Finally, the automated dispenser category is eliminated because product failure, particularly in the case of cash dispensers, will have a high impact.

All the application categories that qualify the pre-selection based on user acceptance criteria are SHAs, IT and telecommunication equipment, consumer equipment, toys, leisure and sports equipment, medical devices, and non-WEEE applications.

SHAs typically have medium-low product requirements; apart from possible fire risks, general product risks are low making this application category receptive to changes and suitable for printed electronics. Modern IT and telecommunication equipment are energy efficient and are expected to last between 3 and 5 years, hence the reparability needs are low (relatively in comparison to, for example, LHA); product risks are much lower than for previous application categories, and the application of printed electronics seems feasible. Consumer electronics are found to be suitable applications as well; apart from their expected lifetime, the other product requirements of the consumer and IT and telecommunication equipment are similar. Additionally, the product risks associated with the consumer equipment are low too. Toys, leisure, and sports equipment have lower product requirements and risks, making them suitable for printed electronics; particularly for toys in the proximity of children, the use of toxin-free printed electronic circuitry may be beneficial. The application in medical equipment is feasible but challenging because, unlike personalized tests, larger equipment may require more power and are expected to have long lifetimes. Hence, a medium score (as an average between large medical devices and personalized tests) is awarded for the product requirements of medical devices. The failure impact score is low for medical devices as their failure can be detrimental to human health. Finally, the non-WEEE application category is selected for further assessment; printed electronics can easily meet the product requirements in such novel applications. These have been touted as prospective applications for printed electronics because of the low risks associated with these products.

4.2. Technical, sustainability advantage, and final selection

In Table 8, the specific products within the preselected application categories are scored based on the extent to which printed electronics can meet the technical requirement and offer sustainability advantages by replacing PCBs. Furthermore, the technical and sustainability advantage scores for each product are combined with the technical feasibility score from the user acceptance criteria for the application categories into the total MPAS score. Those specific products with a total MPAS score greater than 2.5 are finally selected and proposed as suitable prospective applications for printed electronics.

Printed electronics are unsuitable for many SHA applications; they cannot outcompete current PCBs in high-power products with long lifetimes such as vacuum cleaners. Similarly, considering the flammable nature of printed electronics, toasters are unsuitable because heating coils in toasters elevate the potential fire risks. Blenders and grinders, apart from heating up and requiring moving parts, may also be subjected to moisture and humidity during operation which is unsuitable for printed electronics. Printed electronics, in the present state of technology, cannot fulfil the technical circuitry requirements in PCs that are usually very complex, multi-layered, generate heat and require power. Similar to PCs, printed electronics are unsuitable in smartphones because they utilize multi-layered PCBs with complex circuit designs; additionally, the risk of fire is worrisome because of the occasional instability of Li-ion batteries (Maraqa et al., 2018; Wang et al., 2012). It is also unlikely that printed circuits will be able to meet the power requirements and complex circuit designs while coping with the heat generated from the display of modern smart television systems which are similar to today's PCs. Cameras are expected to have long lifespans and require complex circuits to capture and process images, neither of which would be achievable through printed electronics. Audio systems may not require complex circuits, but may operate at higher wattages and generate heat. Additionally, the vibrations generated through sound may have deleterious effects on printed electronics. Modern gaming consoles are similar to PCs in terms of the expected technical requirements; they require a significant amount of power, run hot, and consequently, are unsuitable for the application of printed electronics. Gym or performance tracking equipment are considered in the product class of sporting equipment, and they required technical specifications that may be unfeasible for printed electronics; moreover shocks during use may have an impact on the functioning of printed electronics. Large medical equipment would be similar to PCs with high computational capabilities and power requirements, and the application of printed electronics may increase the risk of failure.

Simple products such as clocks and modern digital watches have low technical requirements and would prove to be good for applications of printed electronics. Mice and keyboards also have low power requirements and their circuit complexity may be achievable through printed electronics. Simple calculators may also be suitable for the application of printed electronics. Graphical calculators would be unsuitable because they have technical requirements similar to smartphones. Radios with external antennae could employ printed circuits (current printing technology may be limited in embedding radio antennas directly in the printed circuits). Although the collection rate of toys is low and they offer lower sustainability advantages, replacing the PCBs containing toxic flame retardants in favor of printed electronics with non-toxic substrates will prove beneficial for the health of children playing with the toys. Most personal medical tests do not have high technical requirements and therefore the use of printed electronics would be suitable; however, such equipment also have low collection rates and a limited sustainability advantage. Many products in the non-WEEE application category exist to support the development of printed

Table 7

Scoring the technical feasibility of different application categories for replacing PCBs with printed electronics based on the user acceptance criteria; the technical feasibility score for each application category is calculated by taking an equally weighted mean of all product requirement and risk scores; the application categories with a technical feasibility score greater than 2.0 are preselected for further MPAS steps.

Application Categories	Products	User Acceptance Criteria									Technical Feasibility of Application	Selection
		Product Requirements						Product Risks				
		Expected Lifetime	*Power Requirement*	*Moving Parts*	*Water/ Moisture Exposure*	*Reparability*	***Score***	*Fire Risks*	*Failure Impact*	***Score***		
Large Household Appliances (LHAs)	Refrigerators, Freezers, Washing Machines, Microwaves, Air Conditioners, Electric Stoves	H[a] 1[b]	H 1	MH 1.5	MH 1.5	H 1	1.2	H 1	MH 1.5	1.25	**L**[c] 1.23	-
Small Household Appliances (SHAs)	Vacuum Cleaners, Toasters, Blenders/Grinders, Clocks	M 2	M 2	H 1	ML 2.5	L 3	2.1	MH 1.5	L 3	2.25	**M** 2.18	✓
IT & Telecomm. Equipment	Personal Computers, Mouse, Keyboards, Telephones and Cell phones, Calculators,	ML 2.5	M 2	L 3	L 3	L 3	2.7	L 3	ML 2.5	2.75	**MH** 2.73	✓
Consumer Equipment	Radios, TVs, Cameras, Audio Systems, Instruments,	M 2	M 2	L 3	L 3	L 3	2.6	L 3	L 3	3	**H** 2.80	✓
Lighting Equipment	Smart lighting	L 3	M 2	L 3	L 3	L 3	2.8	H 1	H 1	1	**M** 1.90	-
Electrical & Electronic Tools	Drills, Saws, Sewing Machines, Lawn Mowers	MH 1.5	MH 1.5	H 1	ML 2.5	M 2	1.7	H 1	ML 1.5	1.25	**ML** 1.48	-
Toys, Leisure & Sports Equipment	Toy Cars and Trains, Gaming Consoles, Sport Equipment	L 3	M 2	ML 2.5	ML 2.5	L 3	2.6	L 3	L 3	3	**H** 2.80	✓
Medical Devices	Large Medical Equipment, Personalized Tests	M 2	M 2	ML 2.5	ML 2.5	ML 2.5	2.3	L 3	MH 1.5	2.25	**MH** 2.28	✓
Monitoring & Control Instruments	Smoke Detectors, Thermostats, Industrial Monitoring and Control Equipment	MH 1.5	ML 2.5	ML 2.5	M 2	L 3	2.3	M 2	H 1	1.5	**M** 1.90	-
Automatic Dispensers	Dispensers for Beverages, Money, Solids	MH 1.5	M 2	H 1	MH 1.5	H 1	1.4	L 3	H 1	2	**ML** 1.70	-
Non-WEEE Applications	Novel applications such as Interactive Posters and Pamphlets, Smart Books, Smart Packaging, and Smart Textiles	M 2	L 3	L 3	ML 2.5	L 3	2.7	L 3	L 3	3	**H** 2.85	✓

[a] The requirements and the risks of an application category are represented in the upper row, where H = high, MH = medium-high, M = medium, ML = medium-low, and L = low.
[b] The competitiveness score in the lower row corresponds to the requirements and risks of an application category as stated in Table 1(a).
[c] The technical feasibility of the specific application category for printed electronics based on scoring as per Table 1(c).

Table 8
Scoring the technical and sustainability advantage from the replacement of PCBs with printed electronics in specific products; the total MPAS score is obtained by taking an equally weighted mean of the technical requirements, sustainability advantages and the technical feasibility score based on user acceptance criteria; specific products with a total MPAS score greater than 2.5 are proposed as suitable for the final application of printed electronics.

Technical & Sustainability Advantage									Technical Feasibility of Application	Total MPAS Score	Selection
Application Categories	Products	Technical Requirements			Technical Advantage	Sustainability Aspects		Sustainability Advantage			
		Expected Lifetime	*Power Requirement*	*Circuit Complexity*		*Production LCA*	*End-of-Life*				
Small Household Appliances (SHAs)	Vacuum Cleaner	L[a] 1[b]	L 1	M 2	**ML** 1.33	H 3	MH 2.5	**MH** 2.75	**M** 2.18	**M** 2.09	-
	Toaster	L 1	L 1	M 2	**ML** 1.33	H 3	MH 2.5	**MH** 2.75	**M** 2.18	**M** 2.09	-
	Blender/ Grinder	L 1	L 1	M 2	**ML** 1.33	H 3	MH 2.5	**MH** 2.75	**M** 2.18	**M** 2.09	-
	Clock	MH 2.5	H 3	MH 2.5	**MH** 2.67	H 3	MH 2.5	**MH** 2.75	**M** 2.18	**MH** 2.53	✓
IT & Telecomm. Equipment	Personal Computers	L 1	L 1	L 1	**L** 1.00	H 3	H 3	**H** 3.00	**MH** 2.73	**M** 2.24	-
	Mouse	M 2	H 3	M 2	**MH** 2.33	H 3	H 3	**H** 3.00	**MH** 2.73	**MH** 2.69	✓
	Keyboards	M 2	H 3	M 2	**MH** 2.33	H 3	H 3	**H** 3.00	**MH** 2.73	**MH** 2.69	✓
	Smartphone	L 1	L 1	L 1	**L** 1.00	H 3	H 3	**H** 3.00	**MH** 2.73	**M** 2.24	-
	Calculator	M 2	H 3	L 1	**M** 2.00	H 3	H 3	**H** 3.00	**MH** 2.73	**MH** 2.58	✓
Consumer Equipment	Radio	M 2	H 3	M 2	**MH** 2.33	H 3	H 3	**H** 3.00	**H** 2.80	**MH** 2.71	✓
	TV	L 1	L 1	L 1	**L** 1.00	H 3	H 3	**H** 3.00	**H** 2.80	**MH** 2.27	-
	Cameras	L 1	L 1	L 1	**L** 1.00	H 3	H 3	**H** 3.00	**H** 2.80	**MH** 2.27	-
	Audio Systems/ Instruments	L 1	L 1	M 2	**ML** 1.33	H 3	H 3	**H** 3.00	**H** 2.80	**MH** 2.38	-
Toys, Leisure & Sports Equipment	Toy Car & Train	H 3	H 3	H 3	**H** 3.00	H 3	L 1	**M** 2.00	**H** 2.80	**MH** 2.60	✓
	Gaming Consoles	L 1	L 1	L 1	**L** 1.00	H 3	L 1	**M** 2.00	**H** 2.80	**M** 1.93	-
	Sport Equipment	L 1	M 2	M 2	**ML** 1.67	H 3	L 1	**M** 2.00	**H** 2.80	**M** 2.16	-
Medical Devices	Large Medical Equipment	L 1	L 1	L 1	**L** 1.00	H 3	ML 1.25	**M** 2.13	**MH** 2.28	**M** 1.80	-
	Personal Tests	H 3	H 3	H 3	**H** 3.00	H 3	ML 1.25	**M** 2.13	**MH** 2.28	**MH** 2.5	✓
Non-WEEE Applications	Smart Pamphlets, Posters, Books, Packaging, Textiles	H 3	H 3	H 3	**H** 3.00	H 3	L 1	**M** 2.00	**H** 2.85	**MH** 2.62	✓

[a] The upper row represents the extent to which technical requirements are fulfilled and the sustainability advantages are realized in a specific product within each application category, where H = high, MH = medium-high, M = medium, ML = medium-low, and L = low.
[b] The competitiveness score in the lower row corresponds to the meeting of technical requirements and sustainability advantage in a product as stated in Table 1(b).

electronics and all the products can utilize printed electronics effectively (Khan et al., 2020). Nevertheless, the collection rates and consequently the EoL score for such applications are expected to be low just like in the case of medical tests.

Products within the same application category have diverse technical requirements and prospective issues with the adoption of printed electronics; because of this, many products from the preselected application categories in Table 7 are finally not selected for the application of printed electronics. Hence, Table 8 highlights the necessity to go beyond the application categories and consider specific products to assess the applicability of printed electronics, which was possible in this MPAS assessment.

5. Discussion

The final list of conventional electronic products in which replacement of PCBs with printed electronics is feasible includes clocks, mice, keyboards calculators, radios, toys, and personal medical tests. Despite the selection of multiple present-day products, it may be too optimistic to claim that soon many electronics will be based on printed electronics. For some of the selected products, considering the present and future market scenarios is necessary: clocks, calculators, and radios in particular are being replaced by smartphones today and are expected to have limited market penetration in the future. Therefore, evaluating the future of the product category is pertinent because it is moot to develop printed circuits for products that are projected to have limited or zero market demand.

The non-WEEE products category is found to be suitable for printed electronics from a technical requirements perspective. However, many of the specific applications in this category, particularly smart pamphlets, posters, and packaging, are designed to align with the inherently shorter lifespans possible with printed electronics. Additionally, there is not much of a question about replacing PCBs in these applications, as such disposable products would simply not be economically and environmentally viable with conventional PCBs. Printed electronics, thus create a new class of applications and products for which the indirect benefits (anti-counterfeiting from smart packaging for example) will also be relevant (Glogic et al., 2021). Such readily disposable products will have short lifespans, not require repairs or maintenance, and are expected to move through the market in high volumes (Keskinen, 2012; Nassajfar et al., 2021). Thus, the EoL score for the non-WEEE applications category is low, as adopting such technology may give rise to large volumes of a new kind of e-waste for which the waste management sector may not be prepared (Wiklund et al., 2021). Another aspect to consider is the 'hybrid' nature of the products within the non-WEEE category as they add electronic functionality to daily items such as clothing, posters, and packaging. The hybrid nature of the products in the non-WEEE category exempts them from the scope of specific legislation and until the legislation catches up with the developments, the waste and disposal problem may be aggravated (Veske and Ilén, 2020). For example, based on the current state of legislation, it is unclear whether smart packaging at EoL should be treated under the packaging waste directive (European Union, 1994) or the WEEE directive (European Union, 2012). Therefore, further research is required to understand the suitable EoL for such non-WEEE applications and for updating the existing legislation to ensure coverage of all hybrid electronic applications. The waste from non-WEEE applications should be dealt with responsibly and recycled as per principles of urban mining (Brunner, 2011; Cossu and Williams, 2015; Hummen and Sudheshwar, 2023); this is in order to avoid resource-use concerns, particularly those arising from the improper disposal and lack of recycling of precious silver in the conductive tracks of printed electronics (Nassajfar et al., 2021).

The key characteristics of printed electronics in the non-WEEE application category are short lifespans, limited reparability, disposal in high volumes, and ambiguity of the suitable EoL. Although printed electronics outperform conventional electronics with regard to production impacts, the aforementioned characteristics are seemingly in direct conflict with the principles and goals of circular economy that are of growing national and international importance (European Commission, 2020). Therefore, more research is required to clarify how the principles of circular economy apply to printed electronics and their sustainability. An additional area of research could be to assess whether or not the previously mentioned 'indirect benefits' from printed electronics may also improve the environmental performance of the final application.

The above arguments also highlight the strengths and the limitations of the MPAS methodology applied to select feasible applications for printed electronics. The method may be considered arbitrary because there is subjectivity in the selection, scoring, and weighting of the criteria as well as the establishment of the thresholds for the aggregated scores. Therefore, if this study intended to emphasize sustainability considerations, then a higher weight would have been allocated to the sustainability advantage in the total MPAS score and due to its low EoL score, probably the non-WEEE products category would not have been selected. This subjectivity can serve as a strength in selecting the correct applications because it allows for the prioritization of parameters viewed to be essential by different people: some people may wish to select the most technically feasible applications, whereas others would like to introduce new criteria such as economic advantages. Needless to say, the MPAS method offers immense flexibility to accommodate different priorities and can allow the evaluation of both application categories as well as specific products based on infinitely possible criteria for selection.

Finally, there are particular limitations to this study. The possibility of PCBs and printed electronics existing within the same product (Keskinen, 2012; Kokare et al., 2021; Nassajfar et al., 2021) is beyond the scope of this assessment. Such hybrid circuit setups are considered relevant for the future, and when the printed electronics technology is mature. Then, some parts in all electrical and electronic products would become suitable for the application of printed electronics, and the application selection, as presented here, would be unnecessary. Additionally, it would become important to look at individual components within the electronic products and understand where the printed electronics may be applied; such a study would be too detailed even for a single product because extensive knowledge on each component of the product would be necessary.

6. Conclusion

By applying the MPAS methodology, various present-day electronics products were found to be suitable for the application of printed electronics. Apart from the conventional electronic products, multiple novel applications were also deemed suitable for printed electronics, despite the possible mismanagement issues at their EoL. Further research is required to understand the challenges, particularly pertaining to legislation and circular economy principles, posed by the replacement of PCBs with printed electronics in various products. The MPAS methodology nevertheless offers a flexible framework to ensure that the selection of products and applications is in alignment with the desired criteria.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All relevant data used for this research is disclosed within the paper.

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