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The Life Cycle of Smart Devices in 2030: The Effect of Technology Trends and Circular Economy Drivers on Future Products

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A defining feature of smart electronic devices is short innovation cycles – smart phones in 2030 will look very different than those of today. Technology innovations in the microelectronics domain and in related fields along the product life cycle, such as recycling and refurbishment technologies, will have a dramatic impact on product design and the product life cycle. In parallel, emerging circular economy concepts, business models and policies will influence how technologies develop. The interaction between technology innovation and circularity drivers is discussed below using data from life cycle assessments of smartphone products as example. A key focus is the latest research results of the EU-funded Horizon2020 project “sustainablySMART”, which investigates the product life cycle of smart mobile devices and new product design concepts, in particular, modularity of the device as such and on printed circuit board level, as well as robotics-assisted disassembly technologies, rework of semiconductor components and repurposing of electronics in other devices.

Technology-driven Trends

In the early years of the 21st Century, mobile phone development was largely defined by shrinking size and volume, with weight reduced to 100 grams or less. This trend was braked by physics – a minimum size for both, display and keys to ensure ergonomics. With the advent of the smartphone in 2008, technology progress turned from miniaturisation to making mobile phones multifunctional micro-computers. In recent years, the size trend has been even reversed and has led to larger display sizes – which also require larger batteries. As result, the tablet market was cannibalized and the smartphones of today are larger than 20 years ago. An additional effect has been the dramatic increase of the environmental impact: for example, the life cycle assessment of a 3G Nokia phone in 2003 was calculated as having Global Warming Potential of slightly less than 8 kg CO_2-eq. for the production phase (including raw materials) (Singhal 2005); today for the carbon footprint of smartphone production is estimated as being in the range of 30 to 80 kg CO_2-eq. (see e.g. Proske, M. et al. 2016; Ercan, M. et al. 2016; Suckling, J. & Lee, J. 2015) for raw materials acquisition and production. This is also an indicator of the additional functionality squeezed into today's smartphones. Smartphone technology is mature and the next disruptive innovation to change the appearance may well be flexible displays and electronics. Patents on flexible displays have already been filed by Apple and first prototypes of bendable smartphones were recently showcased by Rouyu Technology, Lenovo (Krishnan, K. 2019). Based on recent market releases, one could spectulate that, instead of integrating further functionality, the smartphone of the future will function as a router for peripheral wearable devices, such as smart watches, smart glasses and the in-ear headset *ala* Babel Fish quasi-predicted in Douglas Adams' *Hitchhiker's Guide to the Galaxy*, and stationary and mobile counterparts, such as a wide range of identification terminals and remote-controlled hardware.

Circularity-driven Trends

Circular Design

While the product "smartphone" evolves, or is occasionally catapulted forwards by disruptive technology changes, circular design trends has begun kicking in. However, the effects of evolution and circular design approaches are sometimes contradictory (Schischke 2018):

1. *Reparability*: Some small manufacturers, such as Fairphone (Figure 1) and Shift, have explicitly design smartphones with do-it-yourself reparability in mind. The logic design approach for this is modularity and simple fasteners that can be released without sophisticated equipment or the risk of causing damage to the device. At the heart of the simplicity of repairable design is a battery that can be easily replaced by the device owner.

   Reparability and serviceability can also be realised on PCB-level. Here, individual functions are integrated in distinct PCB modules, which are attached using reversible interconnection technology to a backbone board. Figure 2 depicts such a module for the USB connector of a mobile ICT device, which features embedded components. Embedding technology is a promising approach to compensate for the otherwise increasing PCB footprint, i.e. PCB area, of a modular printed circuit board (see discussion on the environmental price of modularity further below).

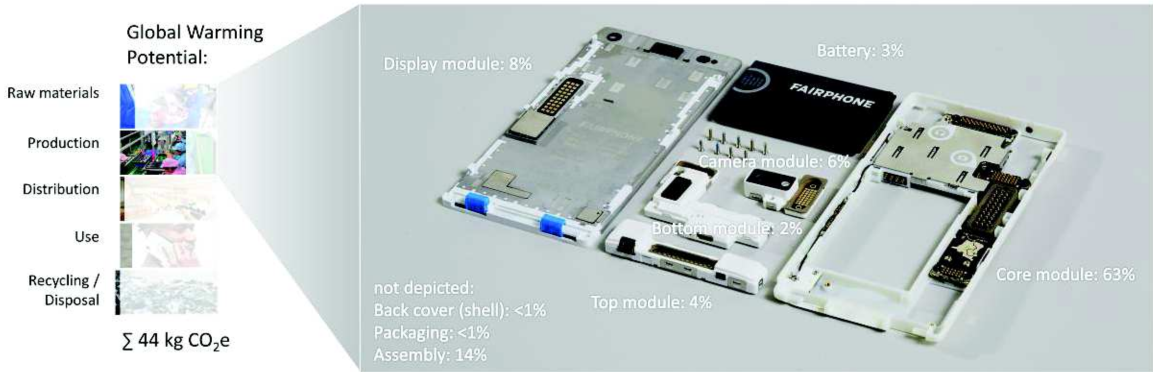

Figure 1: Modularity of the Fairphone 2 and the latter's carbon footprint

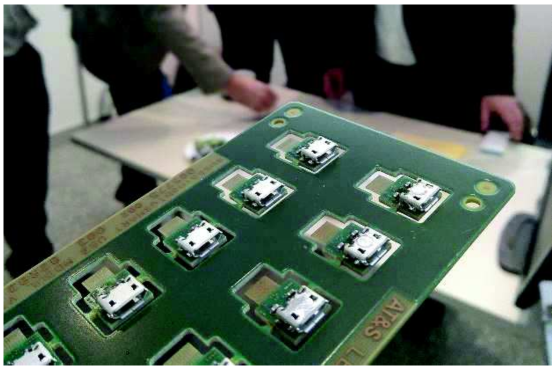

Figure 2: USB module for a mobile ICT device featuring embedding technology

2. *Upgradeability and flexibility*: Whereas hardware “upgrades” for the established smartphone market is shorthand for replacing a device with a better, newer one, the circular economy approach requires upgrading only individual functions. Performance can improve as user expectations increase or change without replacing the base device. Examples are the concepts of the Puzzlephone and of the discontinued Google ARA project. The Puzzlephone is intended to comprise just three modules, the “spine”, i.e. a display unit, the “heart”, i.e. a battery module, and the “brain”, which is the main electronics module, of which there are numerous different variants. In fact, the key component of this modular concept is a proprietary connector specification that is made available for other developers. In this way smartphone developers can make efficient use of an existing platform to develop modules with specific functionalities, The user would easily be able to exchange not only a broken display module or a battery reaching its end-of-life, but also the “brain” module to take advantage of newly released features.

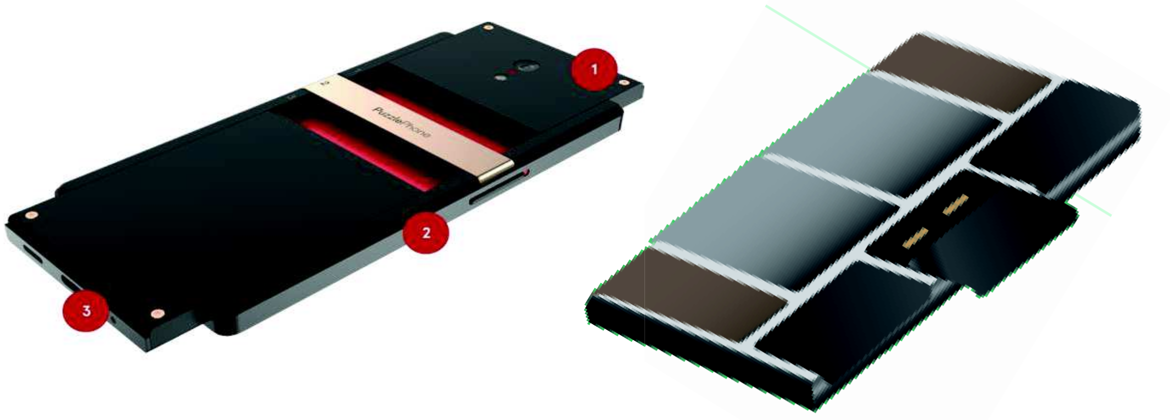

Figure 3: Puzzlephone design study, with brain (1), spine (2) and heart (3) modules (left, courtesy of Circular Devices Oy) and the Google ARA project concept (right)

The Google ARA project was an extreme example of this upgradeability approach. It featured an endoskeleton with a display on one side and numerous slots for modules on the backside (Hankammer, S. et al. 2016): Functionality was fragmented further, but led to significant complexity, which was one of the reasons why the concept was discontinued. However, if it had, as intended, transposed success story of the software apps universe onto the hardware world, sever major rebound effects would likely have materialised: Just as many users download many more apps than actually used, there would have been the risk that users would just own many more modules than slots provided by the Google ARA and actually only use a few. Instead of increased efficiency, the outcome would have been excessive hardware consumption.

3. *Cascading*: Smartphones are powerful mini-computers - with the resulting increased carbon footprint. At end of life, they are still powerful mini-computers, albeit more one or several of the following: a drained battery, a broken display, increasing software

incompatibility, deteriorated performance. At the same time the ubiquitous use of electronics for e.g. home automation or the Internet of Things qualifies smartphones and its components for cascade reuse. For example, the Galaxy Upcycling project, announced in 2017, but still not publicly launched (as of January 2019) is intended to be exactly this: An open innovation community and platform to exchange ideas and hardware solutions for how to repurpose used Samsung Galaxy smartphones for specific applications – for example, monitoring and operating a fish tank remotely is the use case example featured in the promotional YouTube video of the Galaxy Upcycling project. Another example of the cascade approach is the above discussed Puzzlephone concept, which can also facilitate a proper reuse of the main electronics: The company Circular Devices is working on turning several used “brain” modules into a stacked computing array as a workstation (Figure 4).

In fact, components of conventional “mono block” smartphones can also be reused: Sitek et al. (2018) demonstrated a high quality desoldering and rework process for semiconductor components from mobile devices, and similar components have already been repurposed for low-cost memory sticks, toys and the like in non-European countries. This trend is likely to continue with the increasing performance of end-of-first-life components. Technically, this requires a specification of components for repeated reuse, with the challenge being device reliability that can withstand the stress of the de- and re-soldering process. Although semiconductor components are only qualified for a limited number of soldering cycles, research by Sitek et al. (2018) has shown that parts such as memory components can easily withstand more than the specified number of soldering cycles. What remains to be investigated is whether the increased number of read-write cycles on memory chips with extended component use life will become a problem in future: Latest memory technologies with ever increasing storage density will last an ever lower number of read-write cycles due to physical constraints. Reusing these memory components might yield reliability problems.

4. *Multi-purposing*: As a smartphone is a mini-computer, why not using it as a computer? The German company Shift, known also for a concept of modular smartphones, recently announced a project to develop a modular smartphone, which can be turned into a workplace computer with a compatible screen, keyboard and docking station (SHIFTmu bundle; WindowsArea 2018). As such a smartphone with accessories might replace computing devices, which usually have a much higher carbon footprint.

5. *Durability*: A waterproof design, i.e. ingress protection (IP) classes 67 or 68, protects against the most frequent defects of smartphones, namely accidental dropping in water or spillage of liquids. However, the hidden disadvantage of this protection is that, if something else breaks, repair of IP67 devices is generally much more complicated than products not sealed with rubbers and pressure sensitive adhesives and the like. Today, an increasing number of smartphone models feature higher IP classes, which is a controversial trend from a circular economy viewpoint.

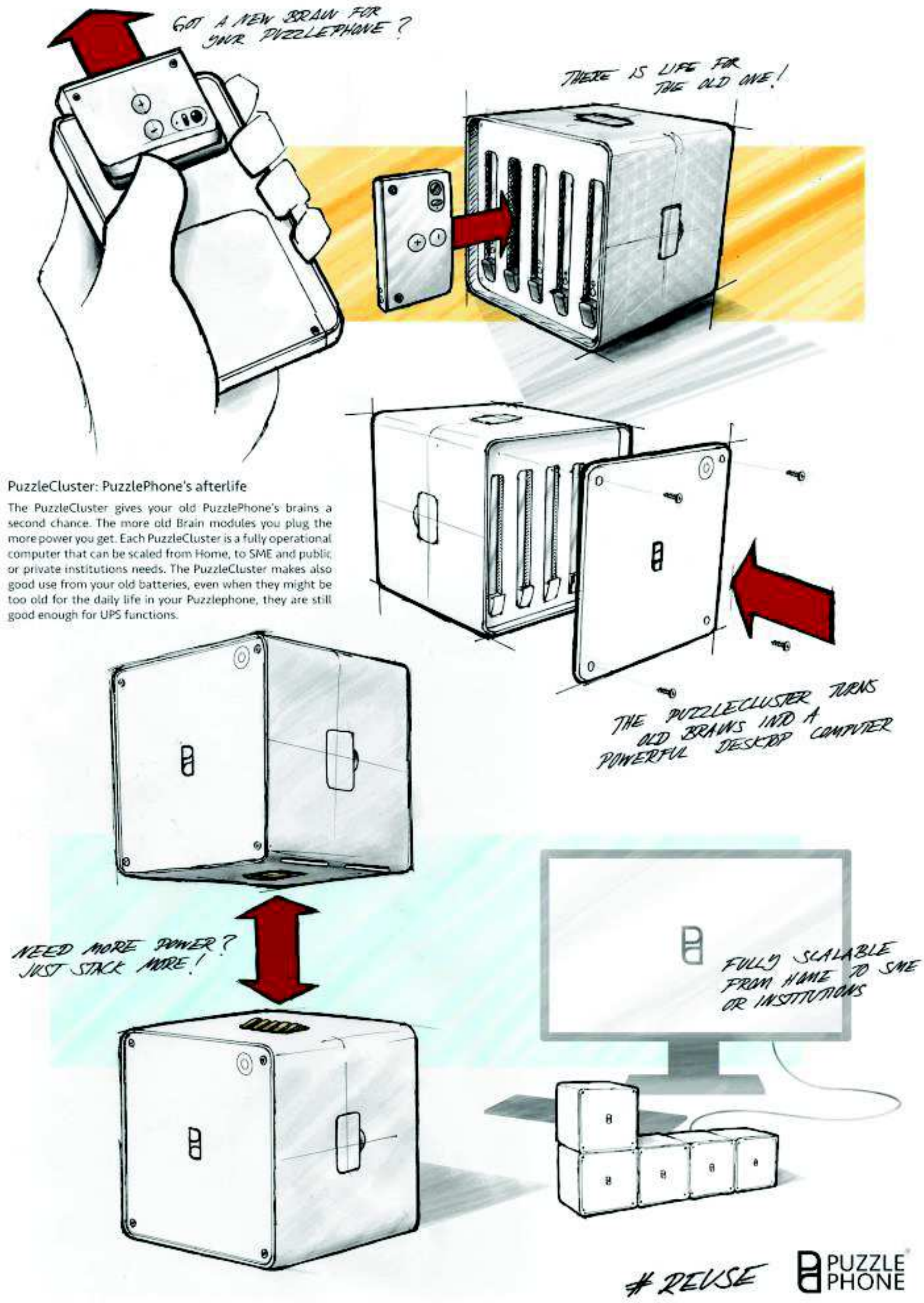

Figure 4: Cascade reuse concept for second life Puzzlephone modules – Puzzle Cluster (image courtesy of Circular Devices Oy)

Figure 5 depicts the product release timeline – to date - of selected modular smartphones.

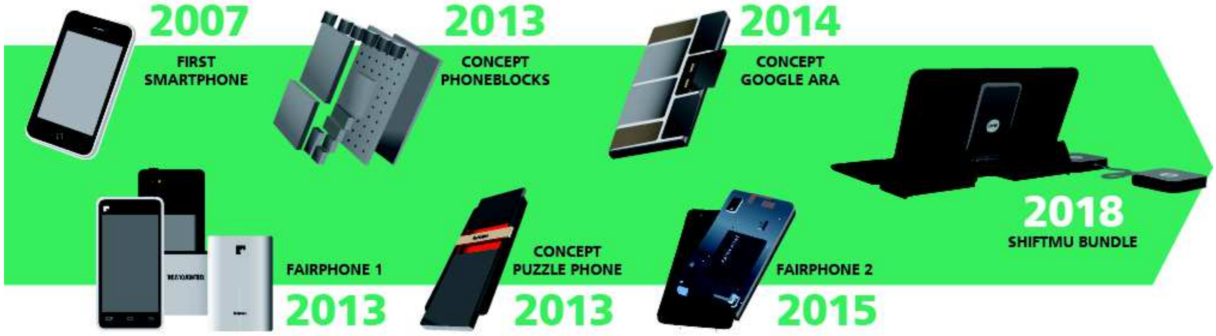

Figure 5: Modular smartphones (selection)

The Policy Context

These technology innovations are emerging in a volatile policy environment, in which the Ecodesign Directive implements increasingly stringent material efficiency requirements, as well the related standardisation under mandate M/543 as regards ecodesign requirements on material efficiency aspects for energy-related products in support of the implementation of Directive 2009/125/EC. Standardization and policy are currently framing circular design. The optimistic scenario is that material efficiency requirements will have an impact on products and product lifecycles similar to the impact energy efficiency labelling and energy consumption thresholds have had as part of the Ecodesign Directive on power consumption. Incentivizing reparability, reusability, upgradeability, but also recyclability (see Fairphone B.V. 2017) all incentivize modular design approaches.

Circular Economy Conflicts

Circular Design does not come for free: Modularity requires additional connectors, potentially additional sub-housings, and potentially larger printed circuit board footprints (Proske, M. et al. 2016). In particular, the connectors require additional materials, which are concerning in environmental terms: The Fairphone 2 comes with pogo-pin connectors with a gold finish, just as the Google ARA design (“spiral 2”) featured gold contacts for the electrical contact and magnets containing neodymium and cobalt for mechanical fixation. Gold is simply the material of choice for reliable, ductile, electrical conductive, non-corroding surfaces, magnets are a convenient way to hold modules in place: There is a range of “modularity materials” (Schischke 2019) found repeatedly in modular devices. Unfortunately, several of these materials are in conflict with sustainability aims. Similarly, life cycle assessments of modular products show that the cradle-to-gate impacts of material acquisition and production are higher for a modular product than for a conventional product. This has been shown by Proske, M. et al. (2016) for the Fairphone 2, by Pamminger, R. et al. (2018) for a mobile digital device, and by Vaija, S. (2018) for a stationary ICT device. To compensate, or actually over-compensate, the additional manufacturing impact of modular design, the circularity potential of modularity has to be fully embraced: repairing, reusing, refurbishing, instead of discarding. Only then, and that has been demonstrated by all of the three studies named above, the environmental impact per functional unit is significantly reduced below the level of a conventional product concept.

Another potentially negative side-effect of long-lasting smartphones is the risk of over-stocking spare parts for long-term reparability. Key components of smartphones are quickly discontinued. Component obsolescence thus requires stocking spare parts for later repairs. As later demand can hardly be precisely forecast, either more spare parts are actually produced than needed or reparability is limited by a lack of spare parts.

In conclusion, the modular approach to smartphone design cannot be assessed without taking into account the following considerations:
Modular mobile devices…

- require a sound modularity strategy: Which parts need to be repaired, upgraded?
- support environmentally benign use patterns (DIY repair, upgrade when really needed, longer lifetime through “growing device”).
- might initially lead to additional environmental and technical footprint.
- limit over-dimensioning of devices‘ functionality.
- might yield significant rebound effects (purchasing of more modules than actually needed –
- the “app effect“)

Technology Outlook

Trend 1: Smartphones become main computing device for end-users

As seen with the SHIFTmu bundle the smartphone as such might become the core module of mobile personal computers, making at least laptops and tablet computers obsolete for some use scenarios. The transition from larger computing devices to smaller ones, which are apparently taking over the function of computers, is underpinned by market data: The global desktop PC market is in steady decline, laptops reached maximum sales figures in 2011, tablets in 2014 (Figure 6). The smartphone market plateaued in 2016-2018, but market intelligence suggests again increasing sales figures in the next few years driven by the introduction of 5G communication. From a sustainability perspective these market figures show two detrimental trends:

- Devices with a high carbon footprint decline in market share and those with a smaller carbon footprint are on the rise
- There is a clear rebound effect: The peak of tablet sales has been higher than the peak of laptop sales, and smartphone sales are now much higher than sales of desktop PCs, laptops and tablets ever has been.

With this latter observation, we have to state that on the global scale despite (environmentally) improving products the trend is rather towards ever increasing absolute environmental impacts.

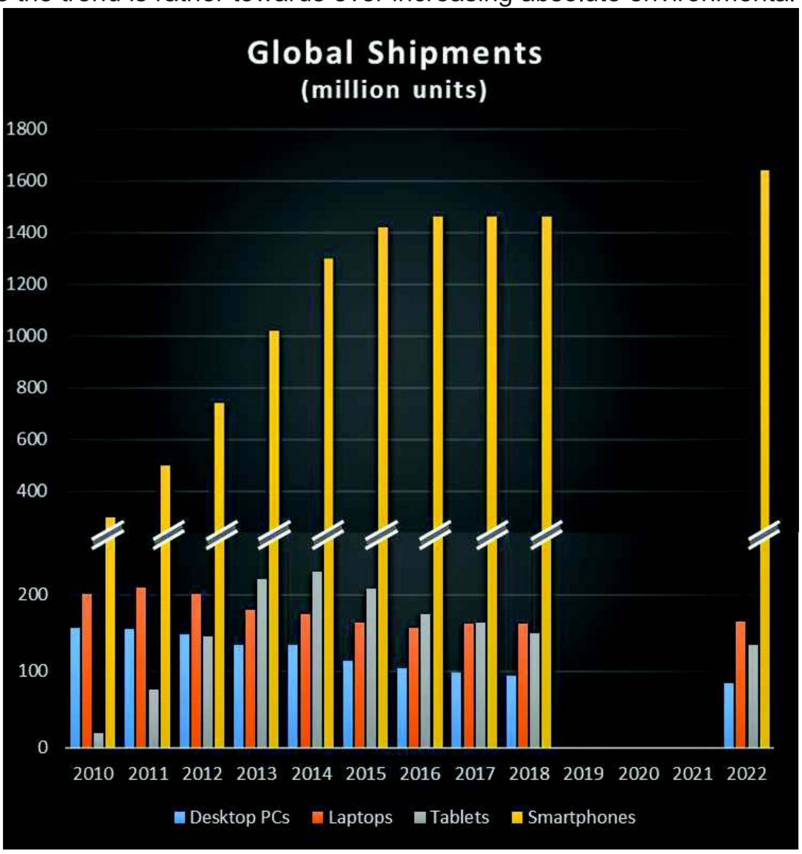

Figure 6: Global shipments of desktop PCs, laptops, tablets, smartphones 2010-2022 (data: IDC)

Trend 2: Wearable and flexible devices

If the predicted trend towards wearable, and flexible devices, continues, the next logical step towards merging technology and circular design trends are modular flexible devices. Inspiration as to the possible manifestation of this in practice includes the way wearable systems are designed today, for example, the mechanically flexible micro battery stripe depicted in Figure 7: An array of rigid segments are the first step towards flexibility. While fully flexible systems might be achieved in the final stage, the intermediate step is likely to be a modular system – great entry point for circularity: as the modular system is upgradeable, repairable, refurbishable – all of which is possible if reversible connection technologies are applied.

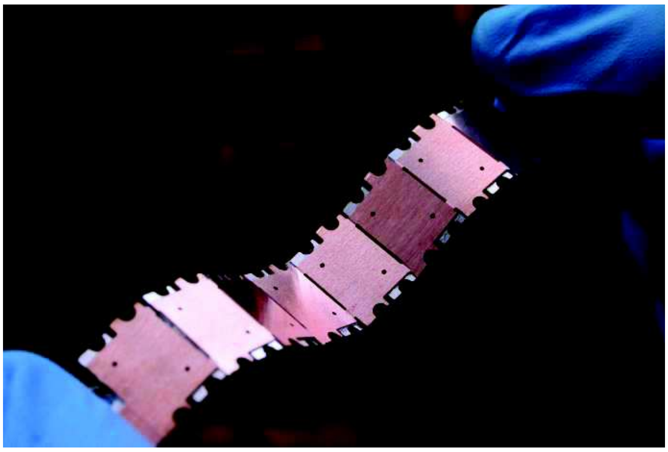

Figure 7: Mechanically flexible micro battery stripe made from segmented battery cells (© Fraunhofer IZM)

An example of this new direction in microelectronic design is the modular smartwatch BLOCKS, the design of which raised some 1.6 million USD on *Kickstarter* in 2015. Various functional modules can be attached along the strap to allow for an individual configuration of the watch. Similar to the Google ARA project, a public development kit is intended to allow third-party developers to customize modules based on Android as the operating system. However, shipment of the watches has been severely delayed – only a few backers have yet received the core module (as of January 2019). But while BLOCKS is not yet a shining business example of a flexible, modular, smart device, it is currently the closest we are to the mobile devices of 2030.

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