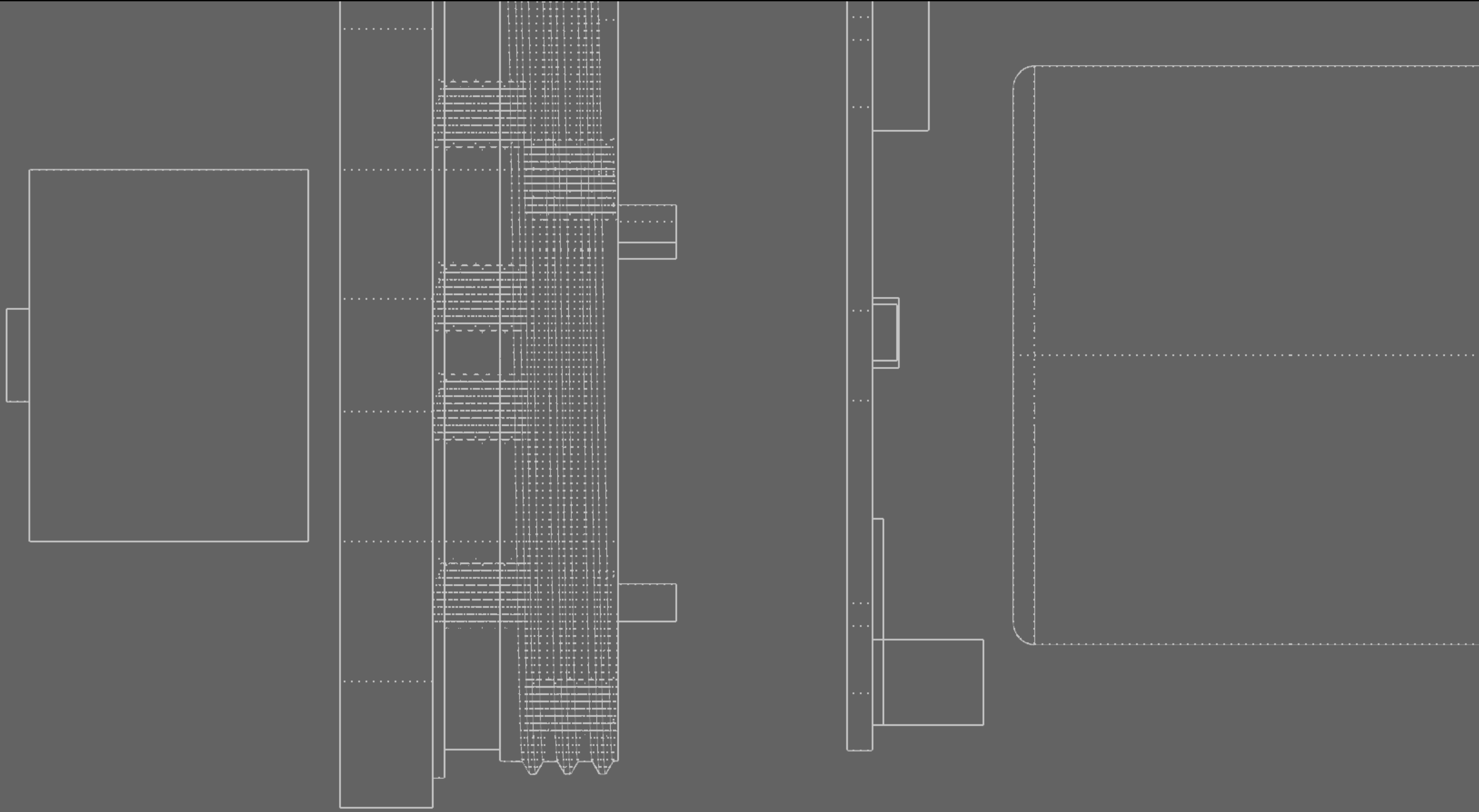


Circular IoT ❙ Longer lasting wireless sensor nodes for industrial applications

---

Master Thesis - Joop Dirrix

THESIS
Circular IoT: Longer lasting wireless sensor nodes for industrial applications

AUTHOR
Joop Dirrix
Studentnumber: 4290798

INSTITUTE
Delft University of Technology
Faculty of Industrial Design Engineering

SUPERVISORY TEAM
Chair: prof. dr. Ruud Balkenende, A.R.
Mentor: ir. Sjoerd van Dommelen, S.

COMPANY
Edge Dynamics
Company supervisor: Mohamed Danad

Preface

In this thesis you will find an elaborate description of the process carried out to transition an existing product, a wireless electronic instrument called an industrial sensor node, to the circular economy. The requirements for the redesign surfaced from an analysis of the circular framework and its underlying principles.

This project concludes my master's degree in Integrated Product Design. Throughout this project I learned the intricacies of an upcoming industry I knew little about before. By joining visits and speaking with stakeholders I experienced the complexity of this product's application.

I would like to thank everyone who was involved directly or indirectly in this project. Mohamed and Zakaria for their support and considering me a colleague from day one and I would like to thank Khadar in particular for the interesting discussions and enthusiasm in sharing everything he knows.

I want to thank Ruud and Sjoerd for their critical feedback and support in harder times.

Lastly, I want to thank my friends who helped me see different points of view and giving their ideas as input and helping me refine my own, and my family for the unconditional faith in me and the tremendous support whenever I needed it.

Executive summary

With the ever increasing number of wirelessly operated connected devices, the environmental consequences that this trend brings about need to be considered. This project has been carried out to explore the possibilities for transitioning industrial IoT sensor nodes into the circular economy.

Wireless sensor nodes are battery powered instruments for monitoring processes and condition of industrial equipment. They need to endure harsh environments and are subjected to critical certification. In general, they are discarded once their internal battery depletes, meaning their embedded potential is lost.

Structuring the analysis of Edge Dynamics' current product on circular aspects using tools such as HotSpot mapping and the Disassembly Map framework, revealed the disassembly steps and activities that inhibit circular activities such as repair, remanufacturing and recycling. These key components are responsible for a significant fraction of the product's environmental and economic footprint, or are subjected to a high rate of replacement.

The outcome of the project is a concept sensor node featuring an optimised product architecture. The concept uses a novel way to configure the internal components as such that the key components have the top priority in disassembly. The redesigned sensor node is faster to repair, faster to assemble and disassemble and houses less components. Moreover, the product is made up of less materials and better fits recycling processes as no materials are mixed.

On a system level, circular strategies such as repair and remanufacturing can considerably reduce the environmental impact of the sensor nodes, as giving nodes a second or third lifespan will prevent the need to use virgin materials for the manufacturing of new products.

On a product level, the current product's key components are sufficiently easy enough to reach and repair that a redesign will only make a significant difference in time savings, and thus costs, on a certain scale. Optimising the sensor node has not increased the embedded footprint. Reusing the circuit boards by for instance repairing sensor nodes can dramatically reduce the lifecycle footprint.

On a material level, using exclusively recycled metals and polymers in the sensor node could reduce its carbon footprint with 4,9% compared to the use of materials containing typical recycling fractions. Moreover, the effectivity of recycling processes can be improved by avoiding the use of mechanical fasteners mixed with dissimilar metals.

Besides the potential reduction of the environmental impact of wireless sensor nodes, a financial incentive is likely at hand as well. Depending on the scale of operation, significant cost reductions can be achieved by faster maintenance and repair when operating a circular business model.

Combining the efforts of each level will lead to the highest potential for sustainable sensor nodes. Edge Dynamics can take a leading role in the industry, offering the first circular IIoT devices.

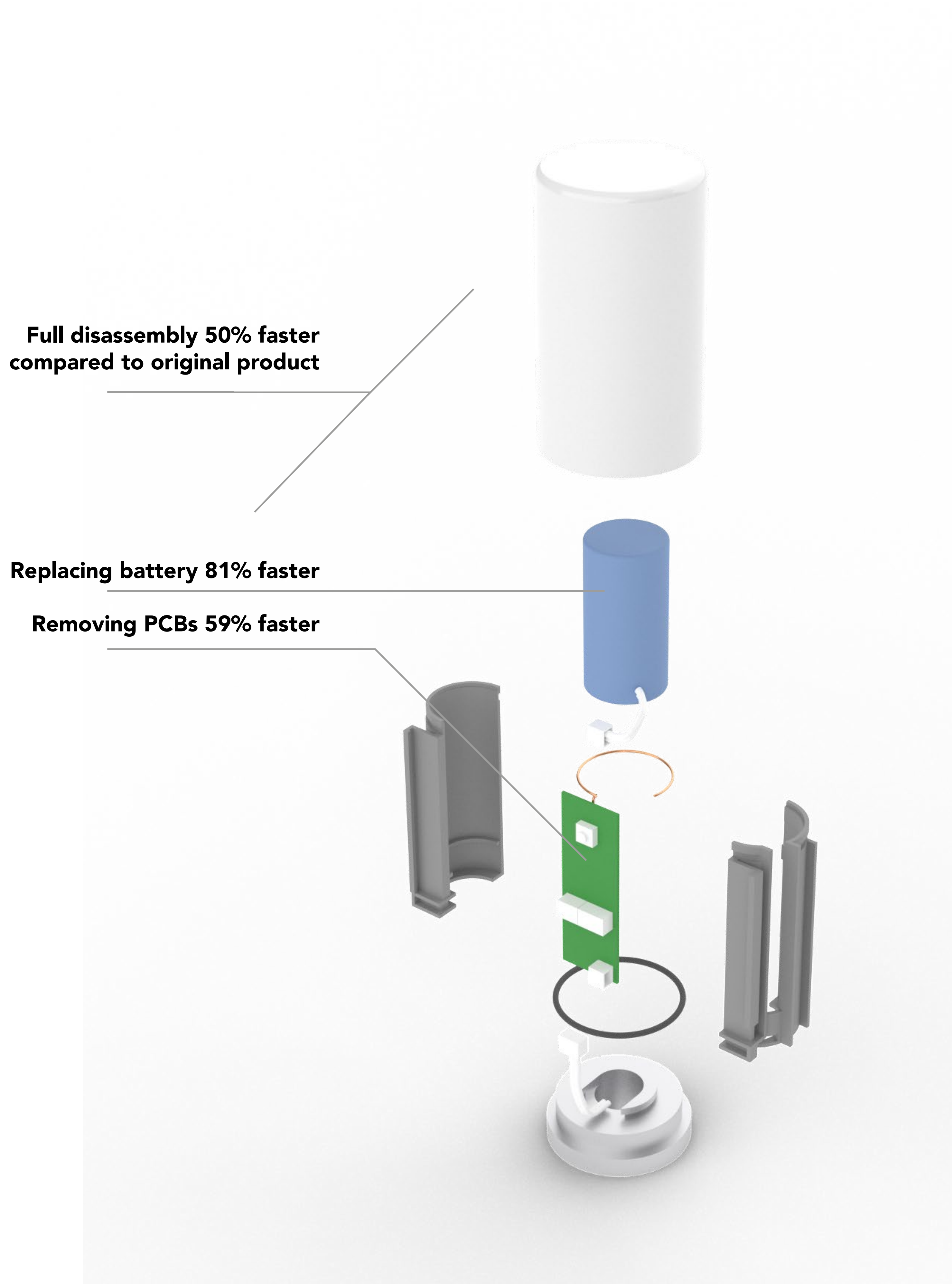


Table of content

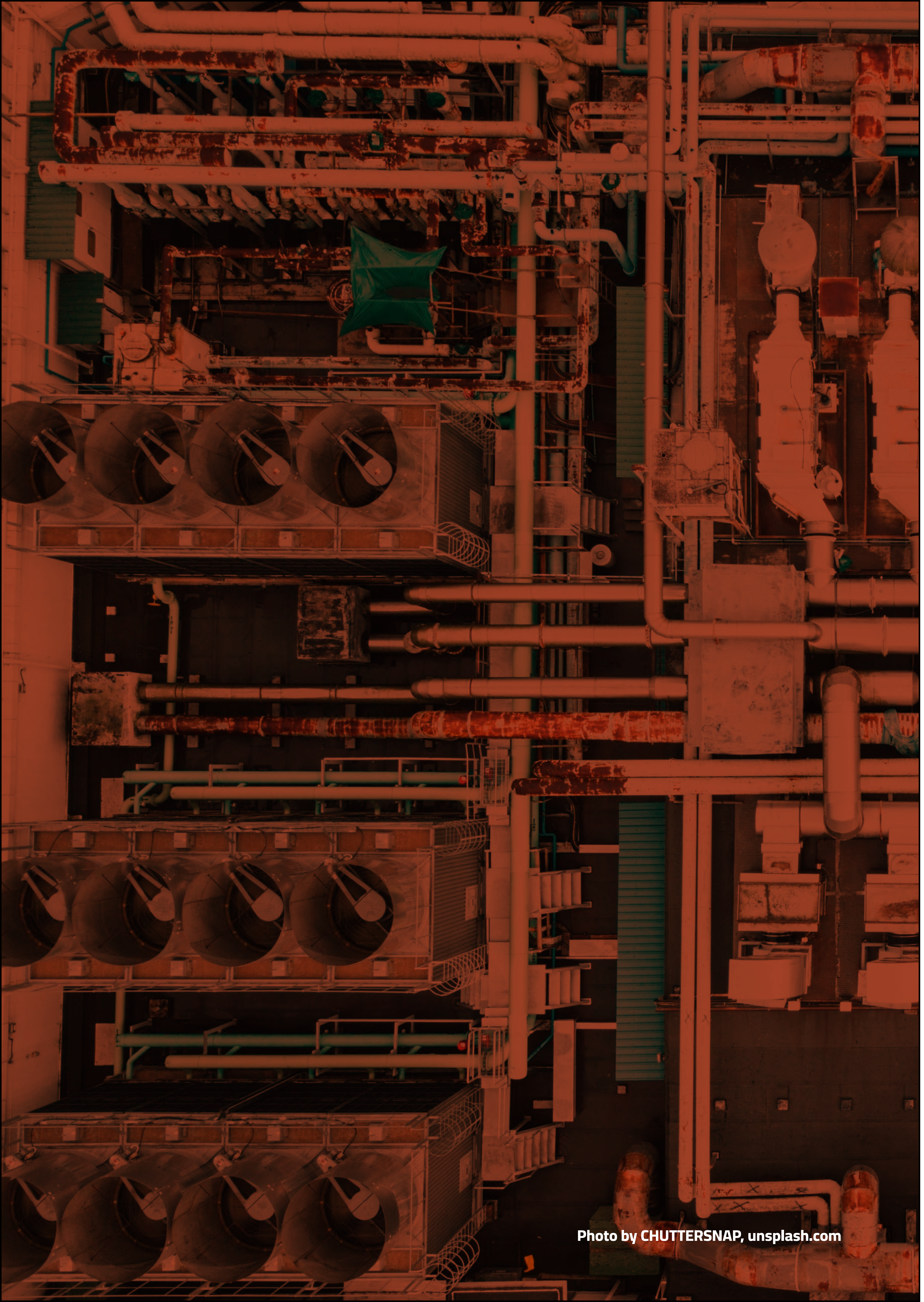


Photo by CHUTTERSNAP, unsplash.com

1 | Introduction

Since the Industrial Revolution, the economy is fuelled by an ever increasing need of material resources. These resources are used to produce products that are consequently consumed on a scale never seen before. The economy has produced an amount of waste that from an economic and environmental point of view is nearing a critical point. To oppose this linear economy, where products undergo a sequence of 'take-make-use-dispose', the concept of a circular economy has been introduced. The circular economy aims to create an equilibrium of materials and energy within the economic system that, in principle, can be sustained perpetually by nature while at the same time support the economic capacity to create value (den Hollander, 2018. p. iii).

Albeit in an early phase, The Internet of Things (IoT) is considered a potential key technology in the implementation of the circular economy. IoT is a system of connected devices such as computers, servers and everyday objects that have unique identifiers and can sense and share data over a network. This leads to novel applications for information exchange. As the number of connected products grows, increasingly accurate knowledge on assets in the field can be captured. This can support the monitoring of products throughout their lifecycles and ease the decision making for companies that implement business models in the circular economy (Ingemarsdotter, 2019). The Internet of Things consists of devices that all share the same characteristics; they possess the ability to connect with a parent device and transmit or receive data. These devices make up a fundamental layer in an IoT system. They register their direct environment through electronic components such as sensors and transducers and communicate using transceivers wirelessly (Sharma et al., 2020).

Due to the many applications, IoT is rapidly expanding. The amount of connected IoT devices is expected to grow to 43 billion 'things' connected to the internet; three times more compared to 2018. Increasingly, these wireless IoT sensors are used to measure processes and monitor equipment. Numerous manufacturing organisations are embracing the IoT potential as part of the transition to Industry 4.0; the industrial Internet of Things (IIoT). (McKinsey, 2019). This growth unlocks many opportunities, but brings a challenge of its own.

Namely, the vast majority of wireless sensors are powered by primary (non-rechargeable) batteries and therefore need a replacement sooner or later. Most manufacturers of these devices either made it impossible to change the batteries, or highly discourage it. Even when the batteries are replaceable, it might not be considered cost-effective to do so. Therefore, millions of IoT devices are likely replaced entirely due to a drained battery. Currently, the world outputs yearly over 50 million tons of electronic waste (e-waste), of which only 20% is adequately recycled. This number will more than double by 2050 and a significant part of this is fuelled by the growing digital IT (information technologies) infrastructure. As the European Union aims to be carbon neutral by 2050, the IT sector needs to address this issue as well (European Commission, 2022). Restructuring operations in a sustainable matter, like applying the circular economy concept, has to be considered. As of today, sustainable efforts within the IoT sector are focusing on providing its services in a sustainable manner, such as energy efficiency and cybersecurity, rather than reducing the need of critical raw materials, which will become an issue in the near future (Fraga-Lamas et al., 2021).

IoT products are discarded once they malfunction. As they are electronic devices, this contributes to the growing global problem of e-waste (electronic waste). The lifecycle of IoT products is not considered in the development and design of these products. In case of devices reaching their end of life, once they malfunction or become obsolete, their remaining value is often lost by the disposal of the devices. A key principle of the circular economy is "the circulation of products and materials at their highest value. Meaning materials are kept in use, either as a product or, when that can no longer be used, as components or raw materials" (EllenMcArthur Foundation, 2022).

COMPANY ROLE
Edge Dynamics is a start-up based in the Netherlands and operational in the IIoT market. The Industrial Internet of Things is mainly targeted at clients operating in the heavy industry, such as the oil and gas industry. Edge Dynamics offers 'plug-and-play' IoT products that can be installed wirelessly on industrial equipment. The products are certified to be used in industrial environments. An industrial environment is an environment that requires attention to characteristics of factory surroundings, worker safety and health (Reinhardt et al., 2008). Clients can use the data generated by these IoT devices for equipment monitoring. As Edge Dynamics is still optimising and exploring their products, they recognise the opportunity to reduce the environmental impact of their business operations.

RESEARCH QUESTIONS
Therefore, this project intents to illustrate the possibilities for Edge Dynamics for the development of circular IIoT products and to take a leading role in the industry. Currently, Edge Dynamics' IIoT products are not designed in a way they fully resonate with the circular economy framework. Therefore the main research question is as follows:

How can product design improve the circularity of Edge Dynamics' IIoT products?

Product design for the circular economy focuses on retaining the value of products and materials by utilising value retention strategies. Moreover, circular product design incorporates business models that facilitate these design strategies. As such, product design and an appropriate circular business model go hand in hand (Bakker, 2022). Finally, recycling is an important consideration inseparable from the circular economy and should be considered as a last resort. The following sub research questions have to be addressed in order to answer the main research question:

RQ1: To what degree are IIoT products currently circular?

- RQ1.1: How can the circularity of IIoT products be assessed?

RQ2: How can Edge Dynamics' IIoT product be redesigned to better fit the circular economy?

- RQ2.1: What are the circular design strategies most appropriate for Edge Dynamics' IIoT products?
- RQ2.2: What are the design principles supporting these circular design strategies?

SCOPE OF PROJECT
Within this project, the focus lies on the product's architecture; the composition and order of the individual components that comprise it. The answers to the (sub) research questions will be used to guide redesigning Edge Dynamics' IoT product with the intention of finding a better fit to the circular economy framework. A product concept will depict the answer to the main research question.

In the next chapter, the approach is discussed. This entails the structure, methods and tools used to execute the project.

2 | Approach

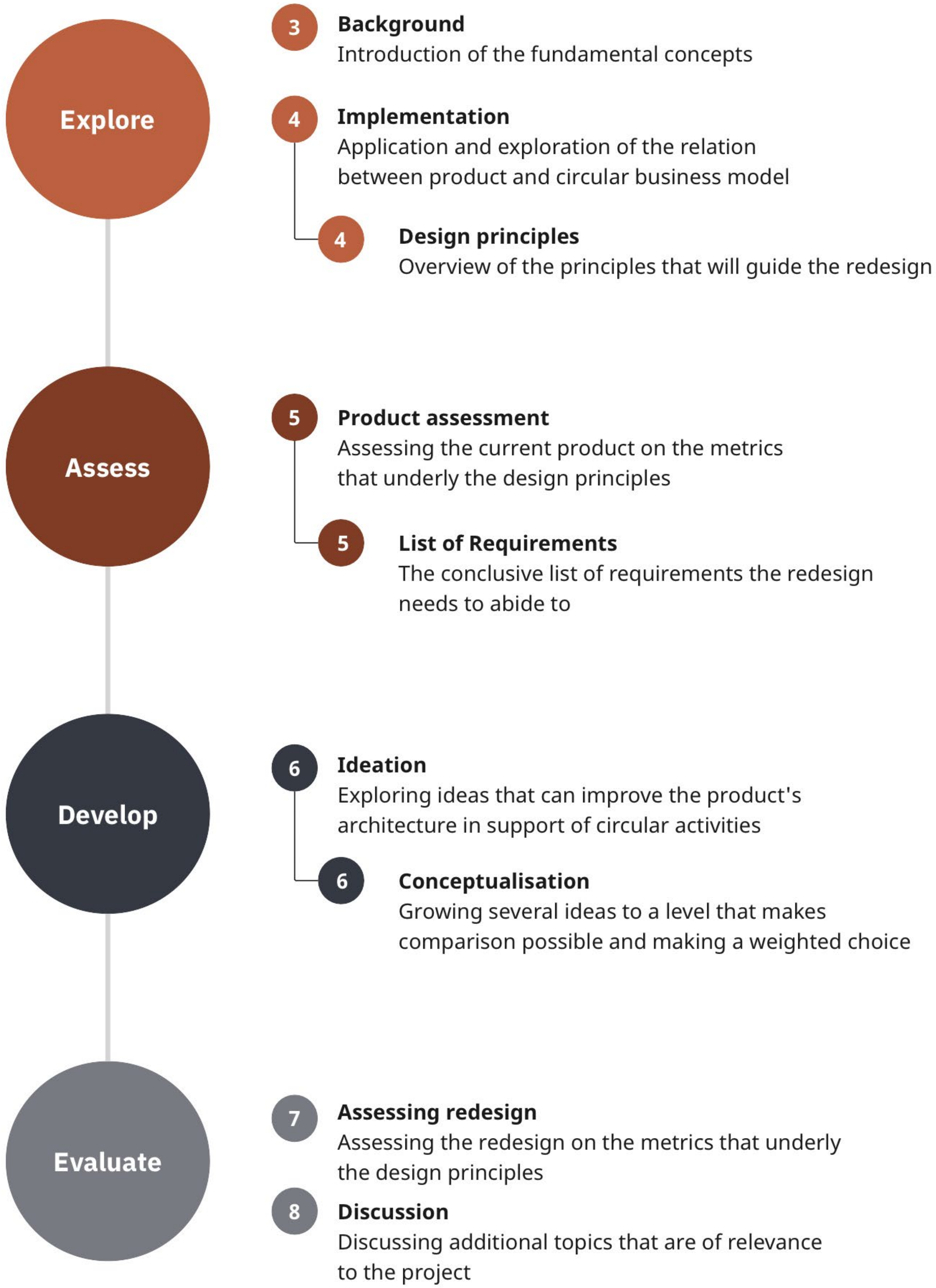
METHODS
For the overarching approach of this project, the basic design cycle of analysis, synthesis, embodiment and evaluation is used (Van Boeijen et al., 2013). To initiate the project, the 1/10/100 method is utilised. By going through the basic design cycle three times, relevant questions are expected to appear quickly and the problem statement and project goal can be refined. The first cycle is meant to be a 'pressure cooker'; in one day a design cycle is started and finished and decisions are made mainly on a short analysis and gut feeling. The second cycle lasts ten days and should include more informed decisions. The third cycle can be considered as the main project cycle, which is taking the remaining available time. Appendix A elaborates on this method.

For gaining a better understanding of the IoT market and product context, informal qualitative interviews with experts are carried out. In addition, literature on relevant topics will be consulted to support the answers to the research questions.

Different tools have been used to analyse Edge Dynamics' current product. A function analysis can expose the underlying functions of the product's architecture. The HotSpot Mapping tool is used to identify the product parts that need to be prioritised. The Disassembly Map tool (de Fazio et al., 2021) will show the hierarchy and disassembly pattern of the product components. Together, the interrelations of different functions and parts are visualised and target areas for improvements can be identified. The results from the product analysis and circular strategies are combined to form a list of requirements.

Idea generation is carried out by applying design-by-analogies (inspiration from comparable situations), structured brainstorming (3-6-5) (Tassoul, 2012) and the How-To method (van Boeijen et al., 2014).

Promising ideas can be refined by prototyping proposed product architectures. Assessing the redesign on the same metrics as the original product facilitates a comparison that will show if circular IoT can be achieved by the framework of this thesis.



3

Background

This chapter introduces the essential concepts that are explored and applied in this project. Firstly, the role IoT has in the heavy industry is touched upon and the fundamental characteristics of the sensor node are explained. Secondly, the basic understanding of the circular economy concept and its underlying framework is described. Finally, the degree to which the circular strategies are applied as of today are discussed.

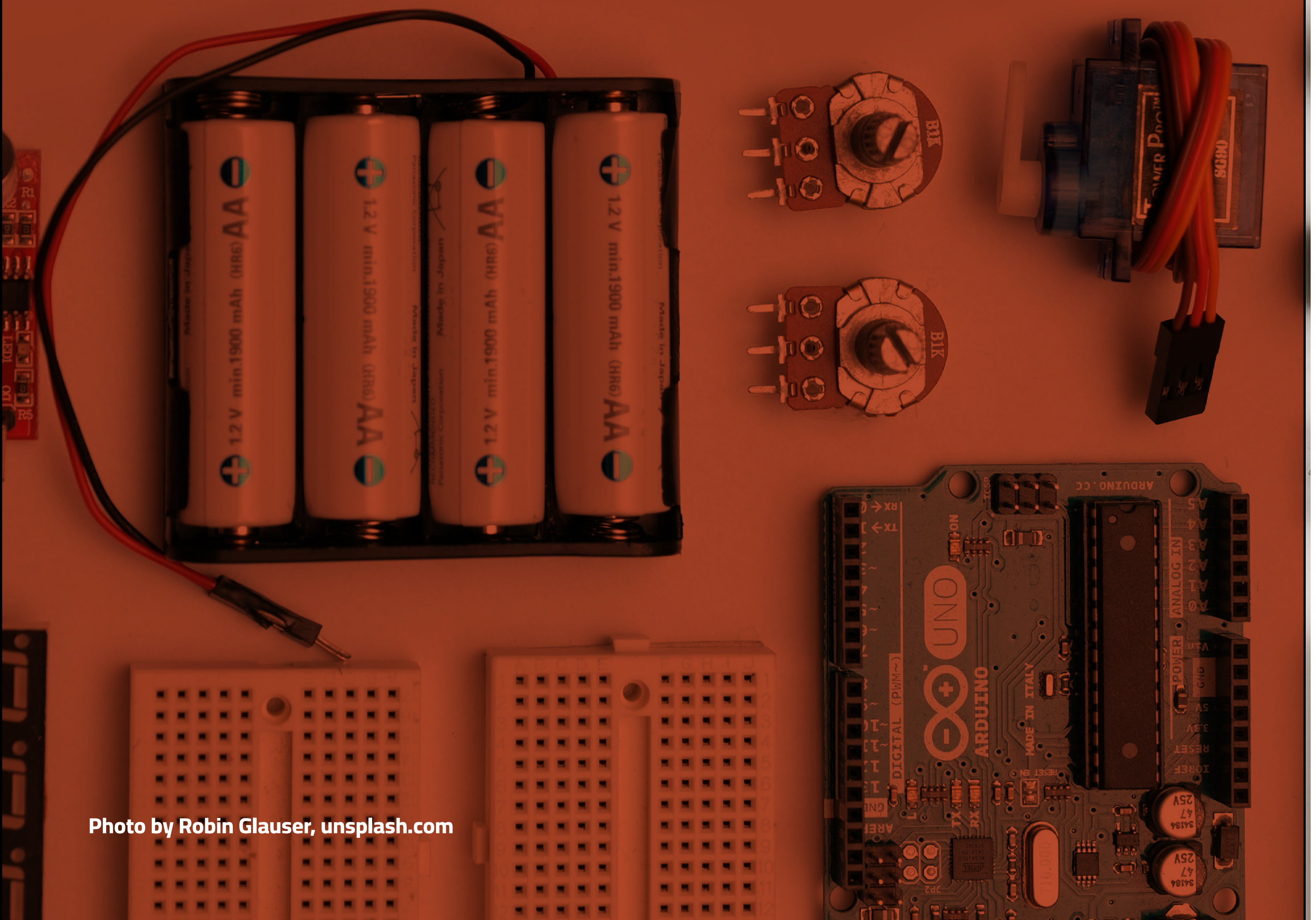


Photo by Robin Glauser, unsplash.com

3.1 IoT in the heavy industry

The Internet of Things (IoT) can be seen as a global network consisting of a variety of devices that are connected together. They rely mainly on sensor, communication and information technologies. IoT is the accumulation of various technological developments since the 1980s. One of these foundational technologies is the wireless sensor network (WSN). WSNs are mainly used for sensing and monitoring and have therefore gained attraction in industries such as logistics, retailing and manufacturing (Xu et al., 2014).

In manufacturing industries like the gas and oil industry, IoT is increasingly used to monitor processes and equipment condition. The latter makes it possible to predict imminent failure of assets, what could prevent costly downtime of production. For critical applications, this has been done by wired sensors within industrial control systems (ICS). Only with the rollout of Industrial IoT has this become cost-effective for non-critical applications. A major part of monitoring applications rely on WSNs, due to their advantages of replacing cables, scalability and lower cost (Mois et al., 2017).

A WSN (figure 1) consists typically of a large number of low-powered sensor nodes. They are the first layer in an industrial IoT framework (IIoT) (figure 2). They measure a certain parameter related to the monitoring of an industrial process or equipment. They then communicate with one or several parent devices, called gateways. Gateways often have a wired connection to a server station or the Internet. This is considered the network layer. On (cloud) servers, the acquired data is interpreted and used for services and applications, such as data analysis. This is the service layer. Finally, the output of the service layer is usually shown through dashboards at industrial control centres and can therefore be considered the interface layer (figure 2) (Xu et al., 2014).

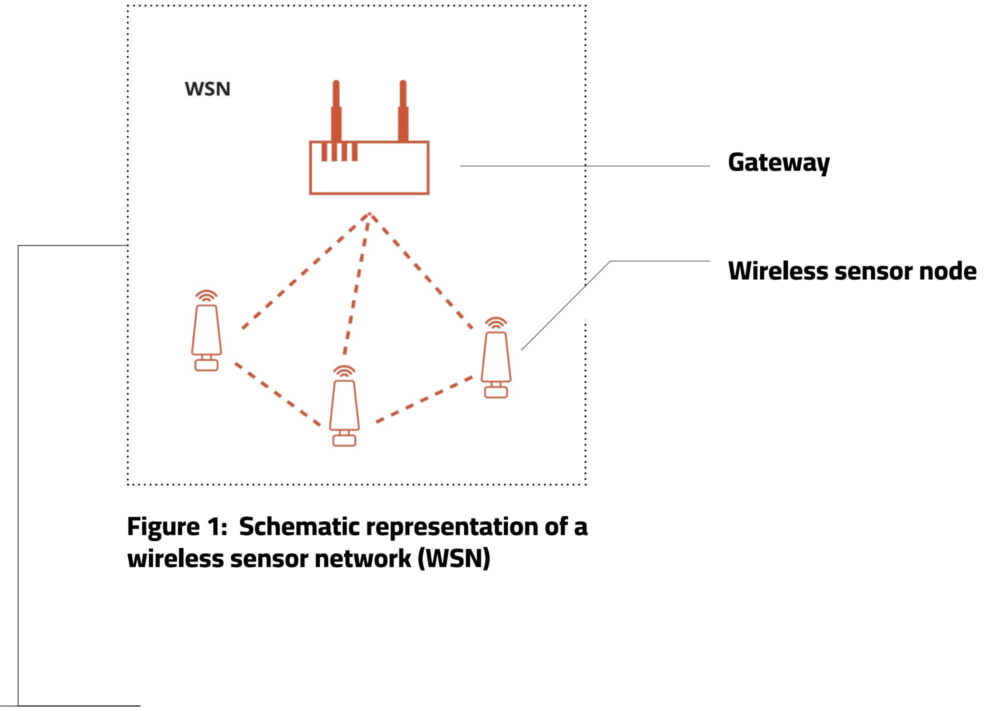


Figure 1: Schematic representation of a wireless sensor network (WSN)

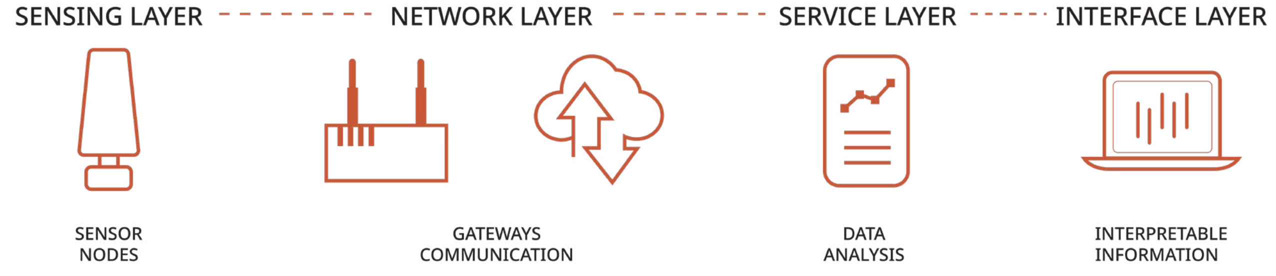


Figure 2: Data flow from devices to control centre

Edge Dynamics develops wireless sensor nodes for the device layer of IIoT networks. They offers a variety of wireless sensor nodes, differing mainly in sensor type. The current product family includes sensors that measure temperature, humidity, pressure or vibration. Other manufacturers offer their own share of sensor nodes. They compete on characteristics such as sensor type, product size, battery life and type of communication protocol. Appendix B shows a comparison of Edge Dynamics' sensor node and its main competitors.

WIRELESS SENSOR NODES: PRODUCT ARCHITECTURE

Still, all nodes make use of the same product architecture and in essence consist of four sub systems to conjointly perform the product's functions. Figure 3 shows the schematic overview of a sensor node architecture, while figure 4 shows the corresponding components of Edge Dynamics' node.

The sensing sub system translates environmental phenomena such as temperature or vibrations to electrical signals. This way the sensor node perceives its surroundings. Virtually any sensor can be incorporated in a sensor node, but for industrial applications mainly vibration, temperature and humidity are measured. The sensors can be integrated onto PCBs (printed circuit boards) if they are small enough, such as accelerometers and humidity sensors, or they are connected by cable as peripheral sensors, e.g. surface temperature sensors (Healy, 2008).

Accelerometers in sensor nodes are used to measure vibration by registering the acceleration of the equipment in three directions. Measuring vibration is prone to disturbance and as such can be influenced by resonation of the sensor node itself (Hassan, personal communications, March 2022). To mitigate the effect of this on the measured frequencies, the accelerometer should be positioned as close as possible to the centre of mass of the sensor node. Or the effect should be accounted for in post processing of the sensor's output (NXP, 2012).

Naturally, the centre of mass of Edge Dynamics' sensor node is located relatively low (figure 5) due to the stainless steel base that is required to securely fasten the node to equipment. Therefore, the accelerometer is positioned relatively low as well, on the bottom PCB. This consideration is relevant to sensor nodes measuring vibration patterns occurring in industrial assets, such as motors and bearings. For measuring other parameters such as temperature or humidity, this is not important.

The computing sub system is tasked with controlling the sensor node's components and execute any computations needed for operation. An essential aspect of the computing sub system is the ability to operate using different modes, such as active mode, idle mode and sleep mode. Using these optimally preserves the sensor node's battery life (Healy, 2008).

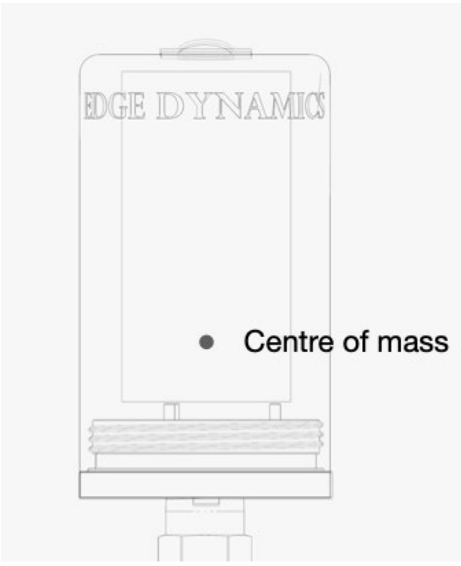


Figure 5: Centre of mass of current sensor node

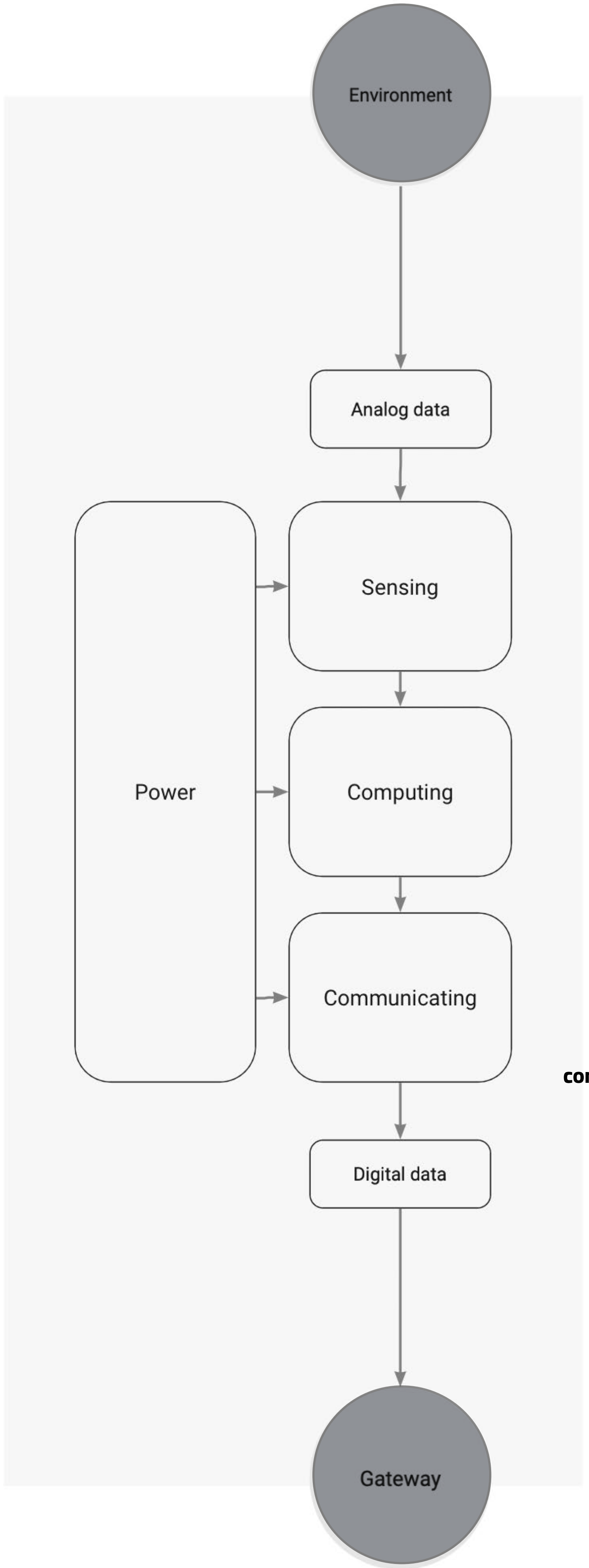


Figure 3: Schematic sensor node architecture

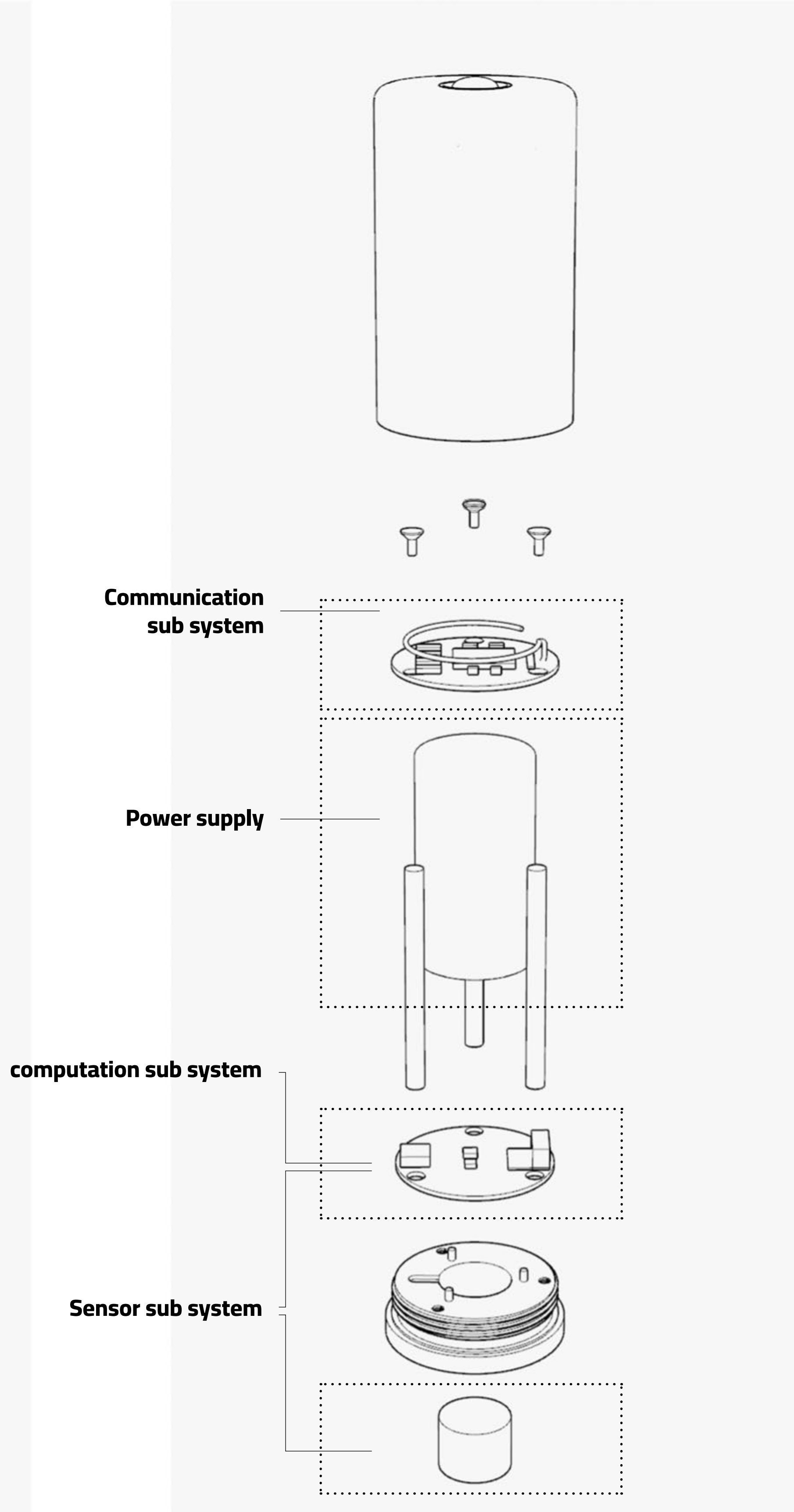


Figure 4: Exploded view sensor node Edge Dynamics

The communication sub system is used to both transmit and receive data from other nodes and gateways. Sensor nodes make use of radio frequencies (RF) to communicate, usually with spectra around 900 MHz and 2,4 GHz (Healy, 2008). Communication can be carried out by a variety of protocols, each with their own characteristics. Common communication protocols used for IIoT applications are LoRaWAN (900 MHz) and WirelessHART (2,4 GHz) (Appendix C).

Figure 6 illustrates the trade-offs of different characteristics between protocols (LoRaWAN, NB-IoT and wirelessHART). It can be noticed that range and battery life come at the cost of higher bandwidth, a clear difference between LoRaWAN (900 MHz) and wirelessHART (2,4 GHz).

Edge Dynamics' sensor node makes use of LoRaWAN as it has excellent range, a low power consumption and low chipset costs. This is useful for industrial applications, as the nodes can cover a large area while operating for a long period.

Sensor nodes use an antenna to communicate with the nearest gateway or other nodes. Depending on the required range, sensor nodes can use different types of antennas. Edge Dynamics' sensor node uses a wire antenna as they have the best range (Appendix D). Placing the antenna as high as possible within the sensor node will benefit the range. Moreover, placing the gateway as high as possible also benefits the range at which a wireless sensor network can operate (Kooijman, personal communications, March 2022). An external antenna can be considered too, but this complicates the sensor node, as it adds components and materials. As the battery is a conductive (metal) component, it will either absorb radio frequencies or reflect them in the opposite direction. Either way, the battery will obstruct and diminish the signals send out by the antenna. Therefore, the antenna should be located above the battery (Kooijman, personal communications, March 2022). In case of Edge Dynamics, this spatial distance between the antenna and accelerometer is covered using a data cable.

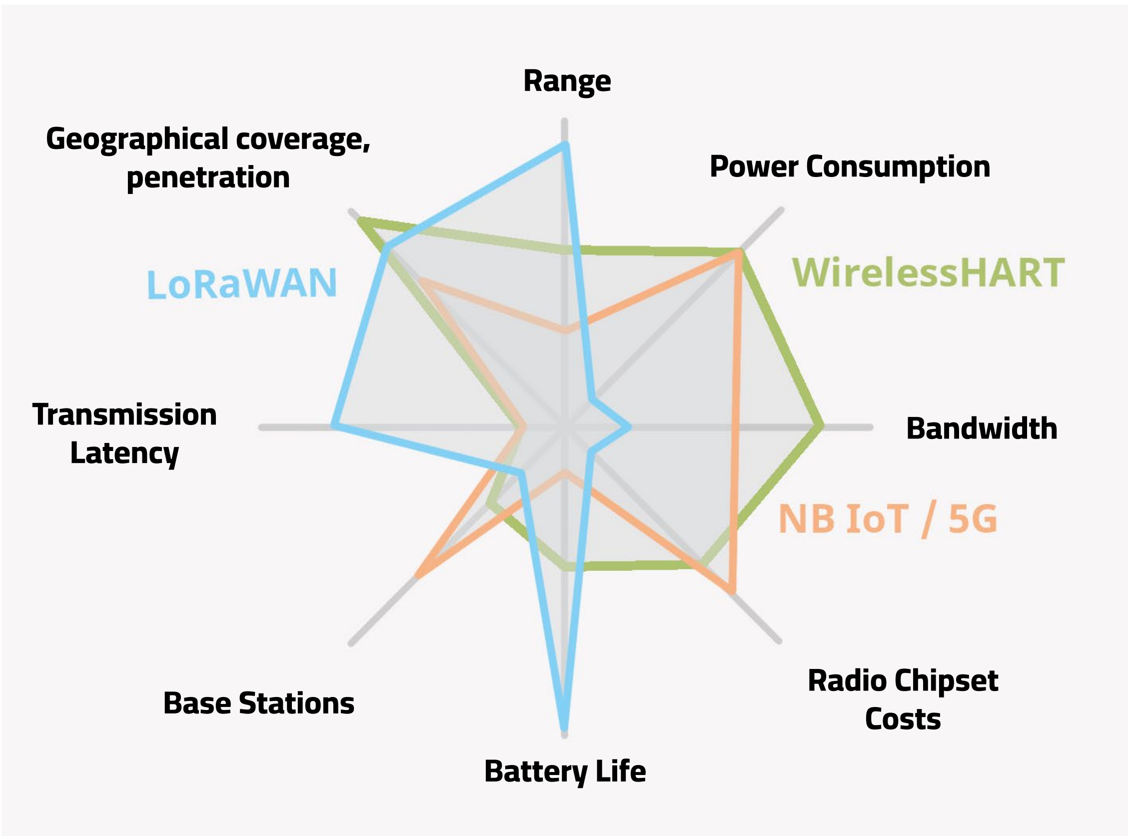


Figure 6: Visual comparison between protocol characteristiscs; performance aspects differ between different communication protocols (adaptation from TWTG, n.d.)

Every type of antenna has their own directional qualities. Antennas do not radiate power equally in every direction. The shape defines the radiation pattern of the antenna, which in turn defines the reception of the sensor nodes. For a sensor node an omnidirectional radiation pattern is preferred, so it performs more or less equally in each direction. The wire antenna used in the current sensor node has an isotropic radiation pattern (figure 7) and therefore approximates an omnidirectional reception (Kooijman, personal communications, March 2022).

The length of the antenna is related to the frequency at which the sensor node communicates. A quarter wavelength antenna has low impedance (50-100 Ohms) and a favourable radiation pattern. As the wavelength of a frequency is calculated by the speed of light (m/s) divided by the frequency (Hz), the wavelength of LoRaWAN (about 900 MHz) is 0,33 meters. A quarter wave length antenna would therefore be around 8,25 cm. The length can vary a bit but should not near half a wave length as this will increase the impedance significantly (Kooijman, personal communications, March 2022). Impedance can be described as degree of reactance and resistance influencing the antenna at its terminals (Hemminger, 2005).

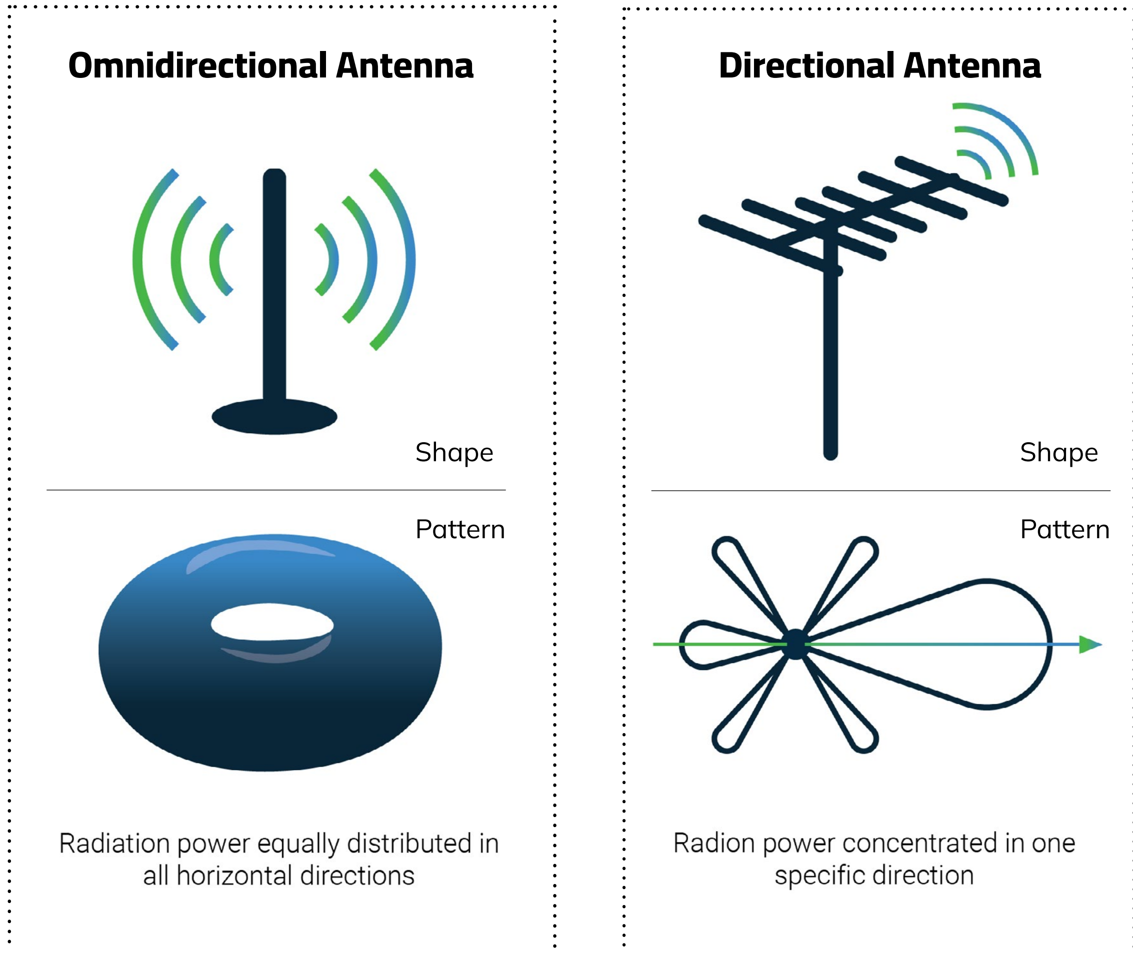


Figure 7: Antenna shape and accompanying radiation pattern (BehrTech, n.d.)

The power subsystem is responsible for powering each of the aforementioned sub systems. Preserving battery life is crucial and therefore every aspect of sensor node hardware and software has to be optimised to conserve as much energy as possible (Healy, 2008). Sensor nodes can be powered by batteries or they can harvest their energy from the environment.

Energy harvesting sensor nodes require a different approach as they depend on the available energy sources (e.g. light, temperature difference). Moreover, the abundance and consistency of these energy sources influences the power available to the sensor nodes (Broadhead, personal communications, November 2021). Battery powered sensor nodes are therefore a more reliable option, although primary batteries become waste once they are depleted.

Secondary batteries can be recharged once they deplete, but they have a relatively high self-discharge rate (around 5% annually (TLI series, n.d.)) compared to primary batteries (around 1% annually (Saft, 2020)). This makes them inappropriate for long-life operations. Sensor nodes are required to operate in harsh environments, which can host varying temperatures, for often long periods of time. Most manufacturers, including Edge Dynamics, use Li-$SOCL_2$ (lithium thionyl chloride) primary battery cells to power their sensor nodes as they perform excellent in these harsh environments.

Another environmental aspect at industrial sites is the possible presence of explosive gas mixtures in the atmosphere. Electronic devices can generate sparks (e.g. short-circuits) which could ignite the gaseous atmosphere, resulting in dangerous situations. Therefore, sensor nodes are required to be certified according to the ATEX directive in Europe. This proves the device is designed in a way the components cannot pose a danger. The certification degrees of protection available are shown in table 1 (ATEX, 2014). ATEX certification can be a tedious process as it is costly and can take multiple years (Hassan, personal communications, December 2021).

Once a sensor node's battery depletes, the node no longer works and becomes obsolete. The sensor node then needs a new battery. However, in many cases the battery is not replaceable (table 2, third column). The products are often discarded instead, which leads to the loss of still functioning products and components and increases the need for new sensor nodes.

Table 1: ATEX certification levels (lower is better)

ATEX zone	Description
Zone 2	unwanted substances (e.g. gas mixture) can only be present 10 hours/year or 0–0.1% of the time
Zone 1	unwanted substances (e.g. gas mixture) can only be present under 10–1000 hours/ year or 0.1–10% of the time
Zone 1	unwanted substances (e.g. gas mixture) can only be present over 1000 hours/ year or >10% of the time

Table 2: Comparison competitor products

	Image	Power	Communication	Battery life	Battery life (adjusted for 1 update per hour)
Edge Dynamics		**3.6V, 8500mAh** primary battery (lithium-thionyl chloride) Note: **Replaceable battery** (in non-explosive atmosphere)	LoRaWAN 900 MHz	8 years (update time: 0,5 hour)	16 years
Yokogawa		**3.6V, 2600mAh** primary battery (lithium-thionyl chloride) Note: **replaceable battery** (in non-explosive atmosphere) but damages casing	LoRaWAN 900 MHz	Vibration: 4 years (update time: 1 hour) Pressure: 10 years (update time: 1 hour) Temperature: 10 years (update time: 1 hour)	Vibration: 4 years Pressure: 10 years Temperature: 10 years
TWTG		**3.6V, 7200mAh** primary battery (lithium-thionyl chloride) Note: **replaceable battery (two batteries)** (in non-explosive atmosphere)	LoRaWAN 900 MHz	Temperature: 3-5 years (update time: 4 hours) **(single cell, 3600mAh)** Vibration: 10 years (update time: 4 hours) **(two cells, 7200mAh)**	Temperature: 0,8 - 1,3 years **(single cell, 3600mAh)** Vibration: 2,5 years **(two cells, 7200mAh)**
Fluke		**3.6V, 2400mAh** primary battery (lithium-thionyl chloride) Note: **Non-repaceable battery**	BLE 4.1 (Bluetooth Low Energy) 2.4 GHz	1-3 years (unknown update time)	-
Emerson		**3.6V, 8500mAh** primary battery (lithium-thionyl chloride) Note: **Replaceable battery**	WirelessHART 2.4 GHz	3-5 years (Update time: 1 hour)	3-5 years
Flowserve		**3.6V, 4800mAh** primary battery (lithium-thionyl chloride) Note: **Non-repaceable battery**	LoRaWAN 900 MHz	4 years (update time: 0,5 hour)	8 years
ABB		**3.6V, 2600mAh** primary battery (lithium-thionyl chloride) Note: **Non-repaceable battery**	WirelessHART 2.4 GHz	3-5 years (Update time: unknown)	-

3.2 Circular Economy: Opposing End-of-Life

CIRCULAR ECONOMY CONCEPT
The circular economy proposes to keep products and materials circulating at the highest level of functionality which means "keeping materials in use, either as a product or, when that can no longer be used, as components or raw materials" (EllenMcArthur Foundation, 2022).
The circular economy is an opposing systemic concept to the linear economy. The circular economy is intended as a system level approach to tackling global challenges such as climate change and waste generation. These challenges are the result of the way our current economic system works. Resources are extracted and used to produce goods and products. These are sold and used by consumers who dispose of them once they become obsolete. This linear economy is deeply embedded in the way our current economy handles goods (Bocken et al., 2016).

PRESERVING PRODUCT FUNCTIONALITY
The circular economy emphasises to keep products in a looped flow where they are used and kept in a working state for as long as possible, thus keeping the product integrity at heart. Therefore retaining the functionality of products is a key activity in the circular economy framework (European Commission, 2020).

According to Marcel den Hollander, preserving product integrity can be done by managing obsolescence (figure 8), i.e. the handling of products that "are no longer considered useful or significant by its user" (den Hollander, 2018, p. 27). A product can 'resist' becoming obsolete when durability is considered in its design. By designing for maintenance and repair, a product can be kept in a working state, therefore postponing its obsolescence. Finally, being able to refurbish or remanufacture products once they have become obsolete can reverse the product's loss of functionality (den Hollander, 2018, p. 30). Table 3 shows an overview and description of the functionality retention strategies that support the preservation of product integrity.

The strategies are translated to product design by applying the underlying design principles, which depict mostly product architecture aspects and features that facilitate one or more circular activities. Among the various design approaches, there is an "almost complete overlap between the sets of design principles in support of postponing and reversing obsolescence". Therefore

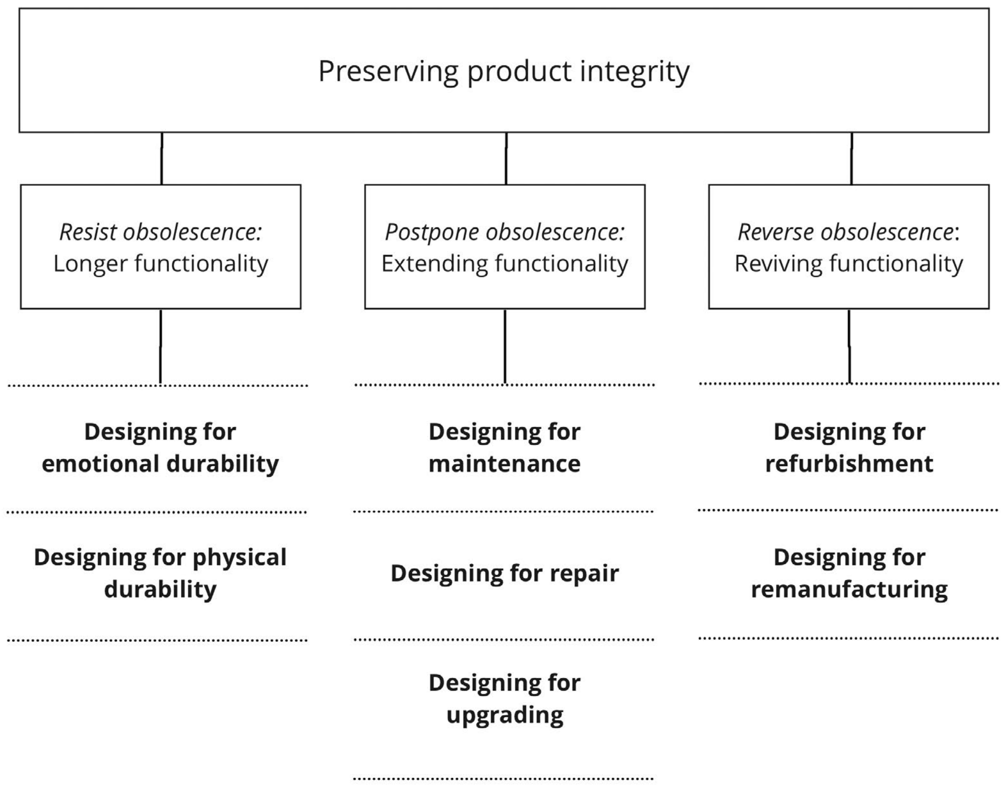


Figure 8: Preserving product integrity framework

"products designed to support one design direction will almost inevitably support, and often need to be designed to support one or more of the other design directions" (den Hollander, 2018. p. 59). The adequate design strategies depend on the foreseen lifecycle of the product in question. This is coupled with the business model incorporating the product. Chapter 4 will elaborate on this. Still, products can reach a point beyond saving, at which they can still be of value.

Table 3: Overview functionality retention strategies

Functionality retention strategies	Description
Maintenance	Maintenance is the execution of regular inspection or servicing or both to retain the functionality of a product. Maintenance is a preventative action (den Hollander, 2018. p.35).
Repair	Repair is the adjustment of faults in an obsolete product, with the intention of bringing the product back to a working state. In general, the warranty on the repaired product is at a lesser degree compared to new products and may be limited to the component that has been replaced. Repair is a corrective action (den Hollander, 2018. p.35).
Upgrading	Upgrading is the action of increasing the performance of a product's capabilities, relative to the original product specifications (den Hollander, 2018. p.35).
Refurbishing	Refurbishing is the process of bringing an obsolete product back to a sufficient working (and cosmetic) state, that is possibly of lesser condition that the original product. This can be achieved by repair or replacement of damaged components, even without the reporting of faults in those components. Generally, the warranty on the refurbished product is at a lesser degree compared to new products and may be limited to the components that have been replaced (den Hollander, 2018. p.36).
Remanufacturing	Remanufacturing involves OEMs (original equipment manufacturers) or a third party contracted or licensed by the OEM to carry out the disassembly and repair of obsolete products in a professional environment (factory). This is done to a degree high enough to bring back products to at least their OEM original performance. The warranty on the remanufactured product is at an identical degree compared to that of new products (den Hollander, 2018. p.36).

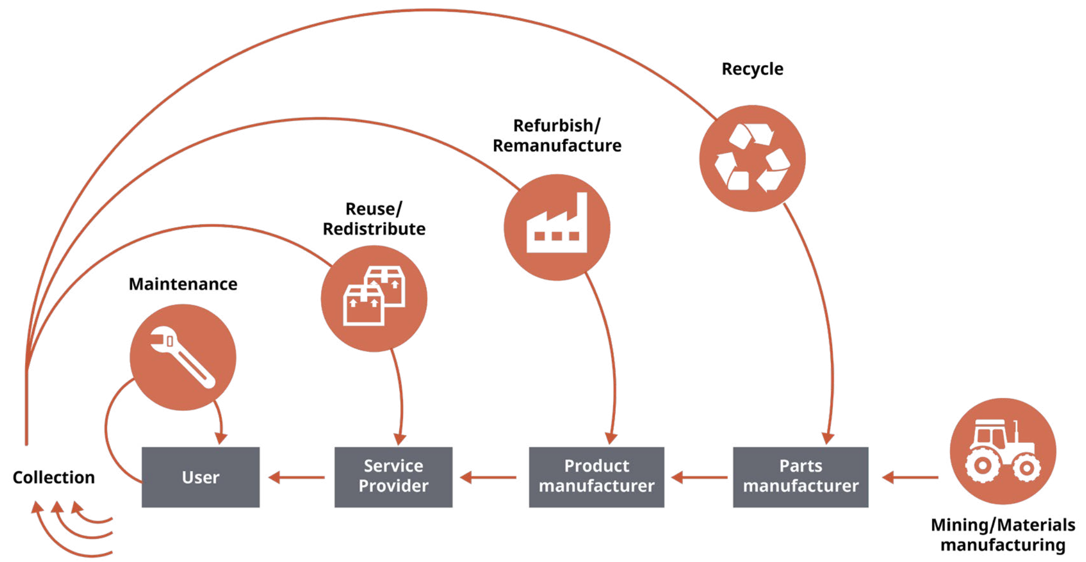


Figure 9: Recovery pathways for products and materials in the circular economy (Bakker & Balkenende, 2020)

PRODUCT END OF LIFE
Recycling is the final circular strategy available after product functionality cannot be restored anymore. It is the most outer loop in the technical cycle (figure 9). Recycling is the process of taking apart and disintegrating products with the intention of reprocessing the (raw) materials for reuse. As this compromises the product's integrity by disintegrating product parts, this is the least favourable strategy (den Hollander, 2018. p.27). Without recycling, products and their materials are mostly lost to landfilling or incineration. Recycling therefore has an essential role in the circular economy and should always be considered in parallel with other circular strategies (edX, 2022). As can be seen in the Value Hill, recycling closes the final loop, as materials return back to the manufacturing of products (figure 10).

Sensor nodes are electronic products and are therefore composed of electronic components, clustered mainly on PCBs and batteries. This means once sensor nodes are disposed of, they become electronic waste (e-waste). Electronic waste has become the fastest growing waste stream with a global increase of over 20% since 2014 to 53.6 million tons in 2019 (Forti et al., 2020).

The dominating circular strategy for handling obsolete electronic equipment is recycling. In the European Union, the collection and treatment of electronic waste is standardised under the (W)EEE directive ((Waste) Electrical and Electronic Equipment). Within the directive, sensor nodes likely are categorised as measure- and control instruments, a category that in 2018 in The Netherlands accounted for close to 9 kilo tons of electronic equipment put on the market. This is an increase from the year before with almost 70% (5.3 kilo tons). This waste category has a collection rate of 37%, little over half of its target rate of 65% (Nationaal WEEE Register, 2019).

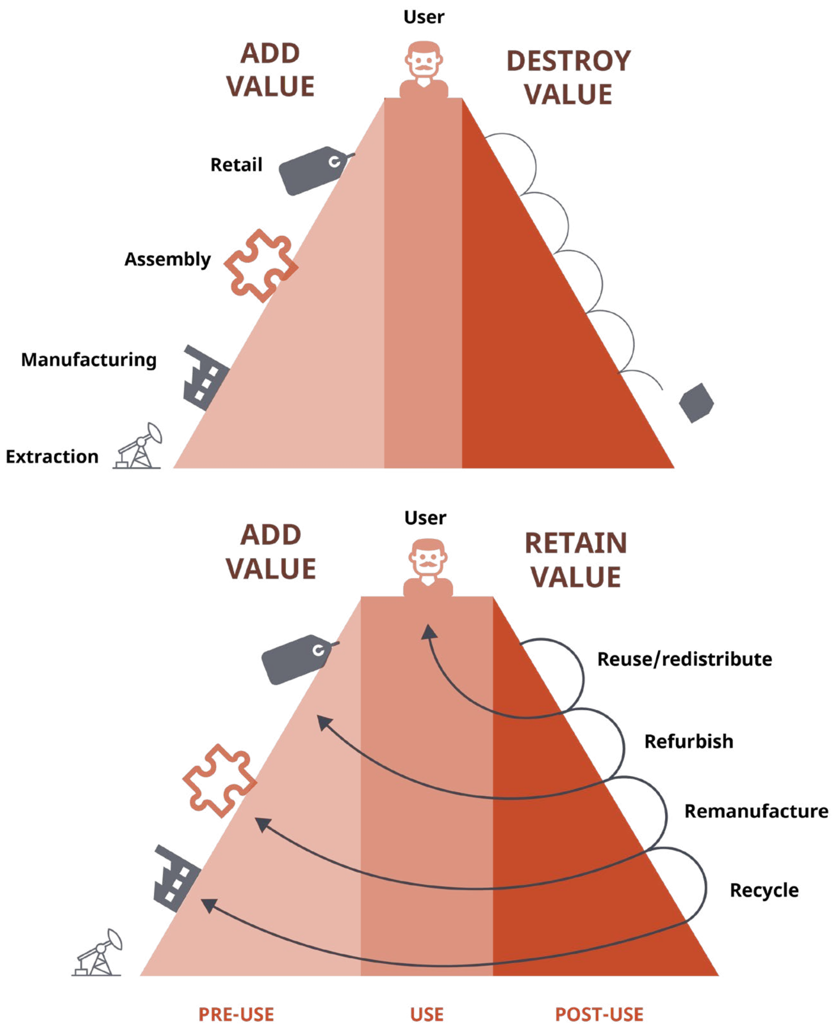


Figure 10: The Value Hill showing difference in dealing with value between linear- (top) and circular economy (bottom) (Achterberg et al., 2016)

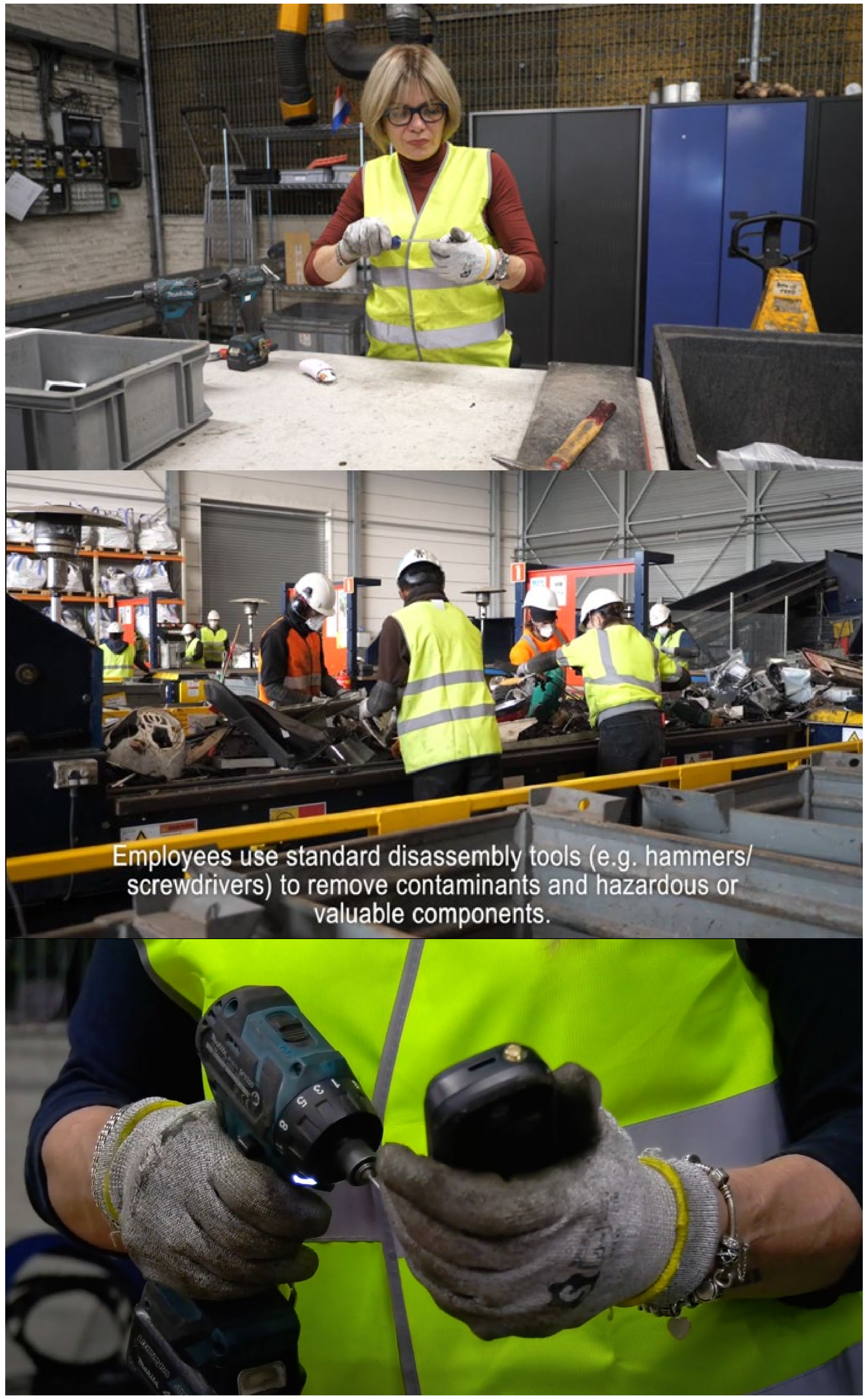


Figure 11: Facility workers opening up discarded appliances

The recycling process starts with the collection of e-waste streams of companies by specialist waste processors (in The Netherlands e.g. Coolrec and Mirec). For companies, e-waste likely has a higher collection rate than consumer e-waste as they need to keep records of their waste streams and waste is tracked using unique identifiers. Accurate data however seems unavailable and data of consumer and company waste streams are possibly conflated (Baldé et al., 2020). As sensor nodes are battery powered, it is required, according to the WEEE directive, that batteries are removed from devices after collection (WEEE, n.d.). This is done manually by workers at the recycling facility at a variety of stations (see figure 12). They use standard tools and gloves to open devices and remove the batteries (figure 11). Batteries are collected and recycled separately, as they pose a fire hazard in the recycling process of e-waste (Dirrix, personal communications, March 2022).

Next, equipment is mechanically opened using a disintegrator. This provides easier access to internal components that can be hand sorted. This way, e-waste can be pre-sorted which benefits the purity of the waste stream. Now, the remaining waste is ground using mechanical grinders. This will create a stream of small parts that can be sorted using a variety of techniques such as magnets (ferro and non-ferro (Eddy currents)), NIR (near-infrared) cameras and floatation baths (figure 12, step 9). The quality of recycled material streams depends largely on the effectiveness of these systems, which is influenced by several product design aspect, such as colour and type of material and fasteners used in products (edX, 2022).

Recycling therefore influences the design of sensor nodes, as recycling is a process that sooner or later will be used to handle products or components. Thus, it is important to include design for recycling in the development of sensor nodes. Many design principles essential to functionality retention strategies greatly benefit product recycling as well. Still, mainly on the material level, design choices need to be considered regarding (mechanical) separation and sorting.

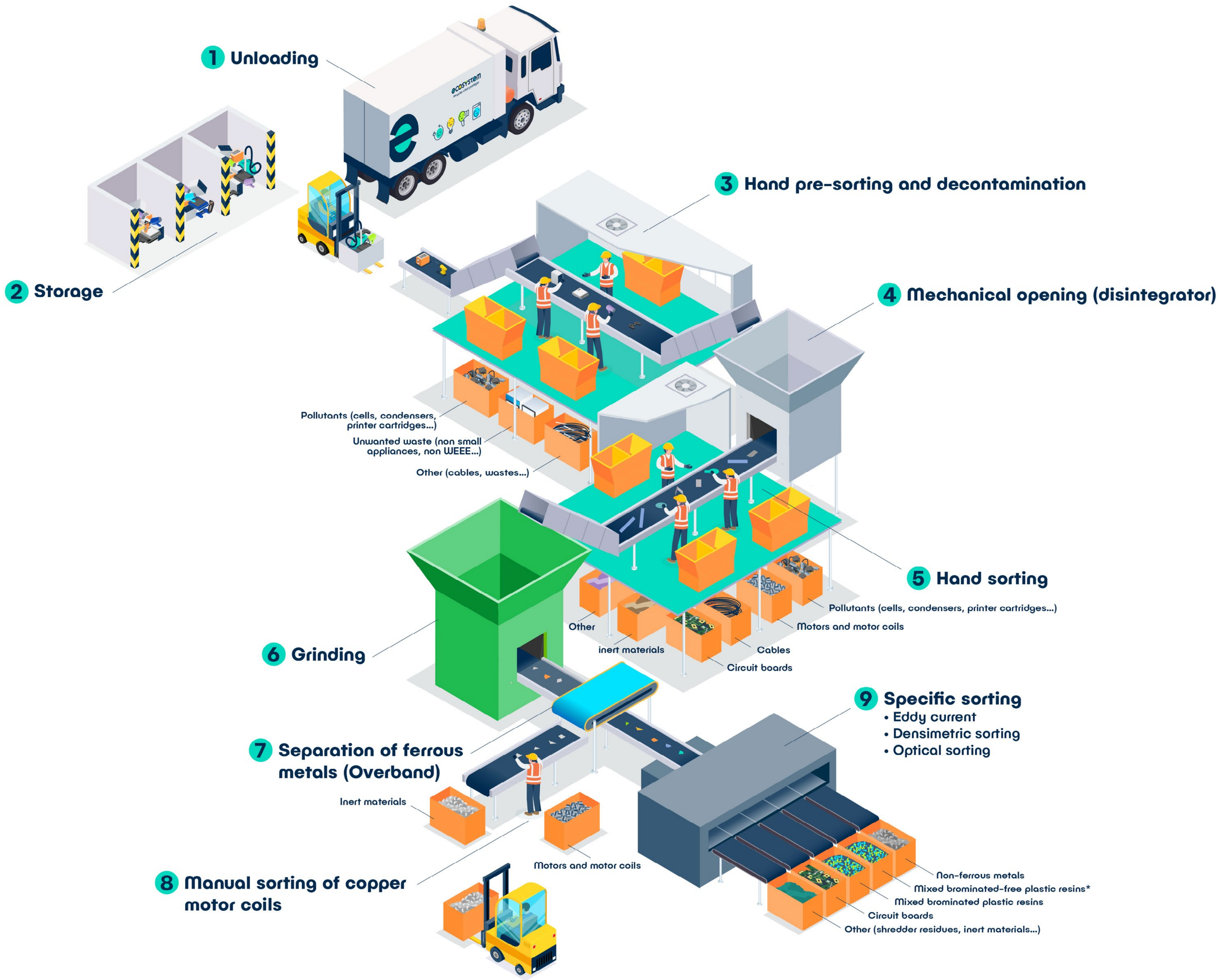


Figure 12: schematic overview of recycling process of small appliances (edX, n.d.)

3.3 Circular Economy: Current practice

Looking at the market of IIoT, a variety of options is available to customers. Several manufacturers offer their sensor nodes as part of a package including services. US based FlowServe for instance offers their sensor nodes exclusively through service plans. They offer full-fledged cloud based data analytics or a less involved on-premise monitoring plan. Both include wireless sensor nodes and system maintenance (FlowServe, n.d.). What comprises this maintenance is unclear.

Edge Dynamics is more flexible when it comes to their value proposition. Some customers like Shell have their own IT backend already in place and only need wireless sensor nodes (Klompe, personal communications, March 2022), while others require gateways and additional services as well.

In any case, the sensor nodes will have to be installed on the equipment that requires monitoring. Moreover, battery powered sensor nodes operating at industrial sites will have to be attended at some point in their lifetime. These activities will be carried out by field technicians, either working for the site operating party (e.g. Shell) or a third party, e.g. the manufacturer (Hassan, personal communications, December 2021). Sensor nodes have to be securely fastened to equipment such as pipes and valves, often outdoors (figure 14). In many cases sensor nodes will be mounted on legacy assets, which are older equipment deemed too expensive to replace and are therefore continuously repaired instead. Hence, sensor nodes are often retrofitted which means they are installed on equipment which was not designed to host (third party) monitoring instruments. This means sensor nodes will likely encounter awkward mounting situations, that are not always ideal to reach (figure 13).

Situations occur where sensor nodes are placed close to the ground or above eye-height

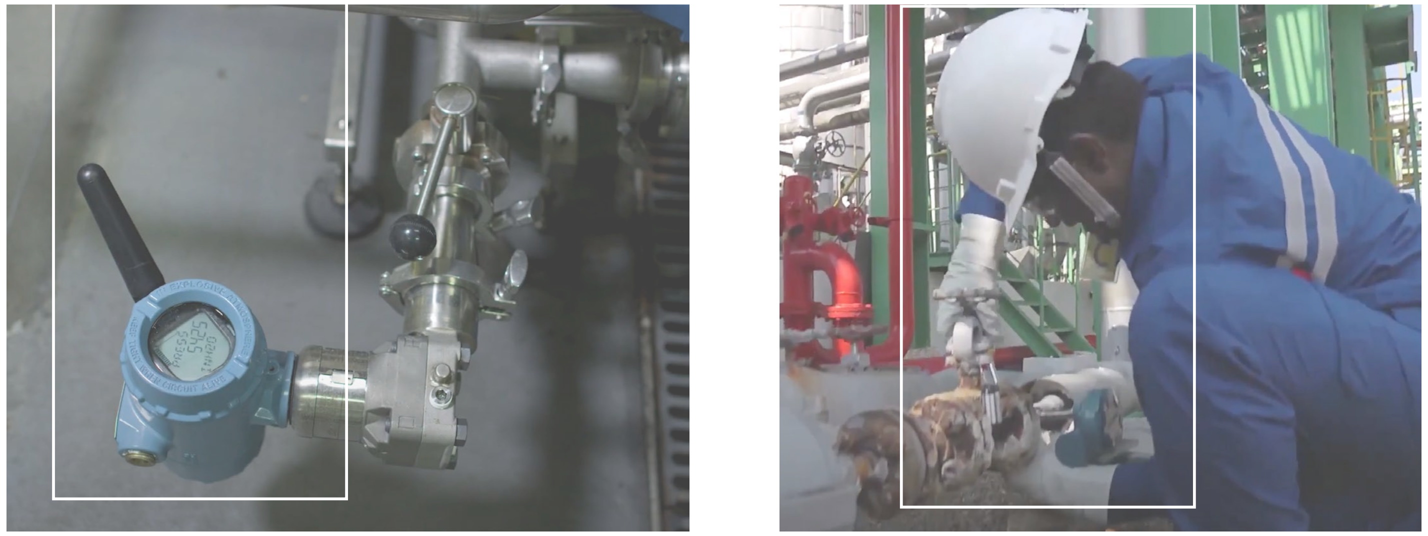


Figure 13: Emerson pressure sensors (Emerson, 2020)

There seem to be three ways how broken sensor nodes can be addressed. In each case it is assumed the issue is a depleted battery, as they rarely outperform other components (Hassan, personal communications, December 2021). It is clear each manufacturer thinks differently of the longevity of their products. Several manufacturers have designed their sensor nodes in such a way it is possible to change the battery and thus make replacement possible. Others have given malfunctioning much less consideration.

Both horizontal and vertical mounting is used. As can be noted, sensor nodes are open and exposed to the elements.

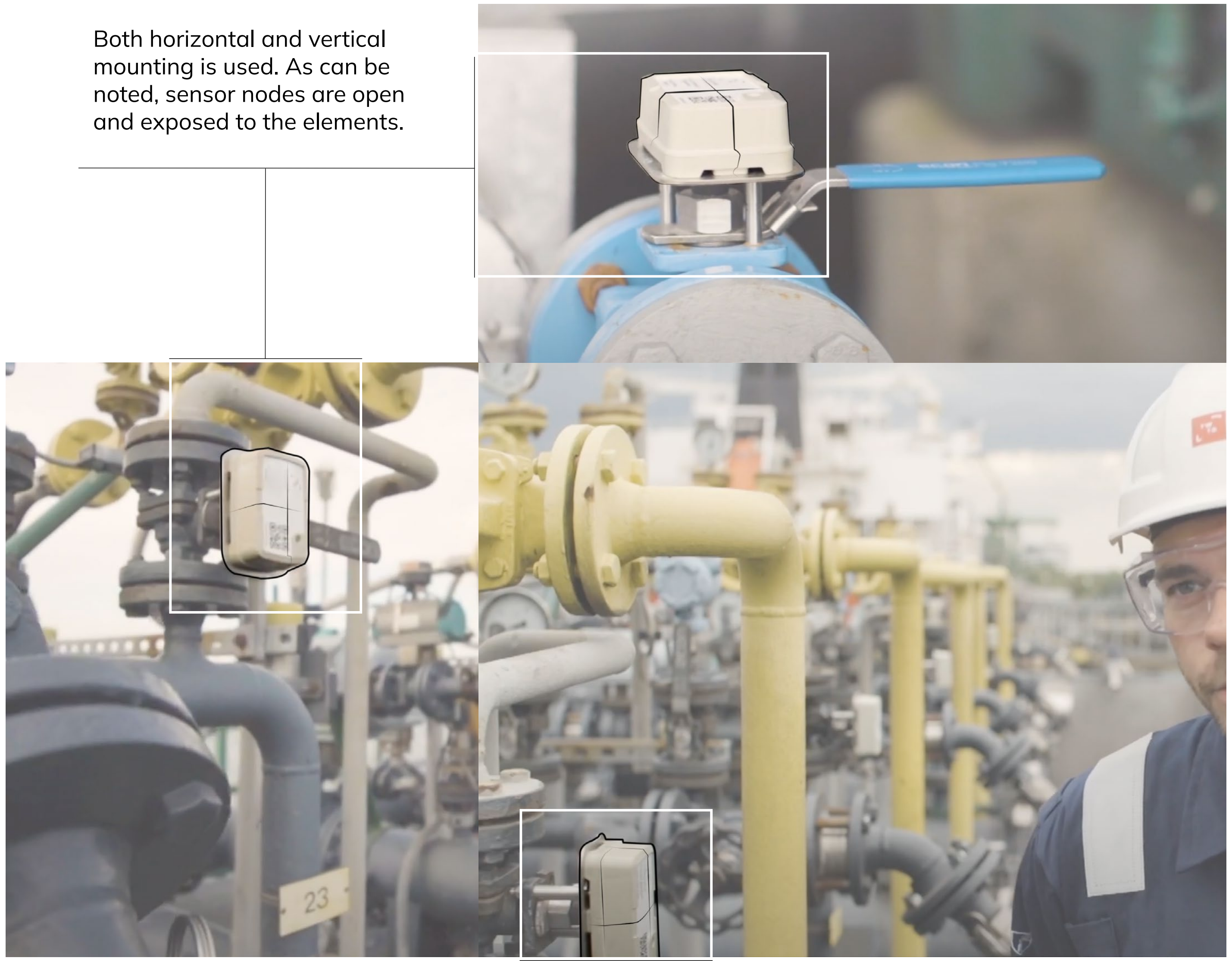


Figure 14: TWTG sensor nodes in use at Vopak Vlaardingen (Vopak, 2019)

The sensor node is maintained on location by a field technician. This requires the necessary spare parts and possibly tools to be brought along.

Emerson seems to be the only manufacturer who designed their sensor node specifically to be repaired in field. They certified the battery and terminals in order to swap the battery in an explosive atmosphere without posing any danger (Klompe, personal communications, March 2022). By requiring only a threaded casing to be removed, access to the battery is quick. Their sensor node's architecture has been specifically composed to facilitate a battery swap without removing the device from its host equipment (figure 15). Namely, the bolt that mounts the sensor node to the host equipment is located beneath the battery, requiring the battery to be removed to unmount the sensor node. The PCBs have been positioned in such a way around the polymer chassis that the battery is accessible after removing the casing. With a hinged clamp, the battery is kept in place. (Un)plugging a connector cable is needed and does seem to require precision. The battery features a pull tab to make removing it easier. Manual separation of the battery (decontaminating) at a recycling facility is likely doable as only the casing needs to be unscrewed to reach the battery.

The sensor node is replaced and taken to the site's maintenance centre and possibly repaired in a controlled environment.

Sensor nodes from Japanese manufacturer Yokogawa facilitate a battery swap as well. Housing one of the smallest batteries among its competitors (see table 2), this seems a necessary feature. Unlike Emerson, Yokogawa states replacing the battery should be done only when no explosive atmosphere is present (ATEXshop.nl, n.d.). To reach the battery, two M4 screws need to be removed. Now, using a flathead screwdriver the casing can be pushed upwards, revealing the inside of the product (figure 16). This unavoidably damages the casing at the bottom area (Khadar, personal communications, December 2021). Now, the battery connector cable can be removed and the battery can be pulled from its holder as it is form fitted in place. Again, the sensor node's architecture has been arranged to provide relatively quick access to the battery. The PCBs are located below and parallel to the battery, while the use of permanent fasteners and irreversible cable connectors is avoided. Although battery replacement is clearly considered, manual separation of the battery (decontaminating) at a recycling facility is likely time consuming as multiple screws need to be removed.

The manufacturers Emeron and Yokogawa utilise a clear structure within their product. They seem to keep components clustered in modules. This modularisation can be a great facilitator for functionality retention strategies as it can structure the product architecture of sensor nodes with clear role in supporting circular strategies. "The product architecture [...] has a significant effect on [...] the whole product lifecycle" as it dictates the way a product is comprised, taken apart, maintained etc. (Bonvoisin et al., 2016).

The interchangeability of components among the sensor node's product family supports these strategies as that would reduce the total amount of unique components. Besides the obvious cost reduction, this can facilitate remanufacturing as it eases component harvesting and reverse logistics.

Clustering components based on their functionality can also provide sensor nodes with a resilience to future changes and expansions to the product family. These modules also facilitate upgrading and remanufacturing, by easing the exchanging of product cores.

The company TWTG does things a bit different when it comes to product architecture. The internal components are accessed from the bottom, requiring the device to be dismounted. To access the battery, first the mounting bracket is removed. Now, the casing can be opened by removing four screws. This reveals two batteries, clamped in place in between connector brackets, fastened to one single PCB hosting all electronics (figure 17). TWTG offers after-sale battery replacement kits, including a gasket for the casing and O-rings for the four screws closing the casing. This way, they likely try to ensure a proper seal of the device as they state that improper assembly will void the warranty (Github, n.d.). TWTG states as well that the sensor nodes should under no circumstances be opened in an explosive atmosphere, implying the battery in some occasions can not be replaced in field.

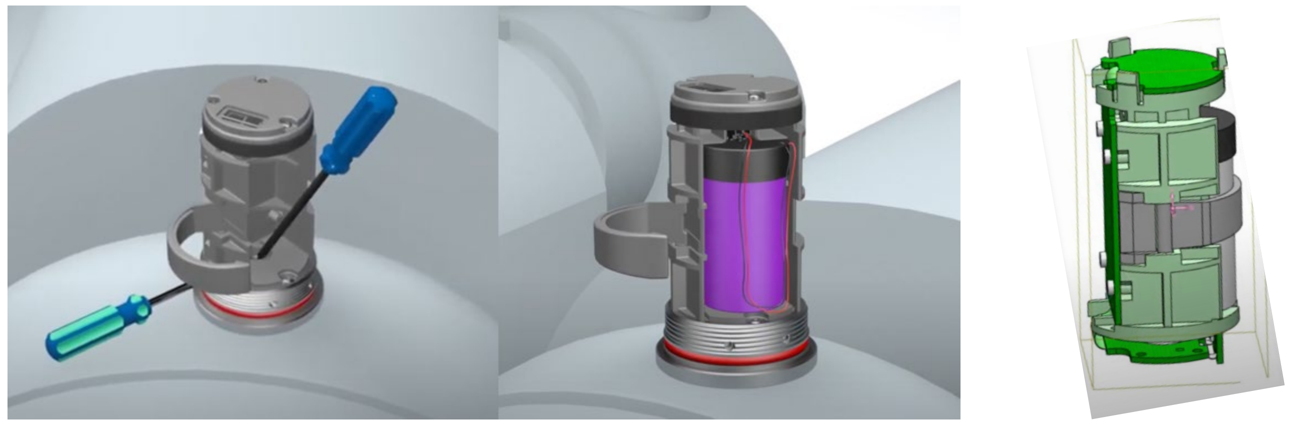


Figure 15: Emerson's sensor node battery replacement sequence (Emerson, 2020)

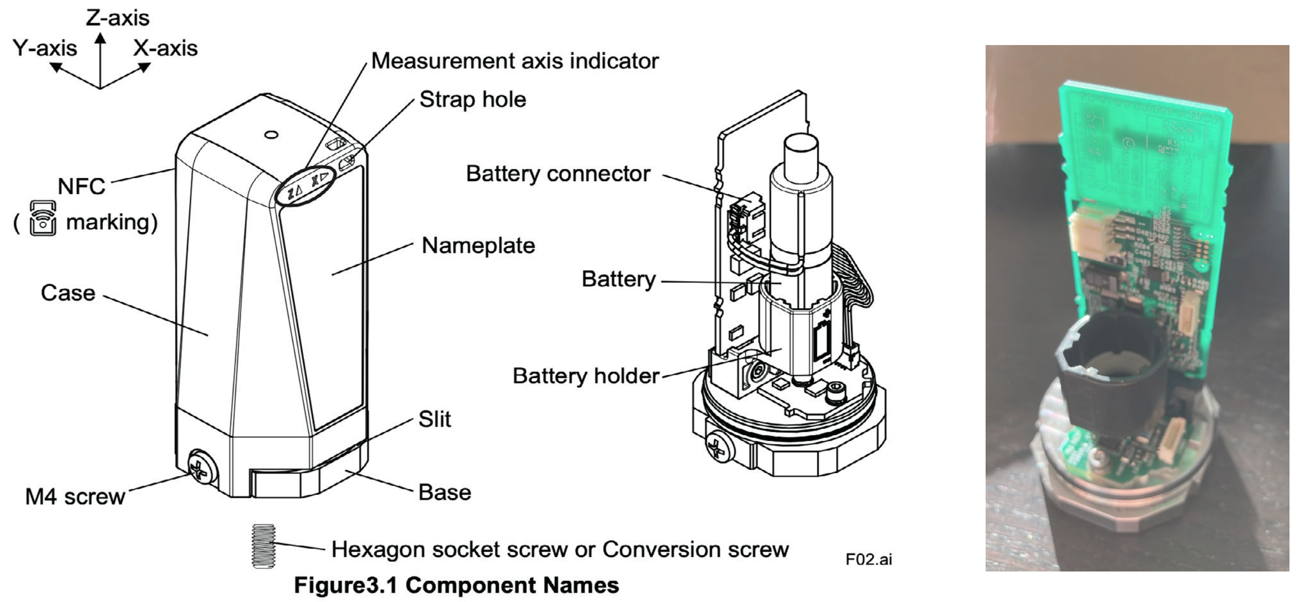


Figure 16: Yokogawa's sensor node (Yokogawa, n.d.)

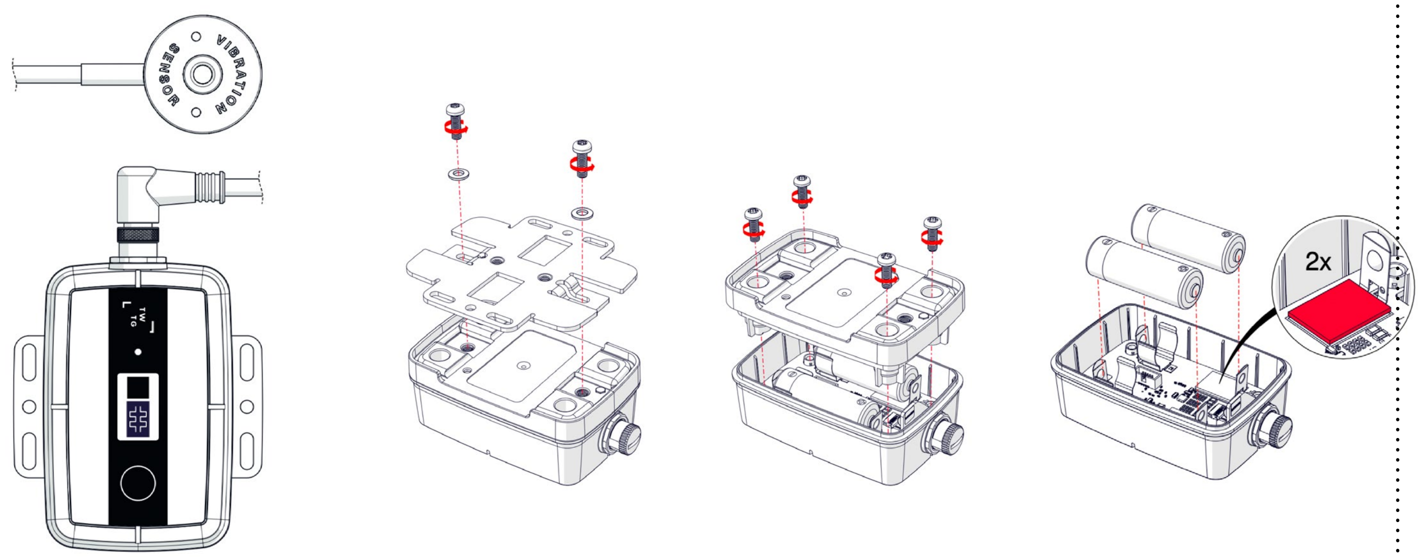


Figure 17: TWTG's battery replacement sequence (TWTG, n.d.)

The sensor node is replaced and discarded. The old sensor node is discarded as waste and recycled at dedicated waste management companies, or it is possibly returned to the manufacturer.

Several competitors consider their products as disposables once the battery depletes (table 2). Fluke sells sensor nodes that are inaccessible as they are entirely encapsulated. None of their documentation mentions repairability. In addition, they can only be mounted using epoxy glue, meaning the sensor nodes are likely damaged upon removal (figure 18). ABB's sensor nodes are not repairable either. They even state on their website why they specifically have disposable sensor nodes instead of repairable ones (figure 19).

Although Edge Dynamics' sensor nodes are technically repairable as they can be fully disassembled with standard tools. Still, repair and other circular strategies are not considered in the design of the product.

Recycling is not considered for irreparable sensor nodes; as mentioned before, removing the lithium battery is an important step in the recycling process as they can pose a fire hazard. Manual separation is therefore of importance.

The considerations made in the design of sensor nodes depend highly on the circular strategies that are used to achieve the corporate goals. Edge Dynamics wants to introduce repairability in a redesign of their current sensor node. They want existing sensor nodes to be able to keep operating as this would reduce costs and materials. This would also reduce the environmental footprint of the sensor nodes, resulting in greener IIoT products. Clients increasingly ask for partners that consider sustainability (Danad, personal communications, December 2021).

However, to benefit from these practices the business context in which the product will be embedded needs to be considered. This affects the selection of appropriate design strategies for retaining product functionality and indicates the underlying design principles that can be considered in the redesign (den Hollander, 2018, p. 77).

Figure 18: Mounting Fluke's vibration sensor using epoxy glue (Fluke, n.d.)

WHY REPLACEABLE OR RECHARGEABLE BATTERIES ARE UNDESIRABLE

The Smart Sensor's main battery cannot be replaced or recharged. Replaceable or rechargeable batteries are undesirable because:

- Replaceable batteries can increase the cost of the sensor to the point where it makes more sense to simply change the entire sensor – and get new electronic components with higher performance into the bargain.
- There is a risk that the user would compromise the hazardous area protection status by inserting the new batteries incorrectly.
- Ingress protection against dust and water could be compromised if the batteries are not replaced correctly.

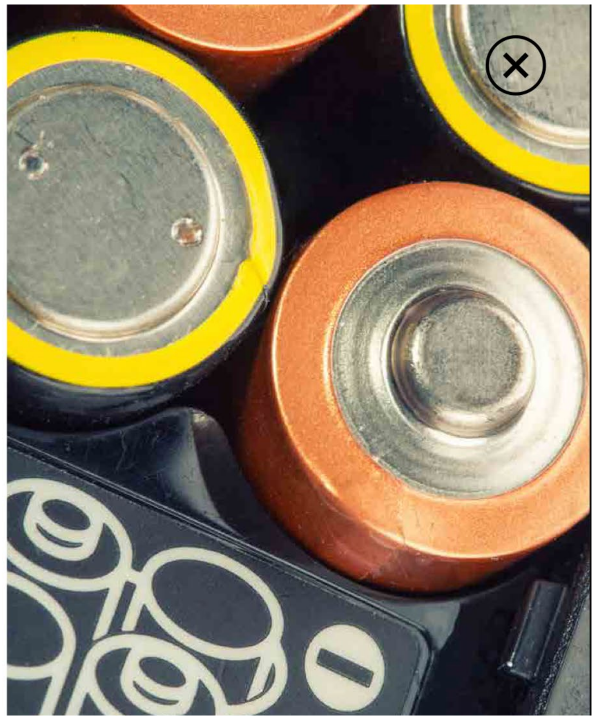


Figure 19: Brochure shows ABB's statement regarding replaceability of batteries (ABB, 2020)

Conclusion

RQ1: TO WHAT DEGREE ARE IIOT PRODUCTS CURRENTLY CIRCULAR?

As of today, wireless sensor nodes are in varying degrees positioned in the circular economy. Some manufacturers have integrated the possibility to replace the battery, therefore supporting maintenance and repair. Others (sometimes seemingly on purpose) offer disposable sensor nodes that end up instantly in the outer recycling loop once the sensor node malfunctions and loses all functionality. It is even then not clear to what degree sensor nodes are recycled.

Edge Dynamics has not considered circular strategies in the development of their product. Their sensor nodes can be repaired but are not intended to be. Edge Dynamics' sensor nodes do feature one of the longest (battery) lifespans on the market, by utilising LoRaWAN and a focus on power efficiency. As such, their node has in some case four times the lifespan of competitor products.

4

Implementation

In this chapter the importance of a circular business model is elaborated on. In addition, the possible business model types are projected onto Edge Dynamics. Lastly, two use cases are explored where Edge Dynamics' sensor nodes are potentially applied. By exploring the probable product lifecycles of the sensor nodes, the appropriate design principles will become apparent.

Photo by Dimitry Anikin, unsplash.com

4.1 Sustainable business models

The circular strategies mentioned and shown in chapter 3.1 in table 3 are essential to any company aiming to operate in the circular economy, as it dictates the way a company handles their transfer of value. To design a product it is essential to understand the business context it will make part of. The majority of current business operations that revolve around physical products is based on the transfer of ownership rights to the product, i.e. selling products. For this way of doing business, it is fundamental to strive for minimising the cost of production, maximising the profit per sale and repeating this process for as long as it makes a profit (den Hollander, 2018, p. 77).

This is not a sustainable way of operating a business, as this promotes replacement purchases (recurring sales). In contrast, a prerequisite for a circular business model is that the preservation of products (their usefulness) must be acknowledged as a strategic and competitive advantage. Therefore, functionality retention strategies must contribute to the profitability and viability of the business venture. The circular business model should be conceived in such a way the product flows in the shortest loops of the technical cycle, while always trying to resort to reverse logistics before using 'virgin' materials and components. In case a business runs on fabricating and selling long lasting products but does not benefit from this prolonged lifetime, the extended lifetime of the product might turn into a threat rather than a perk (den Hollander, 2018, p. 95). This applies to Edge Dynamics, as their sensor nodes have a significant lifespan and they are confident they can increase the battery life even more (Hassan, personal communications, December 2021). Therefore, their current sensor nodes do not resonate with their business model, which is essential for circular products (source).

Several archetypical business models can be applied to Edge Dynamics' sensor node. Business models can be solely product based, solely service based, or a combination of the two known as a PSS (product-service) based business model. This means their value proposition is realised by combining a service and product (Tukker et al., 2006). Figure 20 shows this range of PSS types and the typical characteristics a PSS based business model would have.

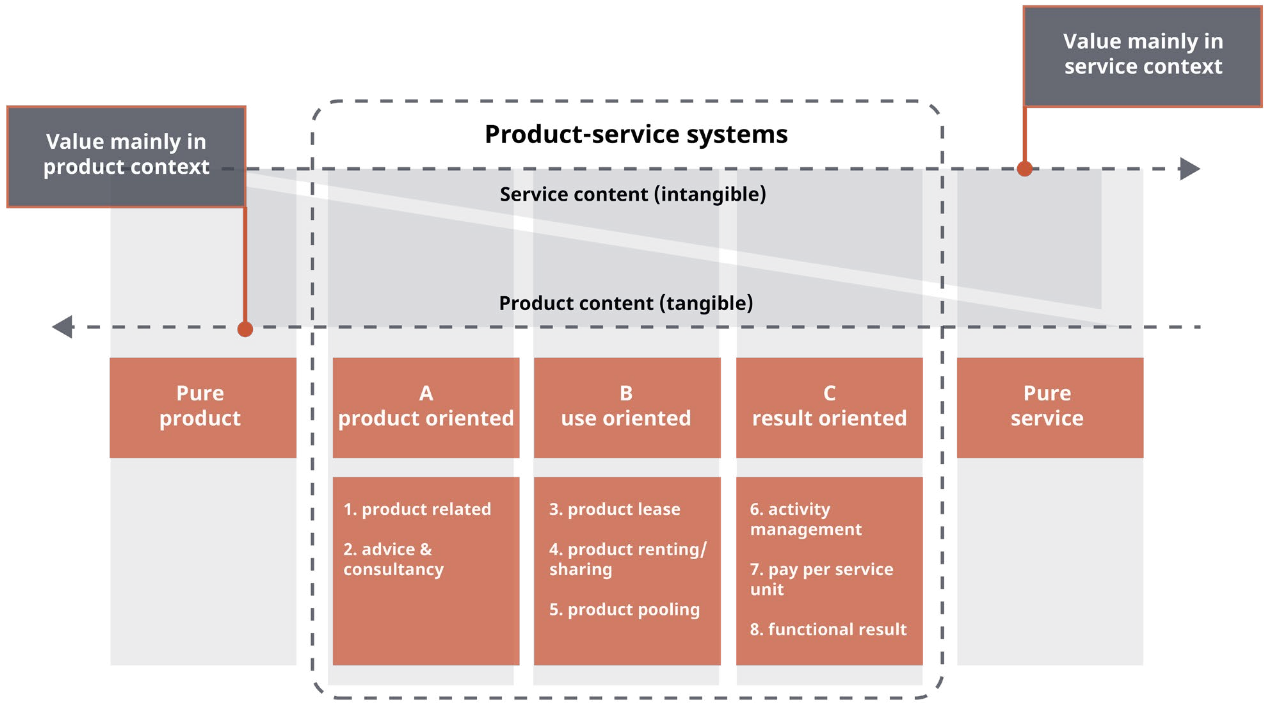


Figure 20: Product-service system clasifications (Tukker & Tischner, 2006)

PRODUCT-ORIENTED CIRCULAR BUSINESS MODEL
A product-oriented circular business model generates a revenue stream by selling high-quality products with a relatively long life. This model is characterised by the sale of durable products at an above average price. Moreover, this business model could offer additional services that are required during the use cycle of the product (figure 21).

Within a product-oriented model, the lack of control over sold goods after selling makes this model more challenging than others to preserve and retain product functionality. This means within this business model it would be crucial for Edge Dynamics to capture enough profit from sales in order to achieve commercial viability (den Hollander, 2018, p. 96). Contractual agreements on taking back products once they become obsolete is a way for Edge Dynamics of recovering their sensor nodes.

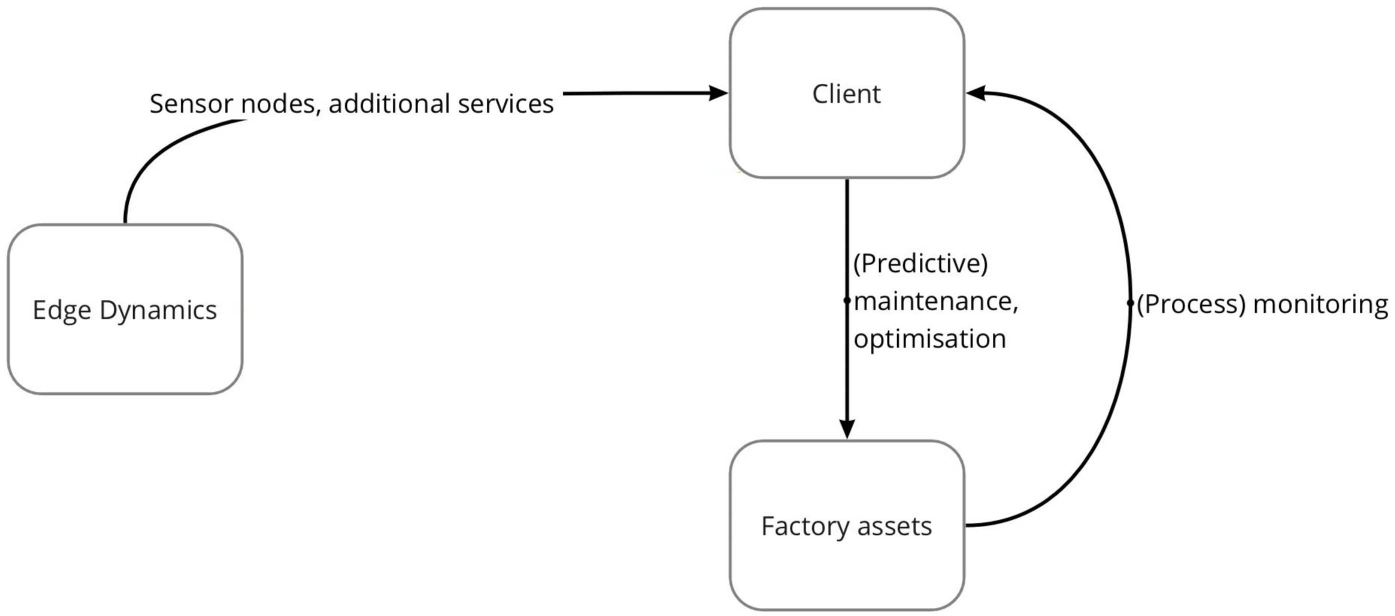


Figure 21: Product-oriented model proposition

PRODUCT-ORIENTED: HYBRID
Alternatively, a hybrid model can be considered. In a hybrid model a dedicated consumable within a product-service system is a driver for recurring revenue, combined with a long lasting product that is either sold or given access to (access model; selling access to a physical product for a limited amount of time). This consumable has to be replaced at regular intervals for the business model to work (den Hollander, 2018, p. 95).

Looking at the sensor node, the most likely component to be subjected to regular replacement is the battery. After all, for the current sensor node to work a battery is required and to keep it operating in the future the sensor node needs new batteries. Therefore, in a hybrid business model, Edge Dynamics would offer spare batteries as a consumable to clients who make use of their sensor nodes (figure 22). However, as mentioned before, the battery life of Edge Dynamics' sensor nodes is relatively long. This means a replacement battery might not be a regularly occurring event. In addition, the current battery used in Edge Dynamics' sensor nodes is a standardised part that can be sourced from varies manufacturers (Alibaba, 2022). This way, Edge Dynamics could be circumvented as supplier of spare parts if clients have reasons to do so (e.g. they deem theirs too expensive). Relying on batteries as short-lived consumable within a hybrid model is also dependent on future changes such as legislation (European Parliament, 2021) or new client requirements for e.g. phasing out primary batteries due to their environmental impact.

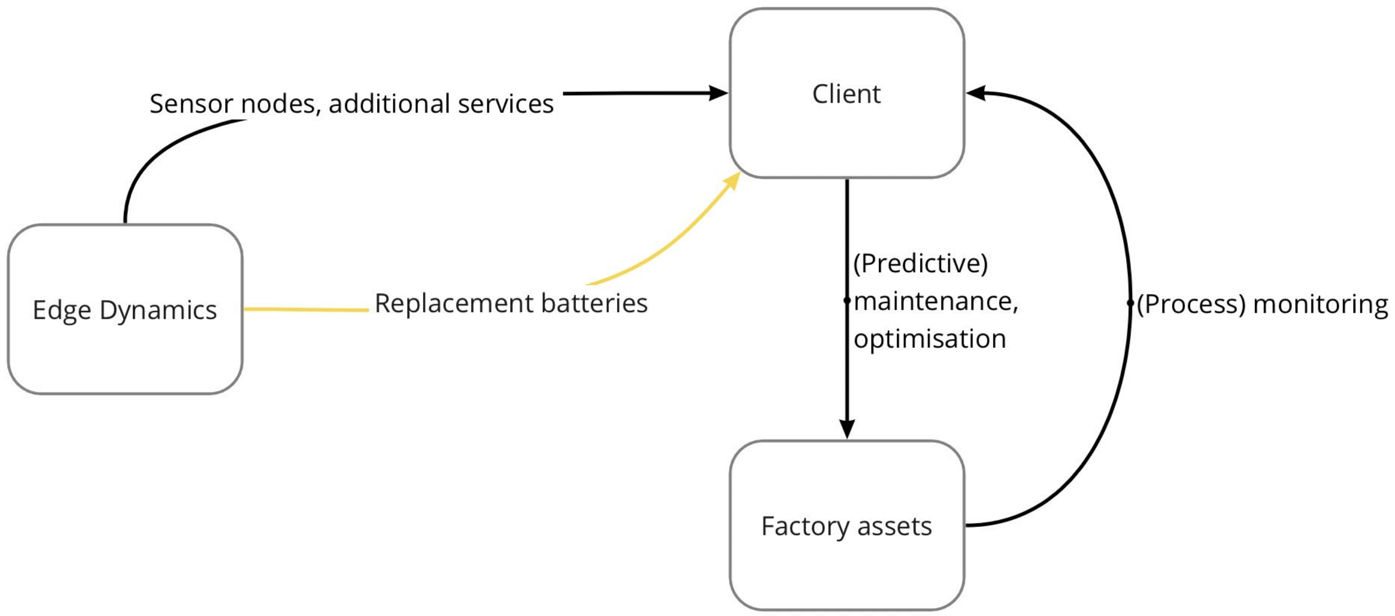


Figure 22: Hybrid model proposition

USE-ORIENTED CIRCULAR BUSINESS MODEL
The use-oriented circular business model is a PSS based business model that generates a revenue stream by selling 'access' to a a physical product for a limited period. The company implementing this business model remains the owner of the products and is therefore responsible for the working state of their products. This business model is better at retaining the functionality of their products compared to the classic long life model (den Hollander, 2018, p. 96). Once an arrangement is terminated, any assets are returned to the company.

If Edge Dynamics would set up a use-oriented business model (figure 23), the IIoT hardware (sensor nodes and gateways) would be provided to clients for time based periods, e.g. monthly or yearly. Edge Dynamics could offer installation support as an additional service. Once installed, the client makes use of the data generated by the sensor nodes. Obsolete sensor nodes, e.g. malfunctioning, are send back by the client and replaced by Edge Dynamics. These arrangements would facilitate reverse logistics and support functionality retention strategies as product components and materials could be used in the manufacturing of new sensor nodes.

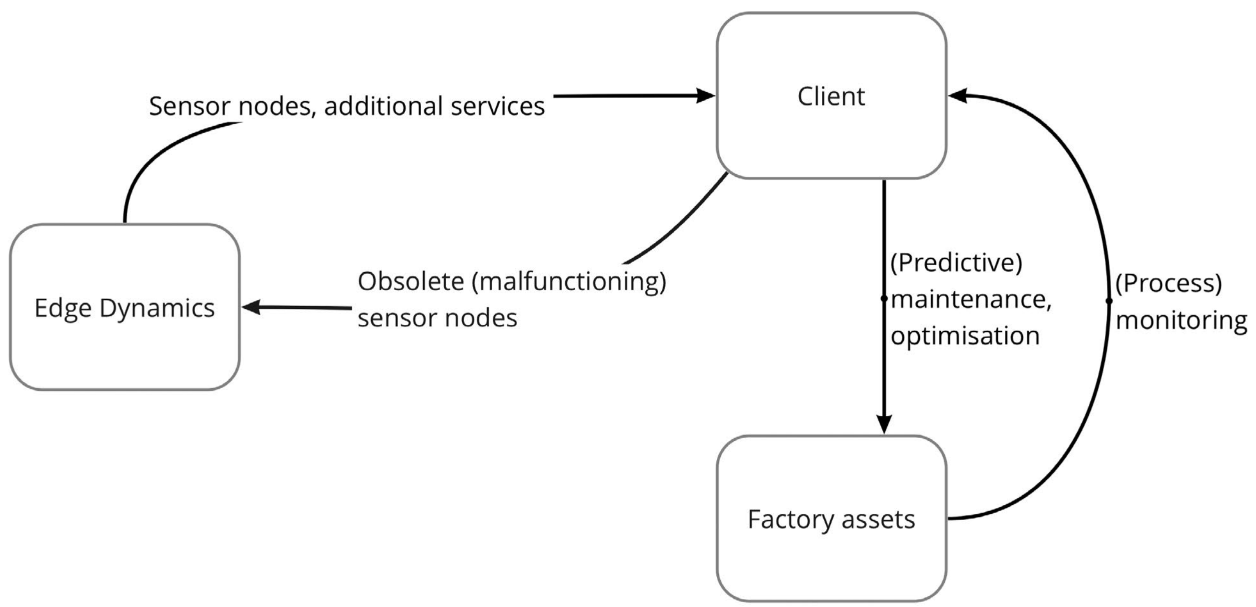


Figure 23: Use-oriented model proposition

RESULT-ORIENTED CIRCULAR BUSINESS MODEL
The result-oriented circular business model is a PSS based business model that generates a revenue stream from selling the performance of an asset instead of the product itself. The result is therefore not related to a particular tangible product or specific technology. The main source of revenue comes from payments for that particular performance (den Hollander, 2018, p. 97).

A result-oriented model as such would look as follows: Edge Dynamics provides and installs the sensor nodes and gateways together with the client (figure 24). Edge Dynamics remains owner of the hardware and charges the client for the value they provide, which can be the performance of the entire IIoT ecosystem (as described in chapter 3.1). The performance can be considered as the data captured by the sensor nodes that is relayed via gateways to the industrial site's control room. It could even be analysis of the data, accessed through a dashboard, which could simply provide site operators with the bare necessities, such as failure warnings or anomalies.

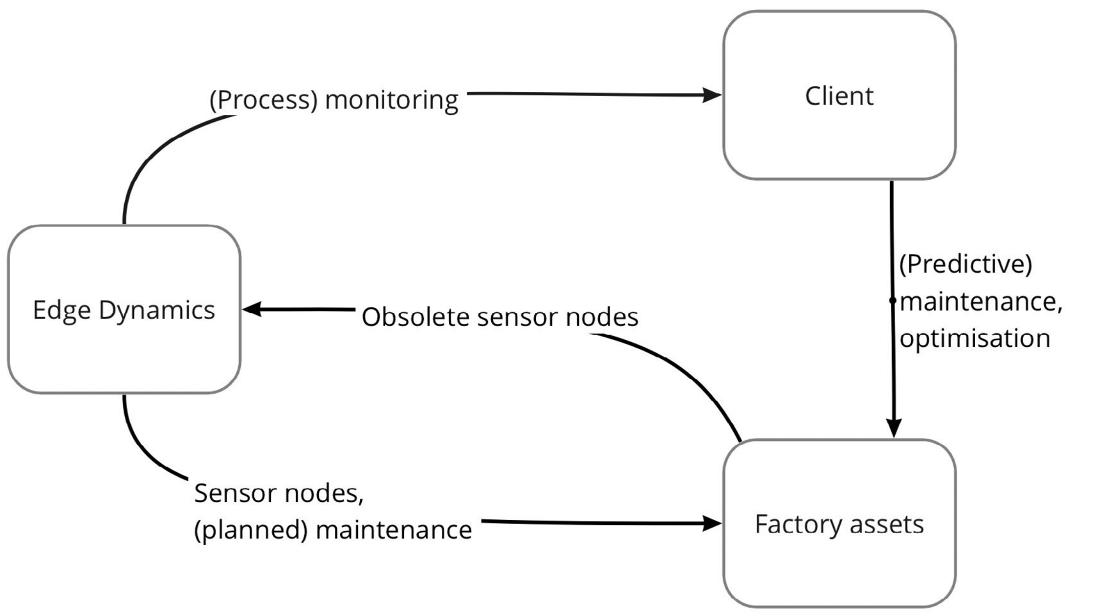


Figure 24: Result-oriented model proposition

4.2 IIoT Use cases

In order to understand the complexity of the business contexts and environments in which sensor nodes will operate, two of Edge Dynamics' potential clients were visited and consulted. Each of their unique settings are used to comprise the conditions the sensor nodes should abide by. This information is essential for an appropriate redesign.

CASE: SHELL PERNIS
Shell is a textbook example of a heavy industry corporation. They operate close to Edge Dynamics' headquarters, at the Shell Pernis site in Rotterdam (figure 25). This site is one of the biggest oil refineries in the world and the biggest in Europe, with a surface area of over 5 square kilometres and a production output of 404.000 barrels of oil a day (Shell, n.d.). Shell has been experimenting with remote monitoring at the Shell Pernis site using wireless sensors since 2018 (KPN, 2019). At Shell Pernis, the vast majority of equipment is outdoors and exposed to the elements. On top of that, many factories are restricted areas within the industrial site; hazardous and explosive gases are present. Operations are monitored by control centres across the area, while maintenance has their own dedicated facilities (Hassan, personal communications, February 2022).

Industrial sites execute so called shutdowns, or sometimes called turnarounds, which are clinically organised temporary undertakings during which a sector's operations are halted (sector = area hosting one or more factories (figure 26)). This is done in order to perform maintenance and repairs on equipment and machinery. Depending on the specific sector within an industrial complex, these shutdowns are carried out every several years or so, usually ranging from 4-7 years (Hassan, personal communications, February 2022).

Each year 2-3 sectors experience a turnaround at Shell Pernis, which can take from four weeks up to several months to perform. These are planned in detail, usually years ahead. During a

Figure 25: Shell Pernis (Shell, n.d.)

turnaround, several thousands of external workers can be present at Shell Pernis from different construction and maintenance parties (Hassan, personal communications, February 2022).

Currently, each sector houses several factory 'blocks', with an entire sector hosting between 300-500 sensors. These sensors are wired as they monitor crucial processes. In the gas and oil industry, major players are expected to implement a similar amount of IIoT sensor nodes over the course of the coming years for various applications. The total number could accumulate to 20.000 IIoT sensor nodes (Hassan, personal communications, February 2022).

ASSET AND PROCESS MONITORING
Industrial equipment is subjected to wear over time. Asset monitoring, or also known as machine health monitoring, is a way of detecting the occurrences of failure and predicting malfunctioning of machines or equipment. The predictive maintenance that can be achieved by asset monitoring is a key activity within the industrial sector for reduction of operation downtime, reduction of costs and boosting productivity. Asset monitoring is a circular strategy as it prolongs the lifetime of factory equipment (Fraga-Lamas et al., 2021). Other applications involve detecting bearing-faults on pumps (TWTG, 2021), humidity monitoring of isolated piping and temperature monitoring of pipes, the latter being an example of process monitoring.

PRODUCT JOURNEY: SHELL PERNIS
A collaboration between Edge Dynamics and Shell Pernis could look as follows. The use cycle of the IIoT hardware starts with Edge Dynamics delivering the agreed upon number of sensor nodes and gateways. Installation and integration is likely done by the client, with a supporting role for Edge Dynamics. When the wireless sensor network is operational, the nodes start monitoring. The sensor nodes operate in an industrial environment, which means they need to be able to endure harsh environments. Here, durability of sensor nodes is crucial to resist becoming obsolete. For example, high and low temperatures can affect battery life, while humid and wet conditions can corrode and harm the electronics of the devices.

The use cycle of sensor nodes is directly linked with their battery life. To keep the sensor nodes in use, they need to be maintained. Maintenance of WSNs can be carried out by Edge Dynamics on planned intervals, ideally in line with site shutdowns. Currently Edge Dynamics can guarantee their sensor nodes have a battery life of eight years, enough to last for the longest period in-between shutdowns (7 years + 1 year buffer). These specified maintenance operations are a great opportunity to address sensor networks as well, because the site will be partly or entirely accessible for several weeks or months. Especially hard to reach areas are (only) accessible during shutdowns as they require special attention (e.g. scaffolding) (Hassan, personal communications, December 2021). Conversely, sensor nodes (with the exception of valve position monitoring) are flexible in installation and can therefore be installed outside the timeframe of shutdowns (J. Klompe, personal communications, March 2022). The sensor nodes' obsolescence can be postponed if they have the ability to be maintained.

The sensor nodes require repair when they malfunction (e.g. the battery depletes). As mentioned before, common practice of maintenance departments is keeping spare parts on site. This way, a field technician will be able to resolve any irregular issue without (physical) assistance of the OEM (Hassan, personal communications, December 2021). Therefore, the possibility to repair sensor nodes is of importance to postpone their obsolescence.

At Shell, workers are required to wear a standard issue outfit when in the field. This outfit includes safety goggles, a helmet and safety work gloves (figure 26). It is up to workers themselves if they use tight or loose gloves and they are allowed to take them off for certain tasks (Hassan, personal communications, February 2022). However, assumed will be that workers changing a sensor node or its battery will wear at least tight safety gloves. With gloves on, the precision of one's fingers is lost to a degree.

Sensor nodes will return to Edge Dynamics once collaboration with the client ceases, or when they are beyond repair. At Edge Dynamics, sensor nodes can be tested and brought back to a new state in a controlled environment. By carrying out remanufacturing activities, the sensor nodes' obsolescence can be reversed. As a result of the geographical location at the coast, devices in operation at Shell have a hard time lasting longer than 12 to 15 years due to corrosion of components (Klompe, personal communications, March 2022).When sensor nodes are beyond repair or remanufacturing, parts that still function can be salvaged and fed back into the assembly of new sensor nodes (reverse logistics). Parts that are beyond reuse are send to dedicated recycling facilities, where raw materials can be liberated and processed for reuse.

PROPOSITION: USE-ORIENTED CIRCULAR BUSINESS MODEL

For Shell Pernis, both a use-oriented business model as well as a result-oriented business model can be considered for a number of reasons. As mentioned before, Edge Dynamics' sensor nodes excel at long operating life, which reduces replacement or maintenance intervals (and therefore costs) for the product owner. Secondly, these models are more sustainable in the long run than a sales model; relying on selling products with a long product lifetime could result in a decrease of sales as the majority of purchases in a saturated market are replacement purchases (den Hollander, 2018, p. 77). Lastly, Shell is more inclined to pay for a service based product than only the hardware as the former can be paid for by using operational budget while the latter is designated as capital expenses. Capital expenses have a higher threshold for approval than operational ones, meaning (in general) clients are more willing to sign up for a service than to buy hardware (Hassan, personal communications, December 2021). However, a result-oriented model is less applicable as Shell already has an IoT system's backend in place and would only require the sensor nodes. A result-oriented model would be more appropriate when wireless monitoring could be offered as a value proposition, instead of only the hardware.

When considering a 10 year period of predictive maintenance applied to a use-oriented model, the cost-effectiveness can be illustrated. In a use-oriented model, the costs of operation would be divided over timed interval payments, likely per month. On a single battery more or less the same amount of communication intervals (sending data to the nearest gateway) can be carried out. A scenario is considered where 1500 sensor nodes are installed at Shell in three different sectors. In this scenario a comparison is made between the rate of communication intervals. Naturally, a higher rate would drain a node's battery faster, leading to higher maintenance costs and fees for the customer. The complete scenario can be found in Appendix C1 [confidential].

The scenario (table 4) shows that there is little incentive for customers to adjust the amount of intervals they receive, as price differences between a high communication rate (e.g. four times an hour) and low communication rate (e.g. one time an hour) is negligible (2,35%). Although this would lead to more or less four times higher maintenance costs, the monthly fee would hardly increase. This is due to the fixed costs (of personnel) taking up 92% of the total costs (Appendix C1 [confidential]).

It is when the amount of sensor nodes in operation is increased that things get more interesting. When Shell (or other customers) would operate for instance 15.000 sensor nodes, the total costs would decrease with 11,6% if the rate is adjusted from four times an hour to a rate of one time an hour. Now, the customer has more incentive to adjust their communication rate to a lower value, leading to less maintenance costs for Edge Dynamics and less use of batteries. It is assumed that fixed costs (personnel) are not increasing when the number of operational sensor nodes is increased to 15.000 sensor nodes.

Table 4: Comparison of cost of operation of 1500 sensor nodes and 15000 sensor nodes (Appendix C1)

	10 year (30 min. Communication interval)	10 year (1 hour Communication interval)	10 year (15 min. Communication interval)
Cost per month (EUR)	14543,58	14430,65	14769,46
Difference in percentage (%)	100,78	100,00	102,35

Use-oriented model - Pay-to-use (per month, 1500 sensor nodes)

	10 year (30 min. Communication interval)	10 year (1 hour Communication interval)	10 year (15 min. Communication interval)
Cost per month (EUR)	25435,83	24306,46	27694,58
Difference in percentage (%)	104,65	100,00	113,94

Use-oriented model - Pay-to-use (per month, 15000 sensor nodes)

**Figure 26: From top to bottom;
Standard issue outfit at Shell Pernis (Shell, n.d.);
Factory block;
Pernis map showing sectors (grid blocks)**

CASE: RIJKSWATERSTAAT (OFFSHORE)
Rijkswaterstaat (RWS) is a Dutch governmental agency involved in construction and maintenance of infrastructure, usually related to roads and waterways. They operate in the public domain in corporation with civilians, companies and municipalities (RWS, n.d.). In agreement with grid manager Tennet and wind farm corporations, Rijkswaterstaat installed naval radar systems on top of offshore substations (figure 27) that relay wind generated power to shore. In addition, they will install naval radar systems on external planes attached to wind turbines. The naval radar systems are used to detect ship traffic as well as bird and bat migrations. With knowledge on migration patterns, wind turbines can be slowed down to mitigate possible deaths of birds and bats due to collision with turbine blades (van den Brule, personal communications, March 2022).

As this equipment is located on open sea, environmental conditions are challenging. Salt water, rain and humidity can all have detrimental effects on electronic devices. Moreover, heat and cold can affect the battery life.

The substations and wind turbines are only accessible by boat. Moreover, the wind farms are restricted areas and thus only designated inspection and maintenance teams will visit the structures. For Rijkswaterstaat, this means they are heavily dependent on the maintenance runs of Tennet and other parties involved to visit their assets. The substations (Borsselle Alpha and Beta) are notably independent and require only 2-3 maintenance runs a year. Wind turbines are visited more often, about 10 times a year. Still, visits are kept to a minimum, as the maintenance runs are expensive. Staff joining these runs require special training and the runs are weather dependent. They are strictly planned and are unlikely available for external parties. However, Rijkswaterstaat indicated they are able to perform (simple) maintenance tasks for RWS (van den Brule, personal communications, March 2022).

Currently, the Dutch part of the North Sea hosts six offshore wind parks. With eye on the imminent obligations in 2030 for the renewable energy transition, at least five more wind parks will be build (Ministry of VROM, 2021).

Figure 27: Borselle Alpha; windfarm park (Orsted, 2021)

ASSET MONITORING
The naval radars used by Rijkswaterstaat are prone to overheating. Air-conditioning (AC) systems can fail (and have failed) resulting in damaged equipment. Moreover, the gears in the radar systems' gearbox can wear over time, which could lead to malfunctioning. Rijkswaterstaat wishes to monitor the temperature inside the technical cabinets of their radar systems (figure 28). With these measurements, RWS can decide to shut down a radar system if temperatures get too high as this could indicate the AC system has failed (van den Brule, personal communications, March 2022). For the gearbox (figure 28), RWS wants to measure vibration frequencies, to predict wear of gears. Frequencies that shift from their baseline could indicate a worn gear and thus requires maintenance.

PRODUCT JOURNEY: RIJKSWATERSTAAT
Currently, RWS is testing Edge Dynamics' sensor nodes at the Offshore Expertise Centrum in Stellendam. Here, radio towers equipped with radar systems mimic the ones installed on the mentioned substations (left side, figure 19). If using the sensor nodes is deemed valuable, a larger order is probable.

In such a case, a collaboration could look as follows. The use cycle starts with Edge Dynamics delivering the agreed upon number of sensor nodes. Installation of sensor nodes is done by the client (RWS) or maintenance third party. On the North Sea, gateways are provided by Skylab and can be used for free for IoT applications (LoRaWAN) (de Jong, 2022).

Sensor nodes will be placed inside technical cabinets of the radar systems using the magnetic base. Now, they will measure inside temperature. Similarly, sensor nodes will be placed inside the housing of the naval radar's gearboxes. Here, they will measure vibration of the gears. As they operate in the harsh environment of the open sea, the sensor nodes need to be durable.

The sensor nodes will relay data to the gateways of Skylab. Once received by Rijkswaterstaat, the information will be shown in their current analytics dashboard at the control centre. From the control centre, the status of sensor nodes can be monitored. If sensor nodes show sign of malfunction or have batteries nearing the end of their life, a maintenance call can be issued to the responsible party. Again, dependence on the maintenance carrier is evident; the unfortunate event of a malfunctioning sensor node will not justify a boat trip, as a single one can cost up to 15.000 euros to host (van den Brule, personal communications, March 2022). Instead, replacement will have to wait til the next planned event.

Once the battery life of sensor nodes will near their known end, the maintenance carrier can be informed. Spare parts or sensor nodes are required to be supplied to the maintenance party. Any remaining components or nodes should be taken back to shore after maintenance has been carried out. Edge Dynamics can establish a take-back agreement to get their nodes back, so they can remanufacture devices or harvest usable components. This way any malfunctioning sensor nodes can be revived. Parts beyond reuse can be send to designated recycling facilities.

PROPOSITION: USE-ORIENTED CIRCULAR BUSINESS MODEL
A use-oriented business model seems appropriate for Rijkswaterstaat as an ongoing collaboration is crucial for proper operation of sensor nodes. RWS would pay for the use of the sensor nodes, which would include any maintenance or replacement. A crucial aspect of the situation for Rijkswaterstaat is Edge Dynamics' apparent inability to perform any type of maintenance on location themselves. An effective circular business model would therefore require close collaboration with Tennet and Ørsted, who have access to the offshore structures and benefit as well from the naval radars installed on their platforms as they are used to monitor the ship traffic around the wind farms.

Maintenance carriers will do annually around 10 trips to wind farms and 3 trips to transformation blocks (van den Brule, personal communications, March 2022), so installation of sensor nodes will be spread out. Consequently, it is unlikely the load of replacement will be too high once batteries start depleting. Once the battery life of sensor nodes will near their end, the maintenance carrier can be informed. Spare parts or sensor nodes are required to be supplied to the carrier. Any remaining components or nodes will be taken back to shore after maintenance has been carried out. Edge Dynamics can establish a take-back agreement to get their nodes back, so they can remanufacture devices or harvest usable components. This way, broken sensor nodes can be of use in the manufacturing of new sensors. Parts beyond reuse can be send to designated recycling facilities.

When considering a 10 year period of predictive maintenance applied within a use-oriented business model, the costs per sensor per month can be used for showing the influence of the way malfunctioning sensor nodes are handled. The complete scenario can be found in Appendix C1 [confidential].

Within the collaboration, parties would agree on a certain amount of time that is available for maintenance per sensor node, as this costs would be covered by Edge Dynamics. Say, an inspection engineer would need 3 minutes to reach the sensor node, 6 minutes to perform maintenance (e.g. disassembling the sensor node to swap the battery) and another 3 minutes to get back to his or her main routine, this would cost the maintenance of one sensor node around €250. If the inspection engineer would take 1,5 minutes (four times quicker) to perform maintenance (e.g. opening the technical room, removing the sensor node and placing a new one, closing the technical room), this would cost €156 per sensor node, saving close to 40%.

Putting the maintenance cost in perspective however shows a less dramatic reduction in costs. In a scenario where 1250 sensor nodes are installed on various wind farms, 82% of the costs are comprised of fixed costs. Now, the cost reduction of faster maintenance is lower at 11,3% (table 5). Still, this indicates that the cost-effectiveness of a use-oriented model in this situation seems to increase significantly by performing faster maintenance. Assumed here is that the fixed costs for personnel (eg. maintaining platform backend etc.) stay the same.

Moreover, prolonging the battery life by a factor of 1,5 (8 years to 12 years) will reduce the total costs by 6,6% in a scenario with 1250 sensor nodes. Combining longer battery life and less maintenance time is obviously the way to go for the highest reduction of the total costs of operating the nodes.

Table 5: Influence of extended battery life and faster maintenance on total costs of operation

	10 year (6 min per sensor node | battery life 8 years)	10 year (1,5 min per sensor node | battery life 8 years)
Cost per month (EUR)	20471	18168
Cost / sensor node per month (EUR)	16,38	14,53
Percentage (%)	100,0	88,7

Use-oriented model - Pay-to-use (1250 sensor nodes)

	10 year (6 min per sensor node | battery life 8 years)	10 years (6 min per sensor node | battery life 12 years)
Cost per month (EUR)	20471	19263
Cost / sensor node per month (EUR)	13,65	12,84
Percentage (%)	100,0	94,1

Use-oriented model - Pay-to-use (1250 sensor nodes)

	10 year (1,5 min per sensor node | battery life 8 years)	10 year (1,5 min per sensor node | battery life 12 years)
Cost per month (EUR)	18168	17390
Cost / sensor node per month (EUR)	12,11	11,59
Percentage (%)	100,0	95,7

Use-oriented model - Pay-to-use (1250 sensor nodes)

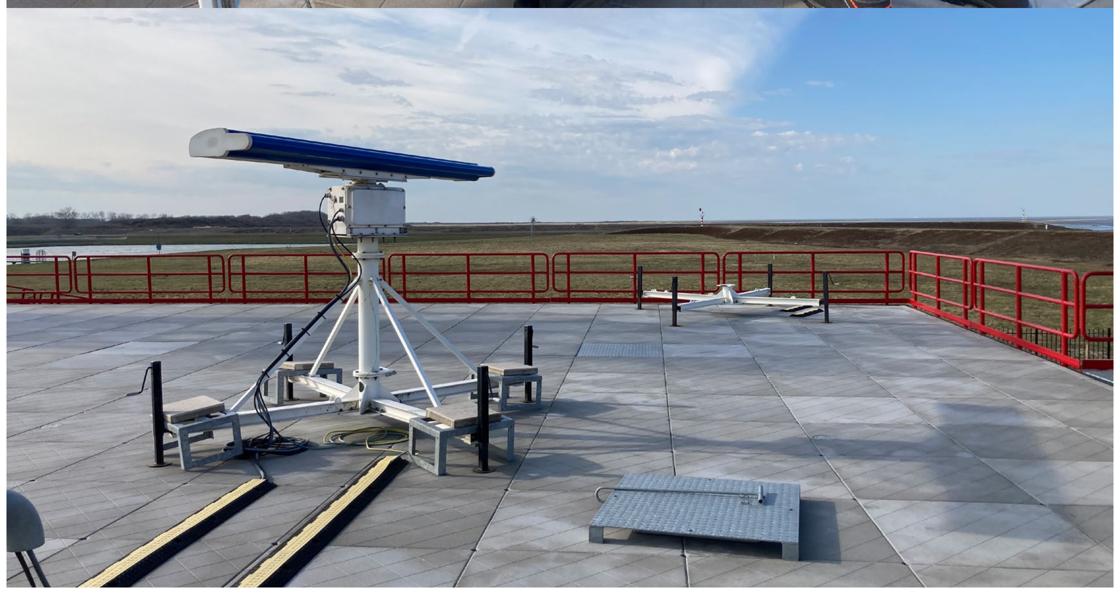


Figure 28: From top to bottom; Inspection engineer Orsted (Orsted, n.d.); Naval radar system mounted in technical cabinet; Radar system for detect birds

The use cases give an indication about the costs involved with circular strategies applied to sensor nodes. For Shell, applying a use-oriented business model to Edge Dynamics sensor nodes showed there is only an incentive for preserving battery life, and thus product lifetime, after a certain scale is reached at which point maintenance costs become a significant fraction of the total costs. Now, preserving product integrity is reflected in a lower monthly fee.

RWS showed that the cost of maintenance is highly dependant on the time it takes to execute maintenance. Lowering the time needed for replacing a sensor node reduces the total costs significantly. Moreover, increasing the battery life would reduce the maintenance costs as well.

The viability of circular business models relies on the specific design of the product they incorporate. The better the product facilitates the characteristics of the business model and circular strategies, the higher the profitability that can be achieved.

DESIGN PRINCIPLES
Based on the concepts and proposed business models described in the previous chapters and the accompanying circular strategies, several design principles should be considered. There is an "almost complete overlap between the sets of design principles supporting the various design approaches for postponing and reversing obsolescence". Therefore "products designed to support one design direction will almost inevitably support, and often need to be designed to support one or more of the other design directions" (den Hollander, 2018. p. 59).

For redesigning Edge Dynamics' sensor node, the design principles in Table 6 on the next page will be used. The selection of design principles is based on their apparent relevance to the product architecture of the sensor node. The selection is elaborated in Appendix E.

The methods and metrics used to assess to what degree the current sensor node resonates with the design principles are described (if applicable). The analysis and assessment of the current sensor node on these principles is described in the next chapter.

Conclusion

RQ2.1: WHAT ARE THE CIRCULAR DESIGN STRATEGIES MOST APPROPRIATE FOR EDGE DYNAMICS' IIOT PRODUCTS?

For Edge Dynamics, the following circular strategies can be of importance:

- Durability of the product (Design for Durability)
- Maintaining and repairing the product (Design for Maintenance & Repair)
- Remanufacturing the product (Design for Remanufacturing)
- Recycleability of the product (Design for Recycling)

RQ2.2: WHAT ARE THE DESIGN PRINCIPLES UNDERLYING THESE CIRCULAR DESIGN STRATEGIES?

The circular design principles relevant to the optimisation of the product architecture are shown in table 6 on the next page.

Table 6: Overview of design principles

Design principle	Description	Method	Metric
Dis- and reassembly	Facilitating the process of removal of parts from and/or placement of parts in a product "while ensuring that there is no impairment of the parts or product due to the process (Brennan et al. 1994, p. 59).	Disassembly Map: The Disassembly Map is used for visualising the disassembly sequence (De Fazio et al., 2021).	Number of disassembly steps Disassembly time
Accessibility	Making "the spatial arrangements of parts and assemblies within a product so that each of these items is readily accessible for replacement or repair in-place" (Moss, 1985, p. 37).	HotSpot Mapping: Target components can be identified using the HotSpot Mapping tool (Flipsen, 2020). Surfacing, clumping, trimming: By using the methods of surfacing, clumping and trimming (de Fazio, 2020), the sensor node's disassembly sequence can be optimised. Surfacing is a way of raising the target components in the disassembly sequence, in order to make it easier accessible. Clumping is the clustering of either target components to remove them all together at once, or removing a cluster of non-target components to (instantly) reveal the target component. Trimming is the act of removing steps in the disassembly sequence in order to simplify and therefore reduce disassembly time and effort.	Number of steps to target components Disassembly time of target components
Standardisation	Enforcing "the conformance of commonly used parts and assemblies ... to generally accepted design standards for configuration, dimensional tolerances, performance ratings and other functional design attributes" (Moss, 1985, p. 36).	Increase interface standardisation: have interfaces between different modules standardised and variety in different interfaces used reduced. This will simplify a product and improve its interchangeability.	Number of non-standard interfaces used in product
Functional packaging	Locating "all components ... performing a given function in ... a unit that is readily removable and replaceable as an entity)" (Moss, 1985, p.36).	Group components per function: group components that are supporting the same function. This will create modules with a clear role within in a product.	Degree of functional compatibility
Adaptability	Allowing a product to be continually updated (Keoleian & Menery, 1993) or to "perform several different functions" (Keoleian & Menery, 1993, p. 64).	Decrease functional coupling: decrease the interface couplings between functional carriers of different modules. A functional carrier is "a component, part or physical element in a product that contributes to a given function or a set of functions" (Klushin, 2018). This will reduce the interdependencies of modules.	Degree of contribution to main function
Modularisation	Enforcing "conformance of assembly configurations to dimensional standards based on modular 'building block' units of standardized size, shape, and interface locations (e.g., locations for mating attachment or mounting points and input/ output line connectors), in order to simplify maintenance tasks by enabling the use of standardized assembly/ disassembly procedures" (Moss, 1985, p. 36).	-	-

5

Assessment of current product

This chapter explains the assessment of the metrics that correspond with the design principles which were identified in the previous chapter. The methods and tools that are used are described briefly. Consecutively, the chapter describes the results that emerged from the assessment. The chapter concludes with the list of requirements that will be used as input for the redesigning Edge Dynamics' sensor node.

Photo by Dimitry Anikin, unsplash.com

5.1 Accessibility and dis- & reassembly

Disassembly is the "process whereby an item is taken apart in such a way that it could subsequently be reassembled and made operational" (CEN/ CLC TC10 European Standard, 2017). Therefore disassembly is crucial to the repairability of products, as its effectiveness relies on the time and effort that is required to bring a product back to an operational state. Both the accessibility and ease of disassembly are important product aspects as they reduce the required time and complexity of circulair activities such as repair and remanufacturing. This leads to lower costs for operating functionality retention strategies and will therefore positively contribute to the circular economy (Vanegas et al., 2018).

HOTSPOT MAPPING TOOL

The HotSpot Mapping tool (HSM) focuses on aspects related to product architecture by identifying the key components and activities used within the sensor node. These components are considered to have the highest priority due to maintenance frequency or failure rate, have the most economic value or have a high embodied environmental impact. HSM is a spreadsheet based tool containing data from the Granta design material database.

The tool shows the activities and product parts that can be targeted for the redesign. Making the disassembly of these key components easier and faster supports circular strategies such as repair, maintenance and remanufacturing in becoming more cost effective. The method works by recording the disassembly steps based on several step characteristics such as activity properties (type of tool, time needed) and material properties (weight, material). The HSM spreadsheet will then show critical activities and critical parts as 'hotspots', by flagging them. Flags will indicate components with the highest impact (90% or more for environmental impact and 80% or more for economic impact) (de Fazio, 2019). Critical activities are disassembly steps that take a long time to perform or are hard to carry out. Critical parts are considered the aforementioned key components (Flipsen, 2020).

Time estimations are an essential aspect of disassembly and therefore need to be known for the HSM tool. Times were calculated based on the eDiM data sheets and estimated based on own recordings of disassembling the sensor node. eDiM (ease of Disassembly Metric) makes use of reference tables comprised of predetermined disassembly tasks, such as tool change, tool positioning and removal of the disassembled part. Based on the product specific disassembly sequence, the associated values are summed to give the eDiM metric (in seconds) (Vanegras et al., 2018). The eDiM calculation table can be found in Appendix F.

Video recordings were made of three full disassemblies and used to estimate mean times for each components and for reaching target components by analysing the amount of time used per disassembly step or sequence. Comparing both disassembly times showed a considerable discrepancy between calculated disassembly times and observed times. The calculated time for disassembling the battery was 37% faster than the observed time to do this. The total disassembly time differed 42% in time required. Times observed in video recordings are deemed more accurate and will therefore be used in the HSM spreadsheet and throughout the report. The full sheet and set-up are shown in Appendix F.

ACCESSIBILITY: FINDINGS
The outcome of the HSM tool showed that for the current sensor node the battery is determined as the only priority part (see figure 29). This is the component that is most likely to fail before other parts due to the inevitable depletion of its energy. Product functionality retention for Edge Dynamics' sensor node is therefore highly dependent on replacement of batteries.

In addition, the HotSpot Mapping results show both the communication PCB and sensor PCB are indicated as having a relatively high embodied environmental impact and high economic value for recovery. PCBs are of major concern when it comes to their high environmental impact and high contents of rare metals. The recovery of these precious metals has become an economic drive for e-waste recycling (Wu et al., 2017).

The HotSpot Mapping sheet also shows critical activities; disassembly steps that are taking a significant amount of time to perform. The bar chart in figure 30 shows the mean times of each separate disassembly step. The most time is required for removing screws, spacers and threads. Each of these components appear as a multitude of three in the product and the times shown in the figure count for removing all three parts. These steps can be targeted in order to reduce the total disassembly time of the sensor node and will be considered in the redesign. Moreover, removing the O-ring is a disassembly step with a high distribution.

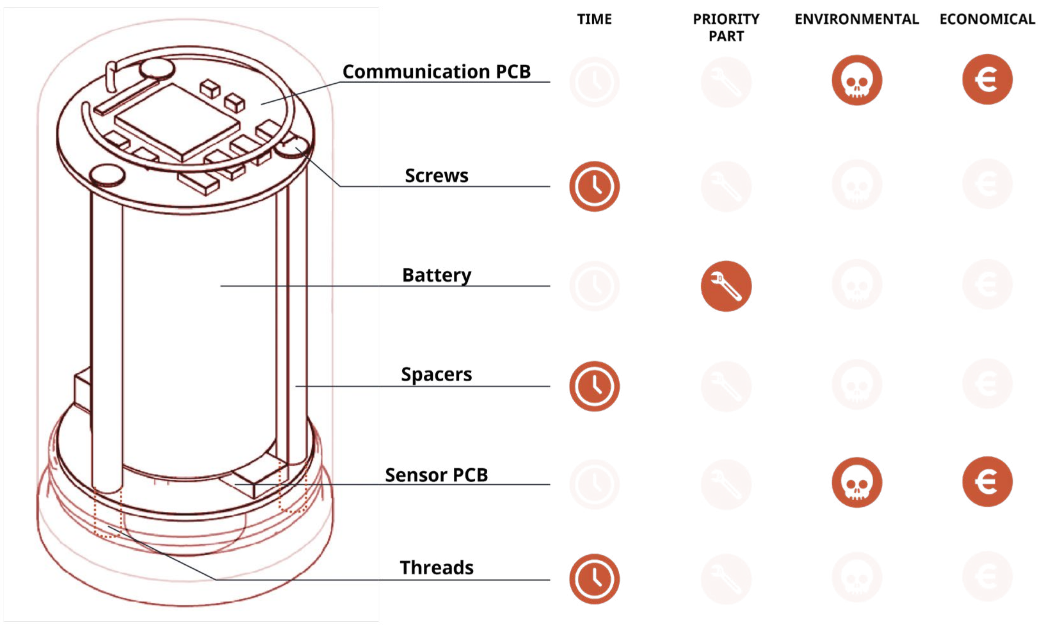


Figure 29: HotSpot Mapping results

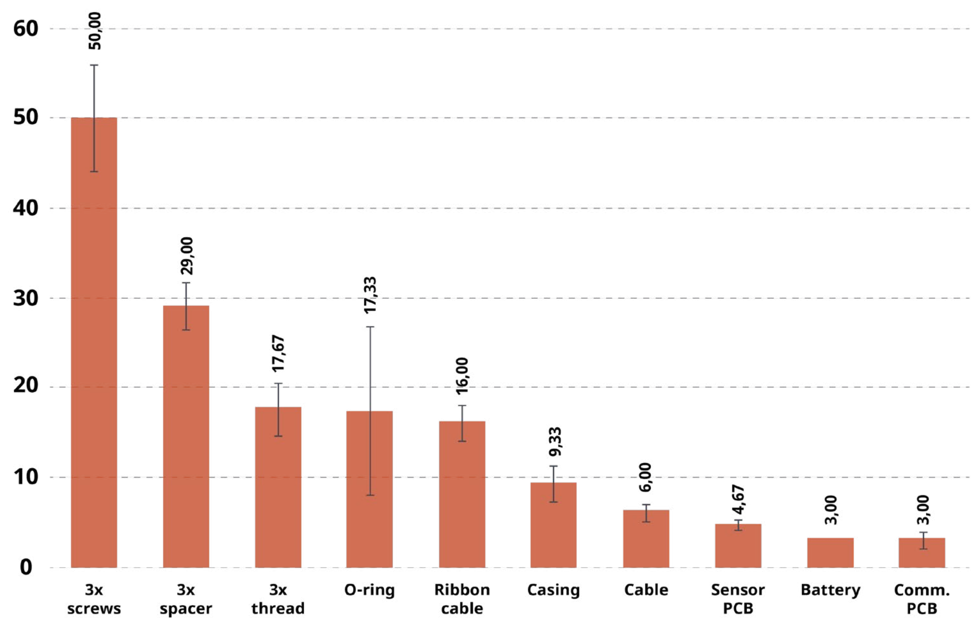


Figure 30: Mean times of steps arranged from most to least required time to disassemble

DISASSEMBLY MAP TOOL
The Disassembly Map is a visual tool that is used to map the sequential order of the disassembly of the sensor node. The steps in the disassembly process are made comprehensible by visually capturing them in a diagram. This diagram provides additional information on a variety of aspects such as the type of tool used, applied force and disassembly penalties. This supports identifying steps that hamper the disassembly.

The Disassembly Map consists of numbered circles that indicate the component number. Arrows connecting these show the direction of disassembly (figure 31). There are three main logic representations shown in figure 32:

- A. Sequential dependency. One part needs to be removed in order to reach the next part(s).
- B. Sequential independency. Parts do not require to be removed sequentially.
- C. Multiple dependency. Disassembling a part requires the removal of two or more parts.

Multiple part numbers together represent a cluster block (figure 32, A).

Action blocks are rectangular shapes that indicate the type of tool that needs to be used to execute the disassembly step and the force that is required to do so. Both these aspect influence the disassembly time (De Fazio et al., 2021). A legenda provided with the Disassembly Map explains the coding of the action blocks.

Figure 34 on page 60 shows the complete Disassembly Map of the current sensor node. The key components identified with the HotSpot Mapping tool are indicated as well in the figure by using indicator icons next to their location. The map symbols describe each variant.

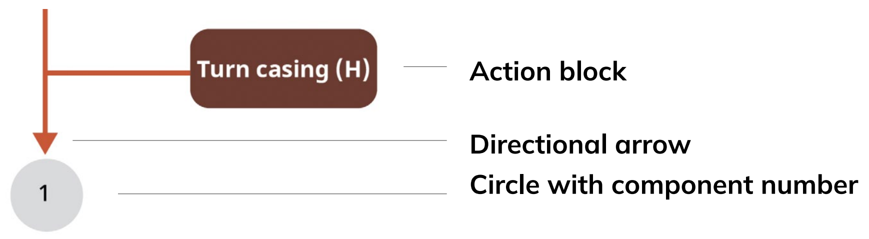


Figure 31: Visual elements of Disassembly Map

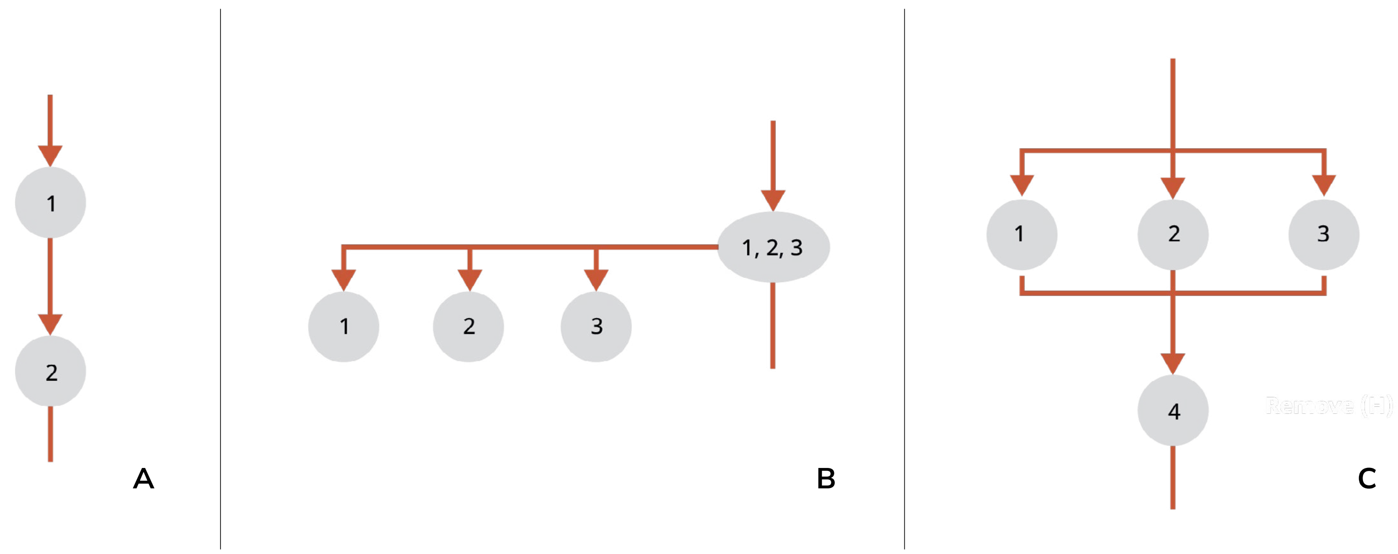


Figure 32: Logic representations; A: sequential dependency, B: sequential independency, C: multiple dependency

DISASSEMBLY: FINDINGS
Looking at the Disassembly Map (figure 34) it can be noted that the sensor node's disassembly is mainly sequence dependent, with one multiple dependency; in order to remove the sensor PCB, all three spacers need to be disassembled. Moreover, it takes a significant number of steps to get to target components. The number of steps are combined with the time estimations and shown in figure 33.

Based on the analysis of video recordings, the target disassembly for the communication PCB requires a mean time of 86,7 seconds with an SD of 4,0 s. The target disassembly for the battery requires a mean time of 89,3 seconds with an SD 4,2 s. The target disassembly for the sensor PCB requires a mean time of 124,3 seconds with an SD 4,2 s. The complete disassembly of the sensor node requires a mean time of 160,3 seconds with an SD 2,1 s.

The three screws that need to be removed to detach the communication PCB take up 56% of the battery's target disassembly time, while both cables take together 25% of this time. These steps are responsible for 45% of the complete disassembly time of the sensor node.

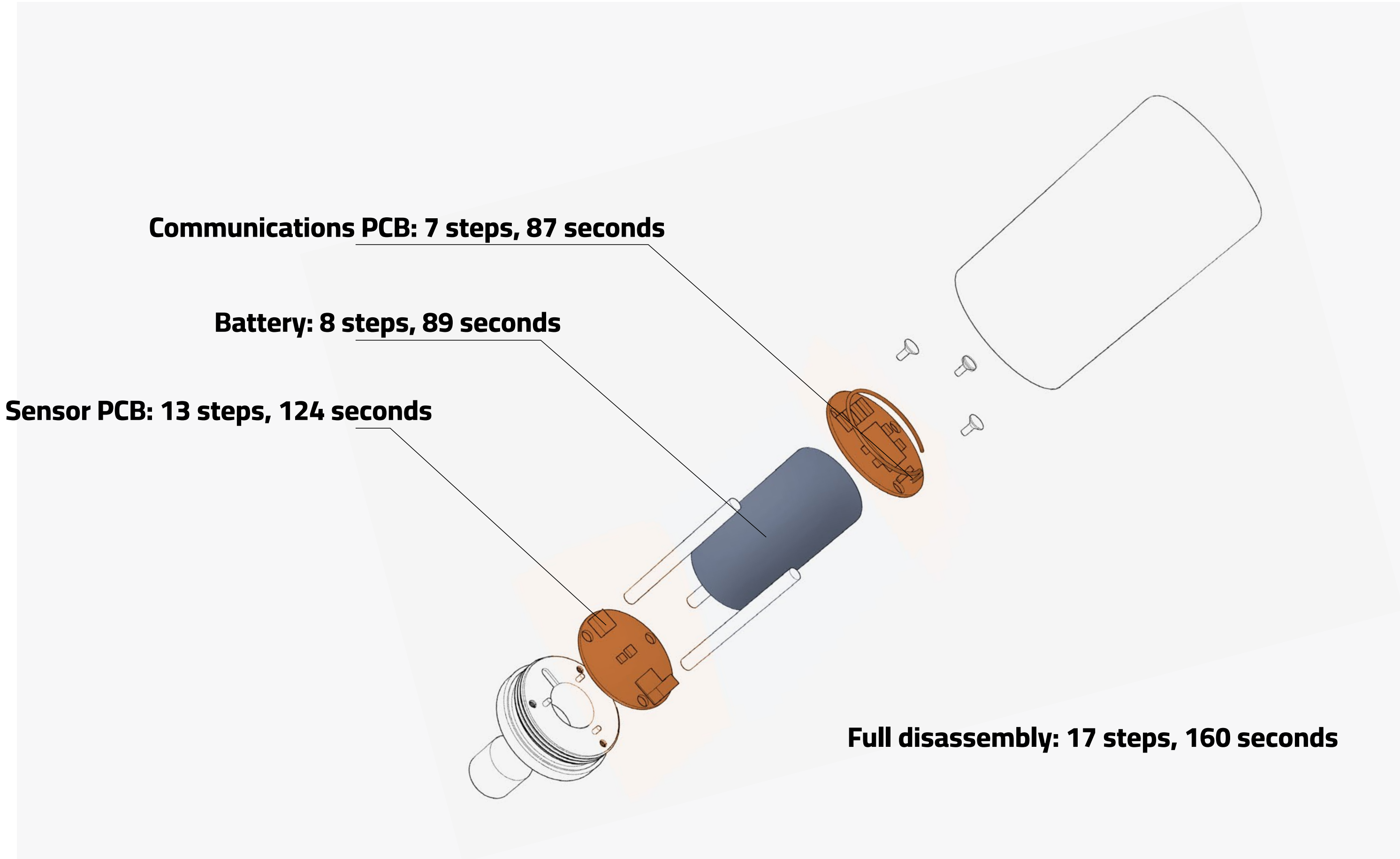


Figure 33: Exploded view sensor node; number of steps and mean time required to reach key components

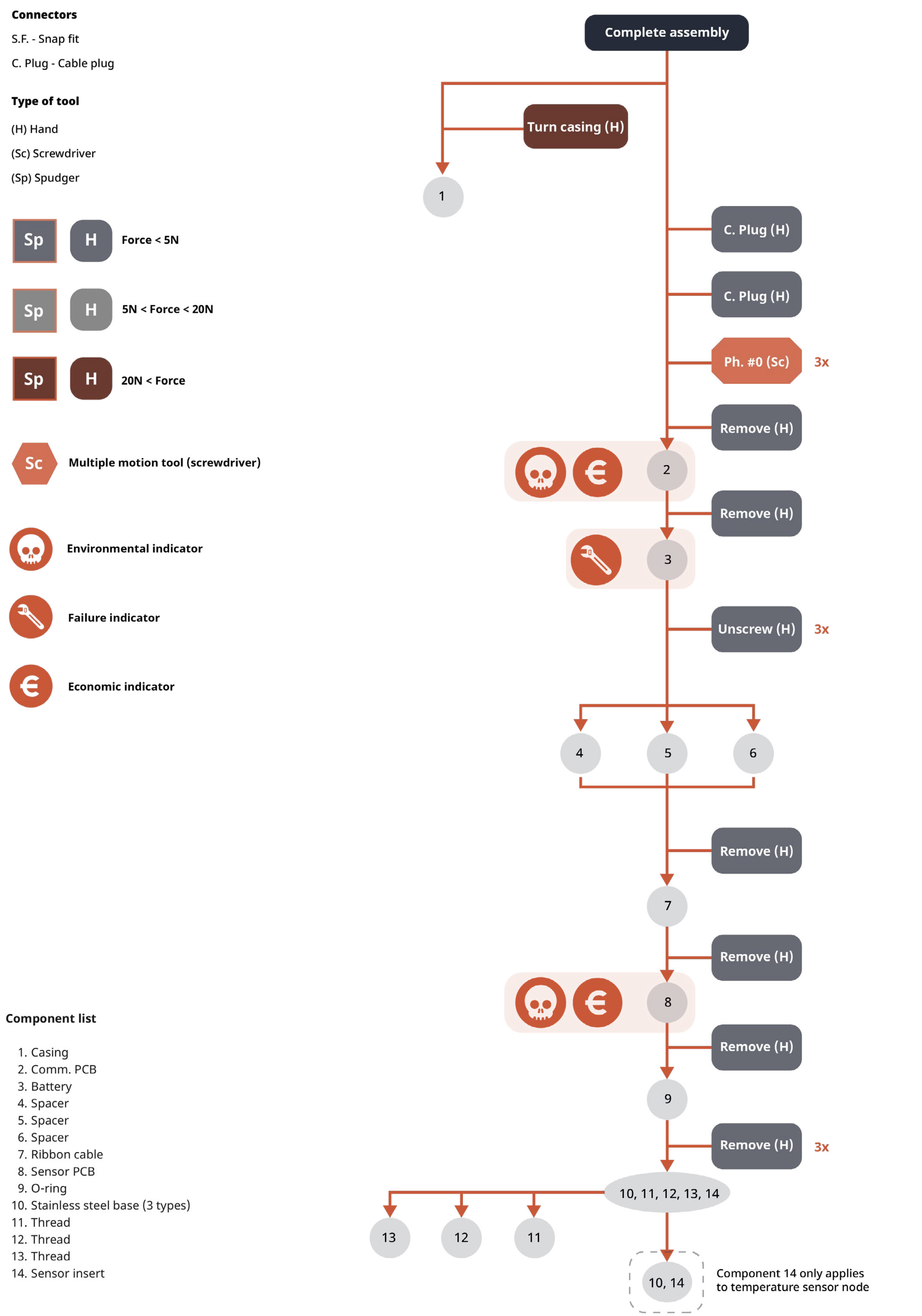


Figure 34: Disassembly Map of current sensor node

As the Disassembly Map is a standardised tool, it does not show product specific intricacies that occur during the disassembly of the sensor node. These oddities are hampering the disassembly (and assembly) of the product. Several were observed and are described on this page.

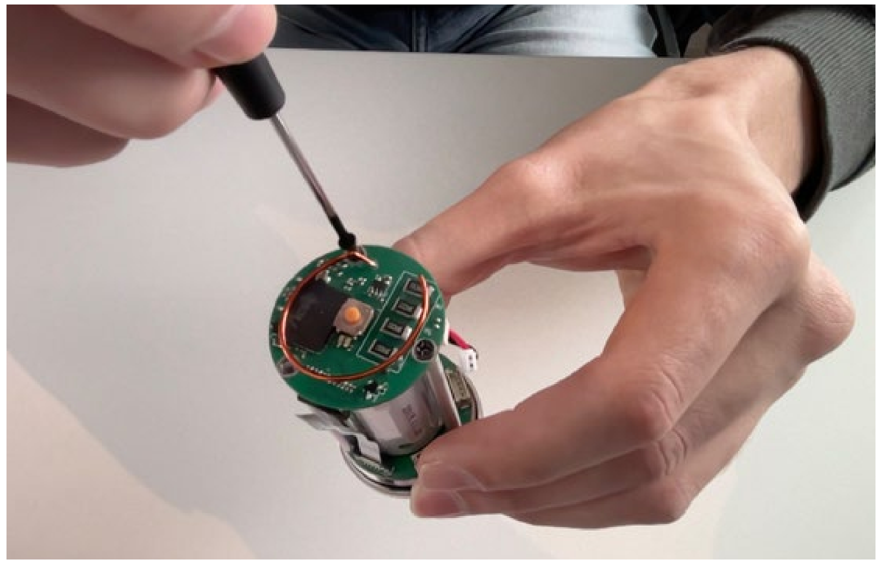


Figure 35: The antenna (copper looped part) crosses the line of movement of the screws used to fasten the communication PCB. Having to repeatedly move or graze the antenna is likely not beneficial to its endurance.

Figure 36: The surface area of the base is small (steel part in hand on the right). Exerting the required force on the sharp edge of the base is uncomfortable.

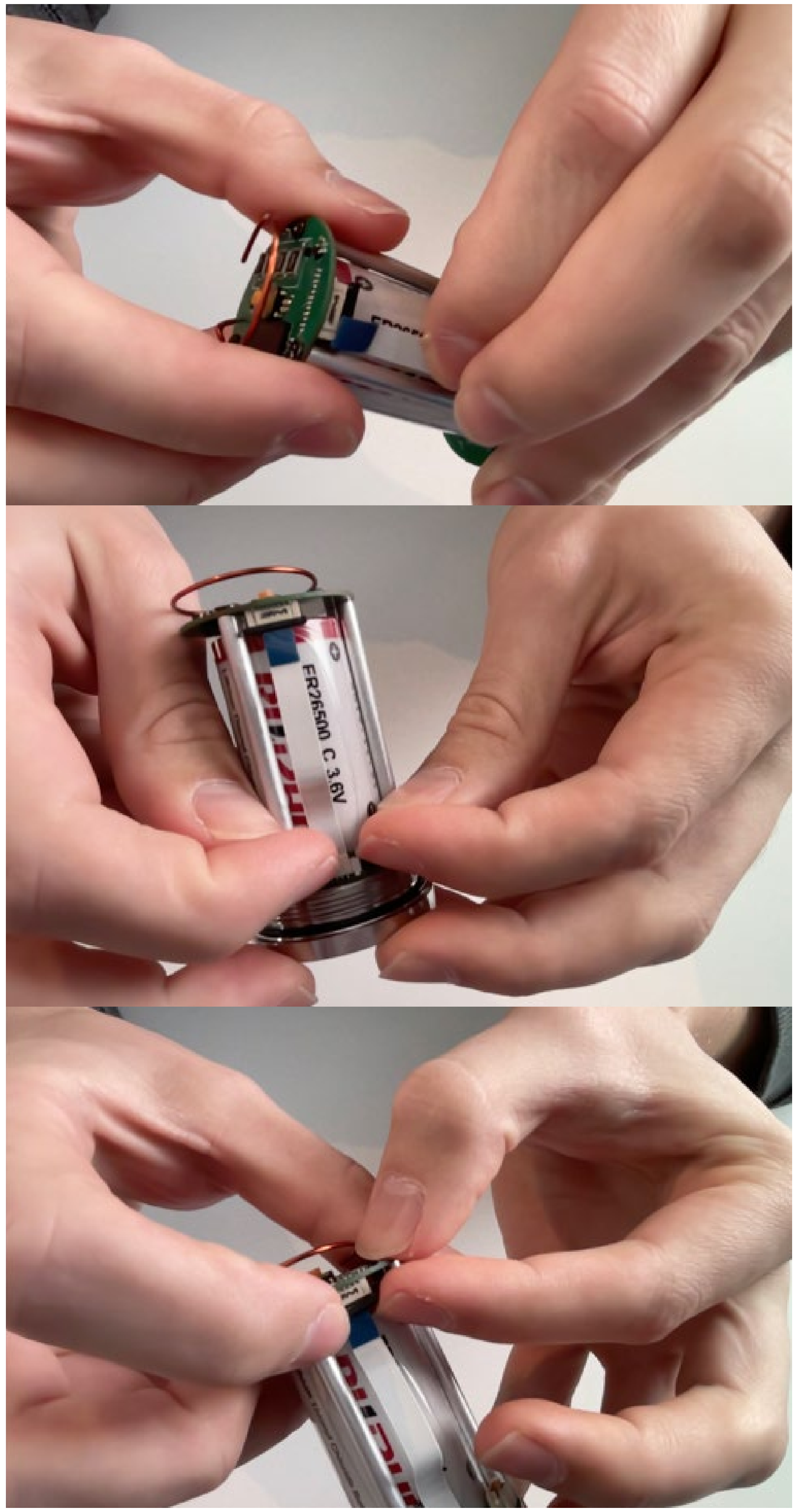


Figure 37: The ribbon cable (white with blue top end) is a small part that is connected on two sides. Precision is required when trying to unlock the cable clips. When assembling the cable, it is easy to insert the ribbon cable in the wrong position as nothing prevents you from doing that.

HANDLING NODES WITH GLOVES
The interaction between the field technician and the sensor node can be simulated to discover possible challenges in handling the node. This showed that it is challenging and likely unfeasible to repair the sensor node while it is mounted magnetically due to the node moving around when handled (figure 38). In case of a bolted mount, the sensor node would be fixed to a surface by screwing the base's female thread onto a bolt or male thread. This only applies to the base component for the vibration version. This secures the node significantly, but applying a large force to take off the casing might loosen the mount (figure 39). Naturally, an area to grip and apply a counter force is preferred. As mentioned in chapter 5, the sensor node's base has a small surface area that can be gripped, making it hard to unscrew the casing. This is underlined when trying to remove the casing on the pressure version of the sensor node. Its base features both a larger surface to grab or can be kept in place with a wrench or pliers (figure 40). It is therefore easier to remove the casing while the sensor node is mounted. Using unpowered tools does not pose a risk in an explosive atmosphere (Hassan, personal communications, March 2022).

Figure 38: Edge Dynamics sensor node magnetically mounted

Figure 39: Edge Dynamics sensor node clearance for counter-force (left), clearance for unscrewing in hand (right)

Once the sensor node's casing is removed, the battery can be replaced. Removing screws and unplugging cables is significantly more challenging wearing gloves than without. The Philips #0 is used for the 2.5 mm screws and is a small tool that is not comfortably operated wearing gloves. Moreover, screws and other components that are dropped are likely lost, especially when conducting repair on heights.

The ribbon cable connector requires high precision to disconnect and requires one to use his or her nails. With gloves it is virtually undoable and requires fiddling with the Philips screwdriver instead to release the cable.

While conducting repair (figure 41), it is challenging to store removed components. They can be either held in one's hands or put in pockets of the technician's jumpsuit. Depending on the situation, components could be placed on surrounding equipment. Either way, it is clear that the less parts have to be removed to reach the target components, the less parts that can be lost during repair.

Figure 40: Edge Dynamics pressure sensor mounted, unscrewing by hand (left), unscrewing using tool right)

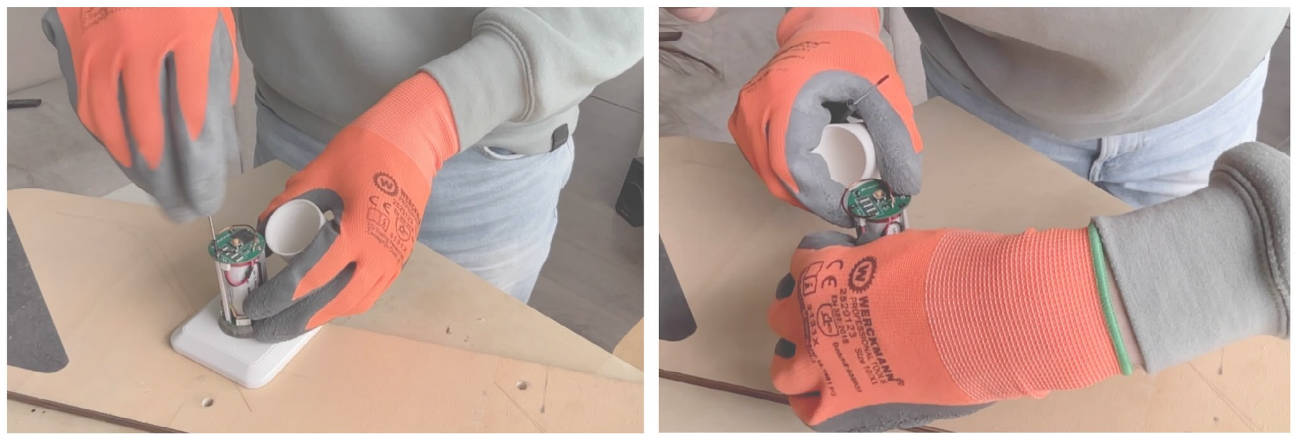


Figure 41: Repairing sensor node with gloves

5.2 Modularity

Measuring to what extent the current sensor node incorporates these aspects could show if there are changes to the current architecture to be considered.

Bonvoisin et al. (2016) state there is no consensus on how to assess the underlying principles but suggest the most promising methods. These will be used with the intent of setting a baseline for the degree of modularity of the current sensor node.

Systematically mapping the underlying functions of the components that make up the sensor node facilitates assessing its modularity (Viola et al., 2012). The results are shown in Appendix F.

PRODUCT ARCHITECTURE: ADAPTABILITY
Components are spatially or energetically (information or energy) connected with each other within a product. This has obvious reasons as they need to fulfil a function together. However, components can be 'coupled' so to say, without carrying out the same function.

Decreasing these interface couplings between functional carriers of different modules will reduce the interdependencies of modules. Analysing the interactions between components, the following can be said about functional coupling based on their contribution to similar functions:

- The sensor peripheral component is physically embedded in the base component (figure 42, left), however these have functionally no resemblance, meaning if one or the other is changed or replaced in the future, the other component is forced to do so too.

- The (power) button is physically dependent on the casing (figure 42, right), as the button can only be used through the flexible top of the casing. The parts are coupled but do not contribute to the same function.

PRODUCT ARCHITECTURE: STANDARDISATION
By having the interfaces standardised between different modules and the variety in different interfaces reduced, the product can be simplified and its interchangeability improved.

An open standard interface means anyone would be able to interact with that particular component, be it replacing a part, fitting another part or communicating with a component. A closed standard interface means anyone within a particular industry can interact with a component. No standard interface indicates that the component is custom and likely only appears on that particular product.

In case of modularity, an open standard would support the supply of (aftermarket) spare parts and modding. A closed standard might mean it will be harder for customers to repair their products if spare parts are unavailable or scarce, possibly resulting in higher prices. No standard means a component is entirely custom to that particular product and no other product outside of the OEM uses it.

The table in Appendix F shows that several components have no standard spatial interface. In many cases this simply means these are custom to this product, likely for trade secrets in case of PCB design and its proprietary firmware, but also for aesthetic reasons.

The product interfaces that interact with other equipment are components that would benefit from an open standard, in order to accommodate as many use cases as possible. That would apply to the base component and the sensor insert.

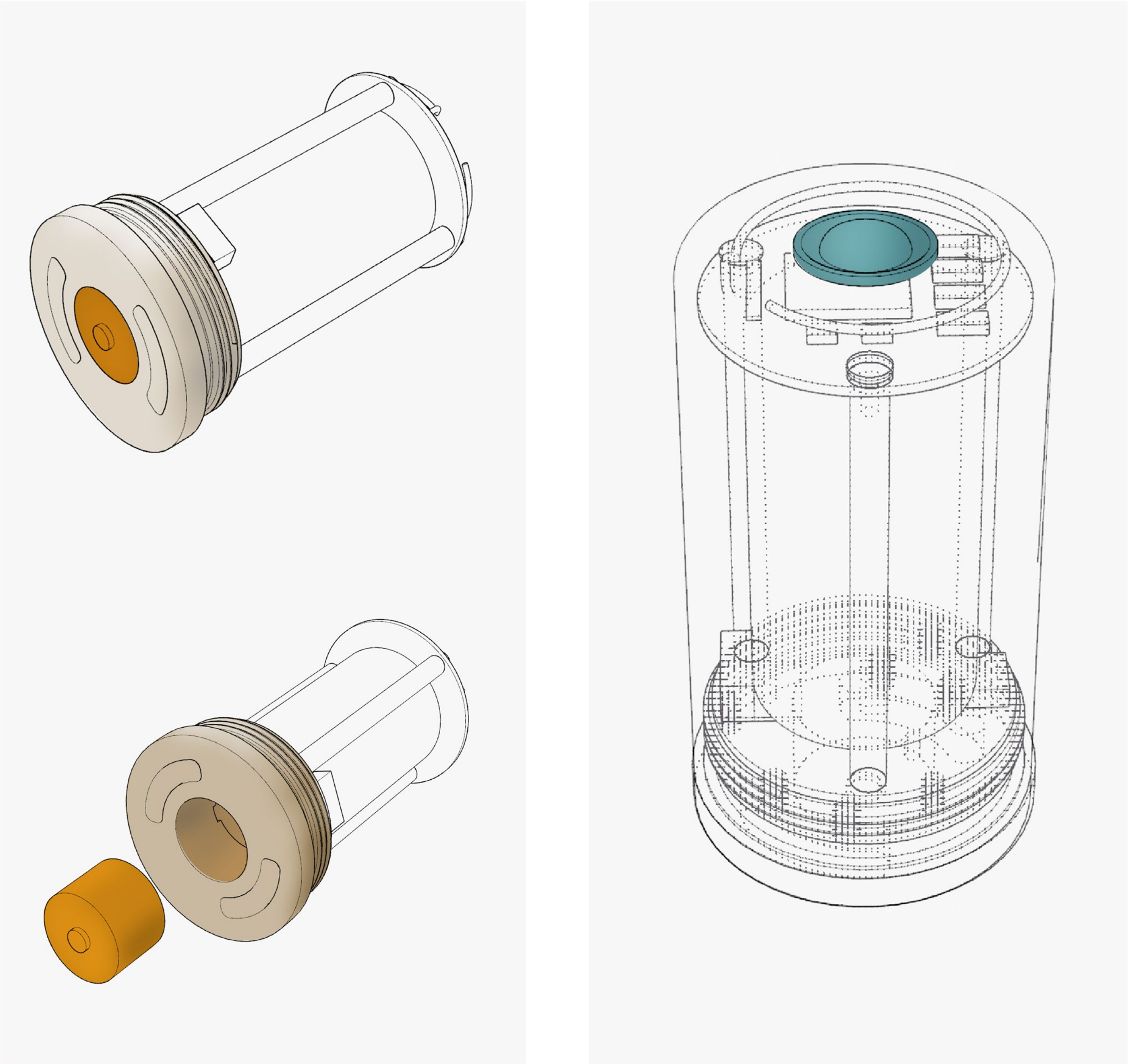


Figure 42: Left; Coupling between base and sensor insert, Right; coupling between button and casing

PRODUCT ARCHITECTURE: FUNCTIONAL PACKAGING

Grouping components that are supporting the same function will create modules with a clear role within the sensor node (figure 43). As can be noted from the figure below, most functions are carried out by a single (integrated) module such as the PCBs, or a combination of components. This miniaturisation and integration is typical for the chips industry which makes modularity more challenging. If a PCB component malfunctions, the entire PCB is compromised. Still, Edge Dynamics has kept components coupled to different functions separate, resulting in a computing module and communication module.

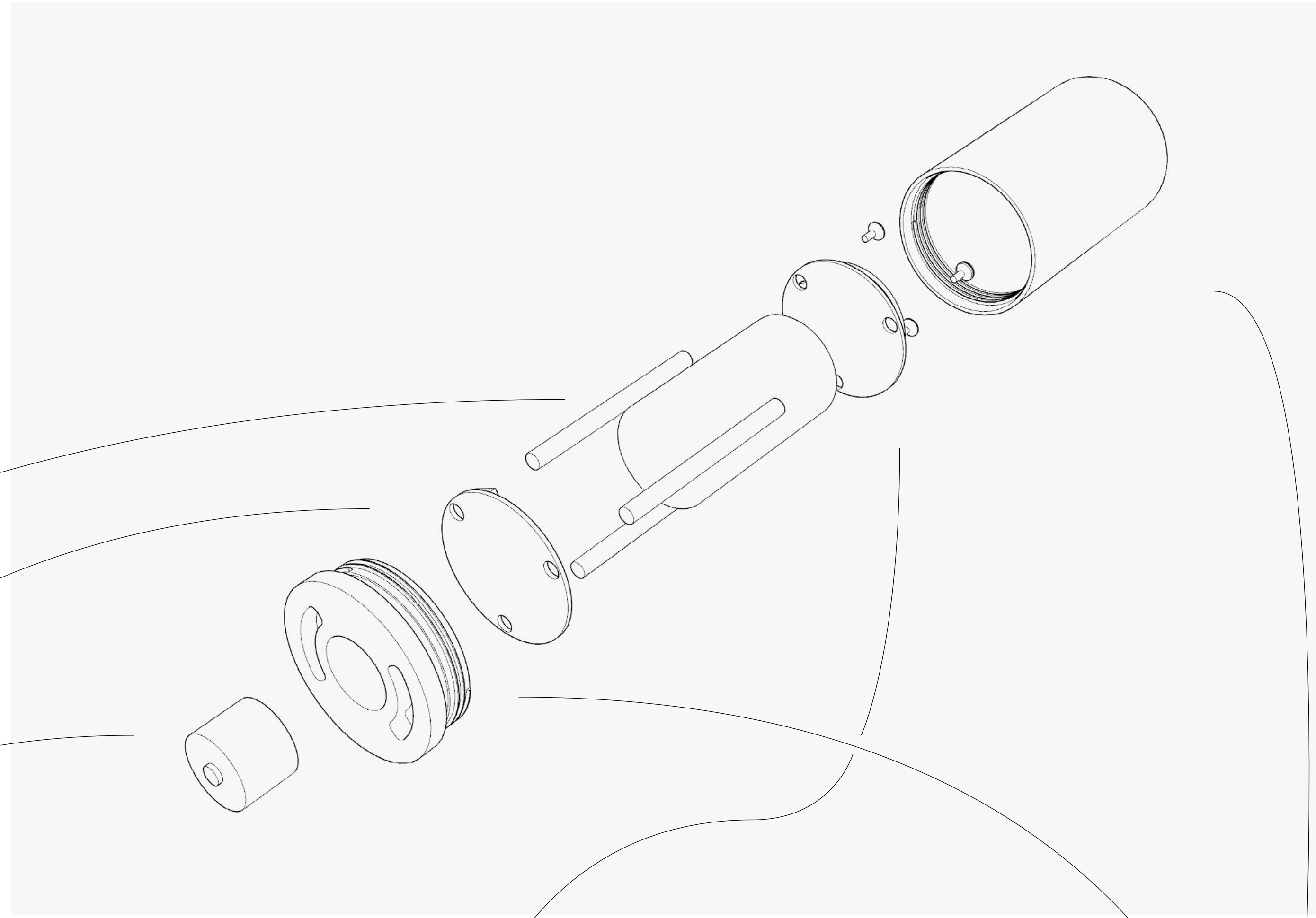
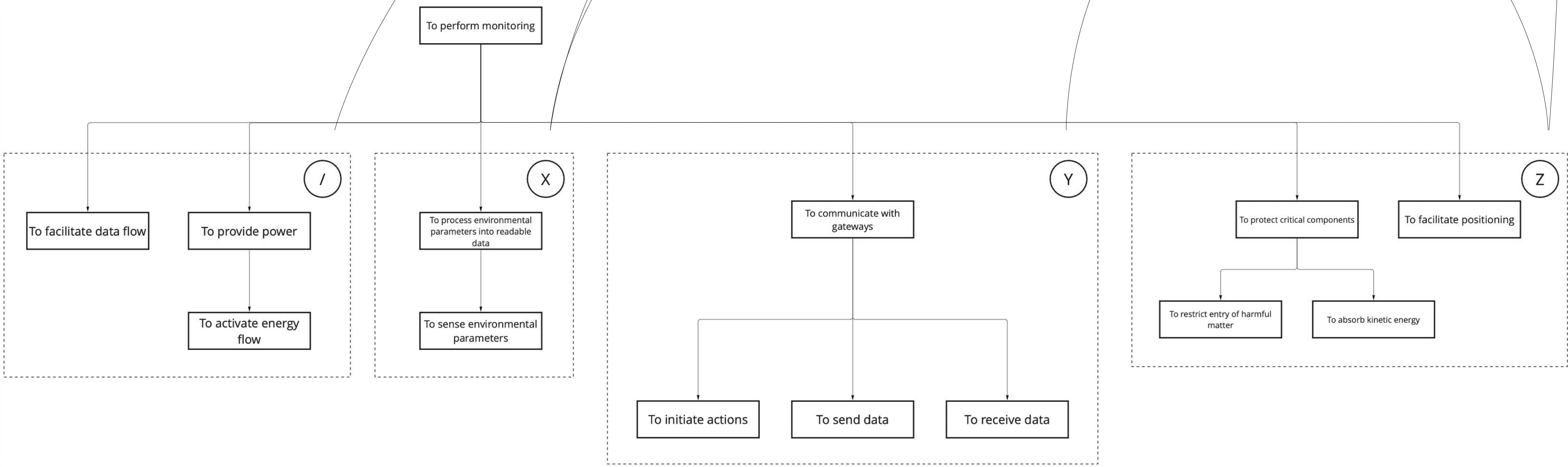


Figure 43: Components with their corresponding functional packaging



5.3 recycleability

The guidelines for Design for Recycling (Appendix G) can be used to evaluate the sensor node's recyclability. Some aspects of the current sensor node are detrimental to its recyclability, while other considerations are in favour of recycling. Below is an overview of observations from the product assessment. These are in addition to the aforementioned remarks on disassembly and accessibility.

Product level

+ The product is already particularly modular with low complexity of disassembly.
– It is tedious to reach the battery, a component that is required to separate before mechanical recycling.

Component level

+ There are no permanent fasteners being used in the assembly of the sensor node. This makes separation of materials easier to achieve.
– Ferrous fasteners (steel bolts and threads) are inserted in non-ferrous metal components (figure 44, aluminium spacer and stainless steel base). This way, ferrous waste streams will get polluted.
– Moreover, neodymium magnets are press fitted into the non-ferrous stainless steel base, likely polluting the ferrous waste stream.

Material level

+ Only a single kind of polymer is used, PBT. This polymer has a density that is distinguishable from the two main e-waste plastics, HIPS and ABS (TNO, n.d.) (figure 45) and is therefore likely easy to separate with flotation techniques.
– Lastly, PBT is considered recyclable, however the global supply of PBT contains virtually no recycled fraction (Granta, 2021).

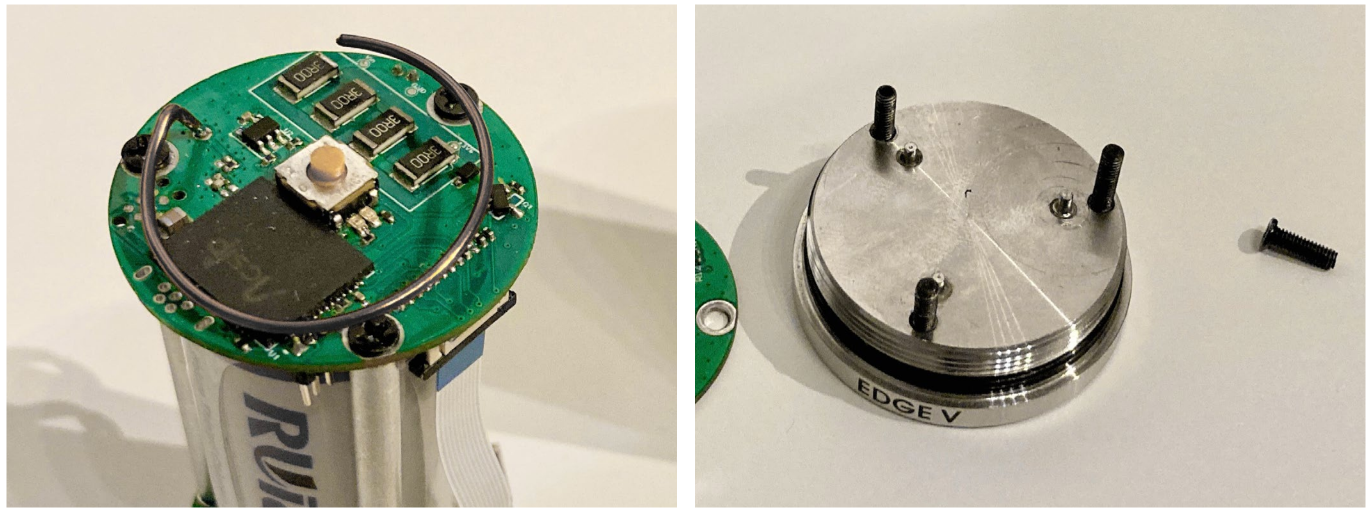


Figure 44: Left, steel screws in aluminium spacers; right, steel threads in non-ferrous stainless steel base

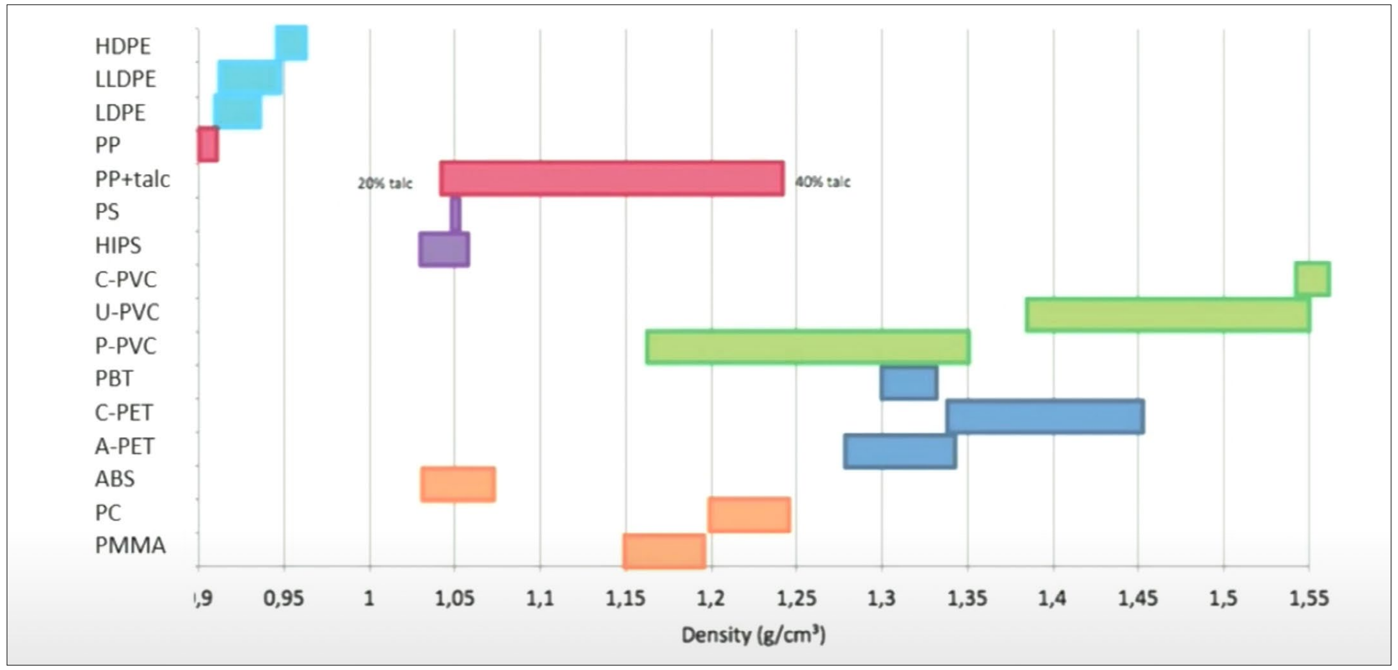


Figure 45: Density variety of polymers (Delva et al., 2019)

5.4 Implementing circularity

The assessment of the current sensor node shows how it performs regarding the design principles and the areas of improvement can be concluded:

- The time and steps that are needed for the disassembly sequence of the key components can be reduced. This will lead to faster access of these components.
- The coupling between the sensor insert and base component can be reduced. This can make the sensor node more resilient in future changes.
- Several aspects hamper this product's recyclability. Improving this can reduce the product's embedded footprint.

Tackling these are aspects can facilitate embedding of the product into the circular strategies and reduce the product's environmental impact.

Another consideration is the financial effects of these improvements. Estimating the implications on the total costs of operating circular strategies can indicate if there is an economic incentive as well.

Comparing a situation where a take-back agreement is in place to one where sensor nodes would be discarded, it shows that for Edge Dynamics there would be a significant reduction in the total operational cost possible, in between 4,6% - 12,8% (table 7), depending on the communication interval (Appendix C2 [confidential]). Assumed here is that 1500 sensor nodes are in operation over a period of 10 years and that only batteries will be swapped for new ones in order to extend the product lifetime.

Table 7: Difference in costs between use-oriented model and sales model (1500 sensor nodes)

	10 year (30 min. Communication interval)	10 year (1 hour Communication interval)	10 year (15 min. Communication interval)
Total 10 years use model (EUR)	1745230	1731677,5	1772335
Total 10 years sales (EUR)	1858750	1811500	1999375
Difference in percentage (%)	106,50	104,61	112,81

Looking at the economic benefits that would be gained from improving the efficiency of maintenance and repair actions, no significant cost reductions seem to surface. If the replacement time for sensor nodes is improved (from 4,7 minutes (282 seconds) (see Appendix C2 [confidential]) to an assumed 10 seconds), the total costs could be reduced with 0,38% (see table 8). This is in case of a communication interval of 15 minutes, which would see the greatest reduction.

Table 8: Estimations cost reduction of decreased replacement time of sensor node

	10 year (1 hour Communication interval)	10 year (30 min. Communication interval)	10 year (15 min. Communication interval)
Cost difference (replacement time = 282 seconds)	14438,99	14560,26	14802,82
Cost difference (replacement time = 10 seconds)	14424,97	14532,24	14746,77
Difference in percentage (%)	100,10	100,19	100,38

In addition, comparing the current repair time of more or less 4 minutes (180 seconds adding one minute for miscellaneous activities) to an assumed achieved repair time of 30 seconds, the sensor nodes would be repaired 8 times faster. However, integrating this improvement in maintenance cost, only a 0,41% (table 9) would be saved on the total costs of operation. Again, this is in case of a communication interval of 15 minutes, which would see the greatest reduction.

Table 9: Estimations cost reduction of decreased repair time of sensor node

	10 year (1 hour Communication interval)	10 year (30 min. Communication interval)	10 year (15 min. Communication interval)
Cost difference (repair speed = 240 seconds)	14464,40	14577,33	14803,21
Cost difference (repair speed = 30 seconds)	14433,91	14537,00	14743,19
Difference in percentage (%)	100,21	100,28	100,41

Now, increasing the amount of sensor nodes in operation, from 1500 to 15000, shows more interesting results. Respectively, the replacement time would see a cost reduction of 2,04% while the optimised repair time would account for a reduction of 2,19% (Appendix C2 [confidential]). Combining these improvements would show the highest cost savings.

The cost reductions give an indication of how much might be saved on total costs by optimising the current sensor node for circular strategies. As can be noted, the reductions are highly dependent on the situation; with a lifespan of 8 years or longer, the savings in increasing the efficiency of disassembling and repairing sensor nodes are minor when put into perspective of the total costs. It is when sensor nodes require repair more often when an optimised sensor node brings significant cost reductions. In addition, the scenarios are highly dependent on the scale of operations, where the more sensor nodes in operation, the more can be gained from optimising the design.

What can be concluded is the following:

- Repairing sensor nodes is a strategy that can significantly reduce the costs of operation for Edge Dynamics
- Improving the speed of repair does not seem to have any significant economic benefit
- Improving the speed of (un)mounting the sensor node does not seem to have any significant economic benefit. (Assumed here is that in case of RWS, sensor nodes are exclusively mounted using magnets, therefore improving the (un)mounting speed is irrelevant)

DESIGN VISION & GOALS

The aim of redesigning the sensor node is to make it resonate more with the circular economy. The product assessment in chapter 5 has shown the current product architecture can be optimised to provide easy access to the sensor node's key components. In order to change that, a redesign will be proposed. The goal of redesigning the sensor node is the facilitation of circular strategies, mainly repair, reuse of components and recycling. Therefore, the following vision statement can be formulated:

Industrial IoT should be integrated into the circular economy by embedding the revival and reuse of obsolete sensor nodes and its components into the manufacturing process, while rethinking their end of life.

Concretely, the design goals can therefore be described as follows:

Quick access to key components. Improving the accessibility of the product's key components and reducing their disassembly time in order to facilitate circular activities (by methods such as surfacing, clumping and trimming (de Fazio, 2021)). Expelling mechanical fasteners and cables as much as possible as they are responsible for a significant amount of disassembly time.

Improved recyclability. Although the considerations for functionality retention strategies will positively impact product aspects that are also in support of recycling, there are still other requisites of importance to recycling that have to be taken into account. In case of a sensor node ending up as e-waste, it has to be possible to separate the battery manually with standard tools (e.g. power drill, flathead screwdriver) and wearing work gloves.

5.5 List of Requirements

The requirements of the functionality retention strategies are merged with the product context requirements and general requirements. Together they form the final list of requirements each concept direction has to abide by.

REQUIREMENTS

Functionality retention strategy requirements:
- Replaceable (standardised, e.g. C-type) battery
- Amount of cables as low as possible in battery disassembly sequence
- Amount of fasteners as low as possible in battery disassembly sequence
- Sensor node replacement possible with work gloves
- Grip area for counter force during unmounting
- Battery can be unlpugged for storing

Product architecture requirements:
- Antenna at highest position (relative to electronic components) within product
- Antenna with point radiation character
- Accelerometer as close as possible to centre of mass

General product requirements:
- Use of weather resistant materials
- Ingress protection IP67
- Analog activation (e.g. button)

ATEX certification requirements:
- Non-static casing material (e.g. PBT)

Recycling requirements:
- Use recylced materials where applicable
- Avoid mixing of materials (e.g. ferrous and non-ferrous fasteners)

The list of requirements will be used to assess concept ideas on how well they resonate with these requirements. In order to do this, a basic lay-out of the envisioned architecture of each of the concept directions is considered.

Conclusion

RQ1.1: HOW CAN THE CIRCULARITY OF IIOT PRODUCTS BE ASSESSED?

- At a system level, Edge Dynamics' sensor node can be projected onto the context of potential circular business applications. This helps to reveal the requirements for these scenarios.

- At a product level, design principles can be distilled that support circular business applications. Edge Dynamics' sensor node can be assessed on the metrics related to the identified design principles. The HotSpot mapping sheet and Disassembly Map tool can be used to analyse aspects related to circular activities. The results show which activities and disassembly steps to target.

- At the material level, considerations for recycling are identified and can be improved on using Design for Recycling guidelines.

It is therefore essential to understand the context in which the product will operate. Still, many if not most design principles underly functionality retention strategies and are therefore of relevance to the sustainability of the sensor node.

RQ2: WHAT ARE THE PRODUCT ASPECTS OF EDGE DYNAMICS' IIOT PRODUCTS THAT NEED TO BE REDESIGNED TO BETTER FIT THE CIRCULAR ECONOMY?

From the variety of analyses, several points of improvement have been identified in order to accommodate the funcionality retention strategies. These will be used as input for a redesign of the sensor node.

- **Quick access to key components.** Improving the accessibility of the product's key components and reducing their disassembly time in order to facilitate circular activities (by methods such as surfacing, clumping and trimming (de Fazio, 2021)). Expelling mechanical fasteners and cables as much as possible as they are responsible for a significant amount of disassembly time.

- **Improved recycleability.** Although the considerations for functionality retention strategies will positively impact product aspects that are also in support of recycling, there are still other requisites of importance to recycling that have to be taken into account. In case of a sensor node ending up as e-waste, it has to be possible to separate the battery manually with standard tools (e.g. power drill, flathead screwdriver) and wearing work gloves.

Furthermore, the redesign needs to abide by the list of requirements.

6

Ideation on redesign

This chapter explains how the requirements and goals uncovered in the previous chapters are used as input for generating potential ideas, using methods such as design-be-analogies and How-Tos. The ideas that have the most potential are pursued and several concept directions are proposed. Conclusively, four concepts are shown and a choice is made using the product profile method.

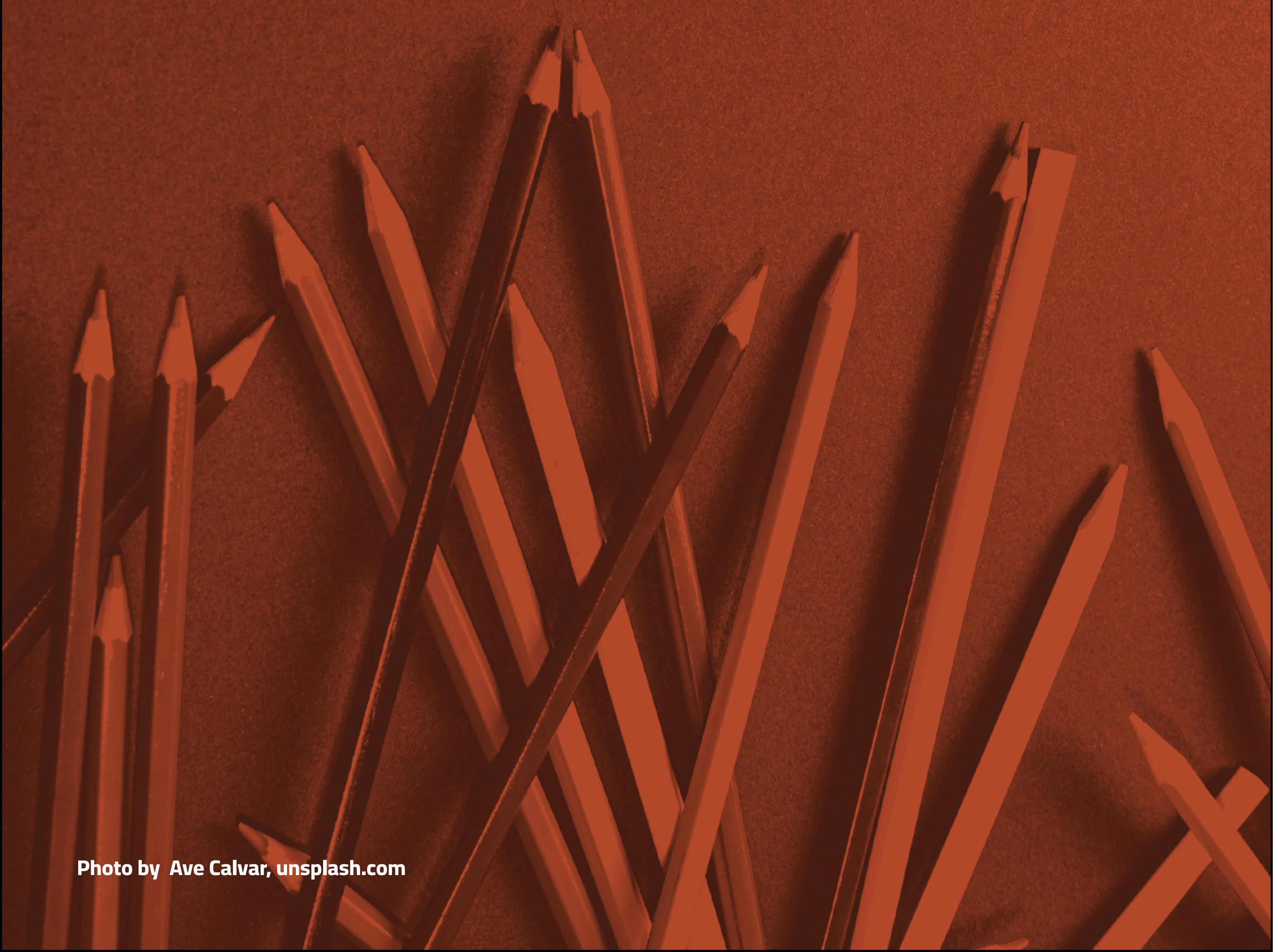


Photo by Ave Calvar, unsplash.com

6.1 Architecture configuration

The possible configurations of sensor nodes seems to be abundant. However, several considerations mentioned in chapter 3.1 limit the options. The position of the PCBs is more or less restricted within the node. It is fundamental that the placement of the antenna is kept as high as possible in relation to other components, while the accelerometer is preferably kept as close as possible to the centre of mass for measuring vibrations. In practice, this is close to the steel base and as such at the bottom of the sensor node.

This creates a space between each of the PCBs. Connecting them to bridge information exchange and power would require the use of cables, something that is preferably avoided. Positioning PCBs close to each other gives the opportunity to connect them without using cables. Instead they can be connected using board-to-board connectors integrated onto the circuit boards. This way, some configurations avoid the use of cables between PCBs.

In addition, the spatial orientation of the sensor node can either be a laying or upright orientation. The latter experiences more instability in a scenario where vibrations are at play (Hassan, personal communications, February 2022) but has a smaller footprint or bottom envelope, likely making it more versatile to mount. Moreover, a laying configuration places the antenna at a lower point than an upright position, possibly leading to a decrease in range and putting the antenna closer to metal objects (such as the equipment the sensor is mounted on) that could absorb signals (figure 46) (Kooijman, personal communications, March 2022).

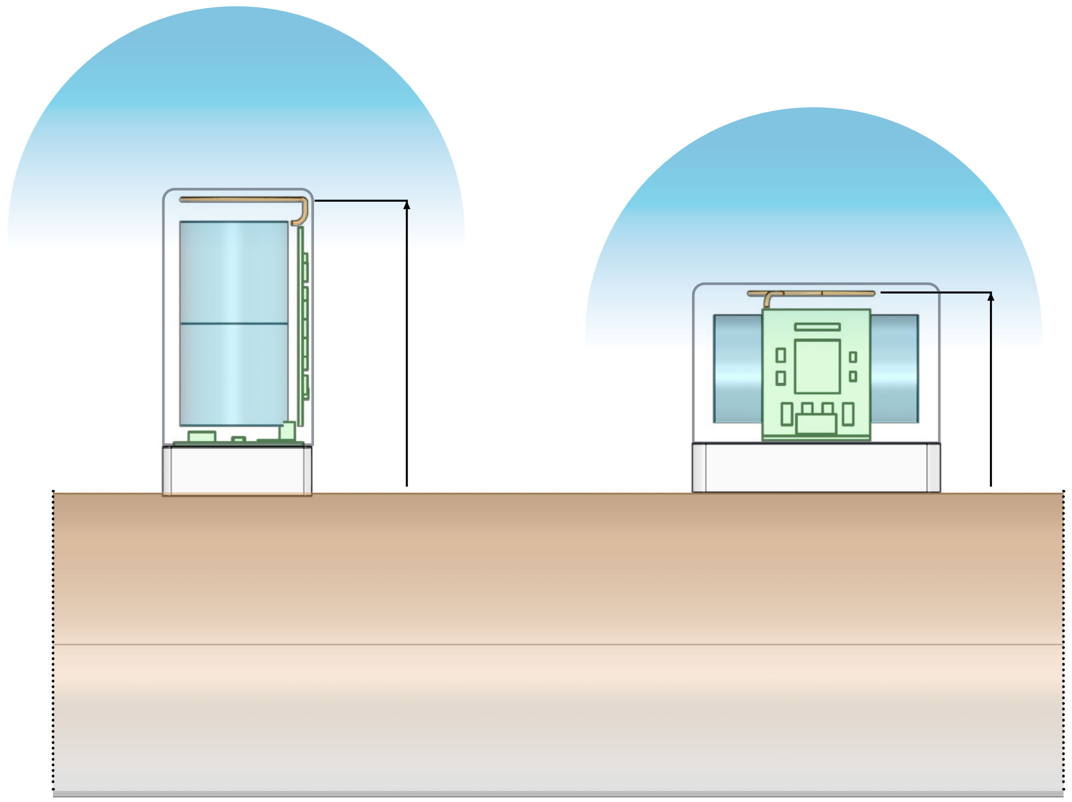


Figure 46: Height difference antenna between spatial positions when mounted on pipe

In addition, a laying position will naturally lead to an asymmetrical shape of the base component. The current sensor node uses a symmetrical base component (round) and can therefore be threaded. This is a simple and effective way to fasten the casing to the base. An asymmetrical base component cannot be threaded and would require a different form of clamping the casing onto the base, such as screws or clips. This would complicate the product or slow down disassembly.

Figure 47 shows an exploration of possible configurations. The aforementioned considerations favour an upright position and as such will be considered during ideation.

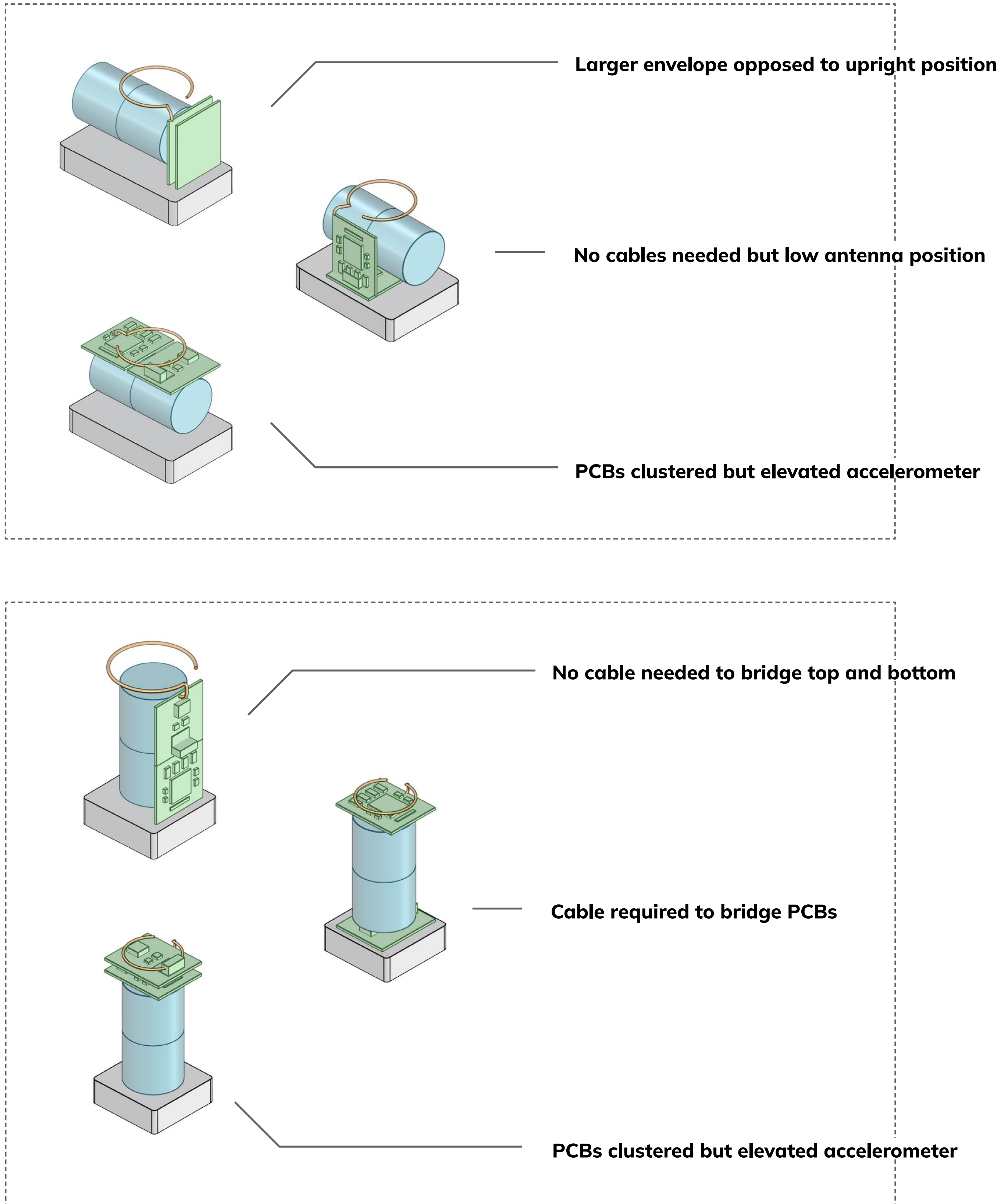


Figure 47: Architecture configuration exploration

6.2 Quick access to battery

As mentioned in chapter 3.3, three scenarios are possible in which sensor nodes are handled with the intent of retaining their functionality. Firstly, sensor nodes can be repaired at the location where they are installed. A technician disassembles the product and addresses the malfunctioning component. This situation could for instance arise if sensor nodes are operated independently by the customer and no spare nodes are present. In this situation it will be assumed only the battery is exchanged.

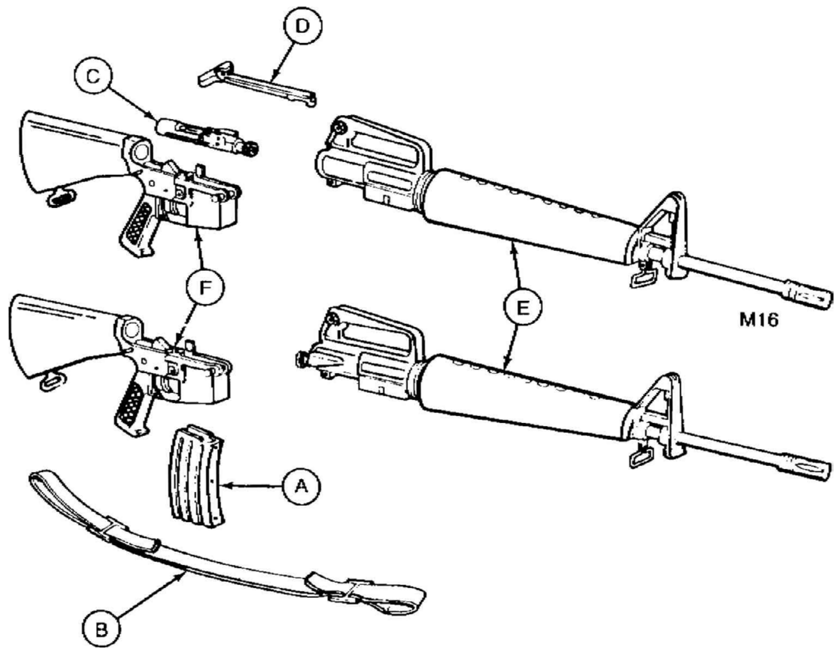
Secondly, sensor nodes can be replaced by a working node and taken back by the site operator or Edge Dynamics. Now, sensor nodes are addressed in a maintenance facility. The first two options are explored separately as they are different in their context and this will likely result in distinct ideas. In the first two situations it will be assumed only the battery is exchanged.

A third option is discarding malfunctioning products. For the third option, the removal of the battery is essential before the product can be recycled.

The generation of ideas will be facilitated How-Tos brainstorming sessions with fellow students. How-Tos are questions that related to the problem, written down and surrounded by possible ideas. In addition, by looking at different situations (analogies), novel ways of structuring the product architecture are possibly encountered that can be applied to the design space of sensor nodes.

SCENARIO: REPAIR IN FIELD
For repairing sensor nodes in field, a similar context can be described as that of infantry soldiers; they are either back at base (at the manufacturer or a site maintenance centre) or they are 'in-field' (installed at an industrial site). Their equipment, specifically the standard-issue rifle (figure 48) that is used by regular infantry, has to be maintained during operations and possibly in combat by soldiers if it malfunctions. It therefore has to be unambiguous how to take it apart and it needs to be possible to do this in field.

Repairing sensor nodes in field, meaning at the location where the node is operating, comes with clearly different priorities than if the sensor nodes would be repaired in a maintenance facility. Considering gloves in combination with an unpredictable surrounding puts emphasis on excluding small parts that need to be loosened or removed and requires sufficient surface area that can be grabbed or manipulated. As such, avoiding any (dis)assembly steps that require precision is important here. The ideas that seem to agree with this the most are continued.



As the sensor node will be maintained on site, the full disassembly can be separated from a 'field strip'; a target component disassembly made as simple as possible to reach and replace the battery at the location of the sensor node.

To effectively take apart a firearm 'in-field', the use of captive pins (fasteners that cannot be completely removed and therefore lost) and the use of bullets as tools to loosen fasteners is common. Possibly using the spare battery as tool in the disassembly (field strip) if necessary; this part is always present during maintenance.

Figure 48: Firearm in its field-strip state; access to components that could require maintenance in-field (Bet Fitchett, n.d)

Executing maintenance in field calls for practicality and ease and thus a key concept for this scenario can be to have interchangeable modules with clear roles (figure 49).

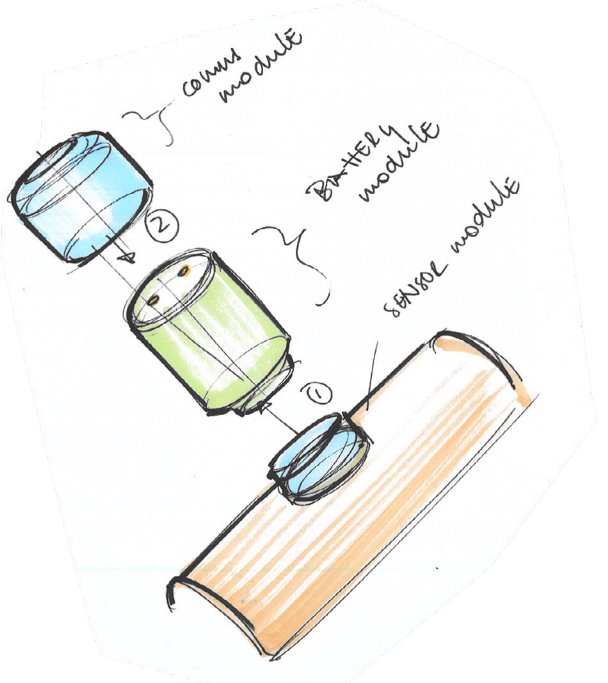


Figure 49: splitting the sensor node into separable modules can make repair quick

An alternative for making handeling easier and quicker is the using the unambiguous battery replacement that is familiar to anyone. A similar replacement sequence known from e.g. power tools makes it foolproof to changing the battery. Moreover, a generic battery slot can be used to develop add-ons such as wired adapters or solar cells that fit the battery slot (figure 50).

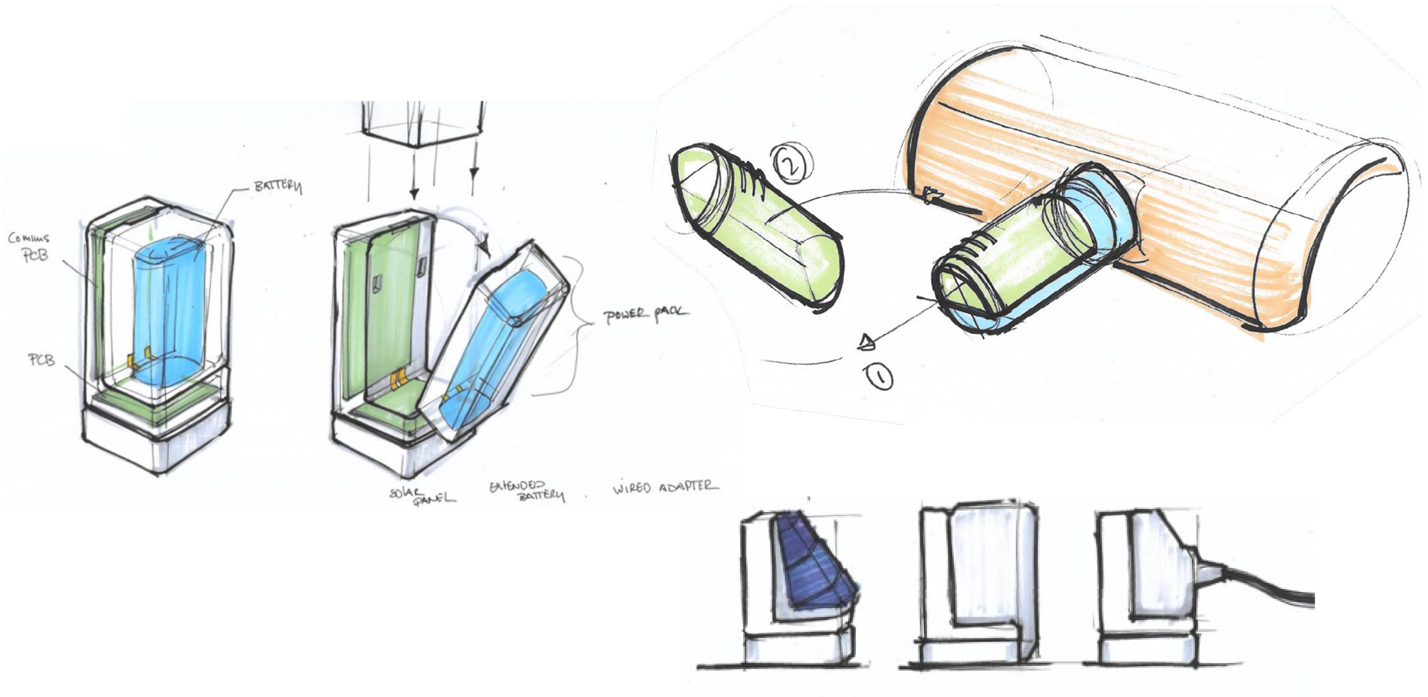


Figure 50: A general battery slot could be used in the future for varying add-ons

A top-bottom architecture could cluster most components, so that these do not bother the technician during repair. However, when the casing is removed in order to access the battery, caution is required as the sensor insert in the base is still connected. This could result in a snapped cable if pulled too hard on removal. By hinging the base with the casing, this can be prevented (figure 51).

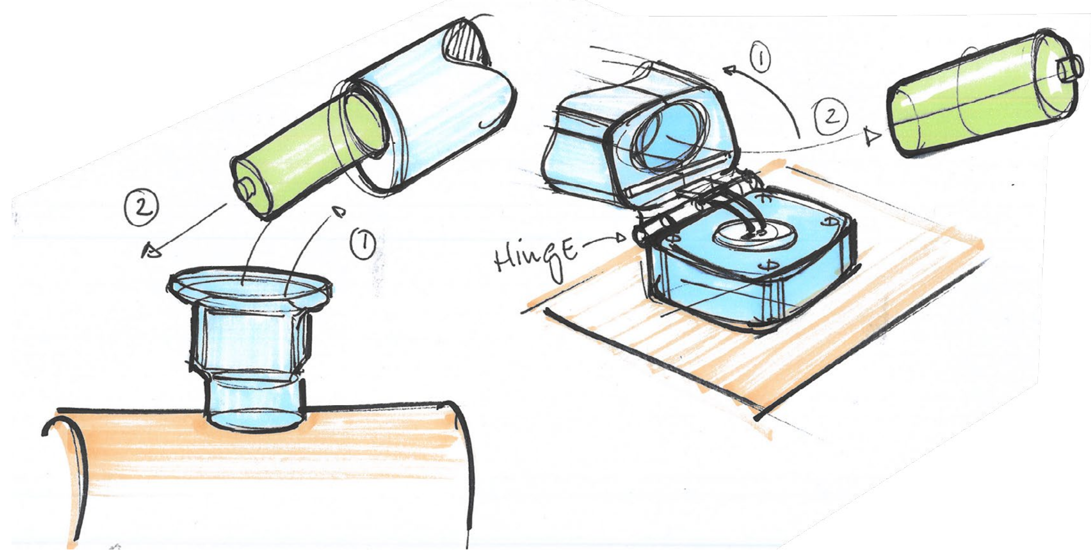


Figure 51: Pogo pins or hinged casing to safely open a sensor node in field.

Similarly, the battery could be extracted from the top, as removing a cap from a bottle. This way, the crucial connection between the sensor insert are not bothered (figure 52).

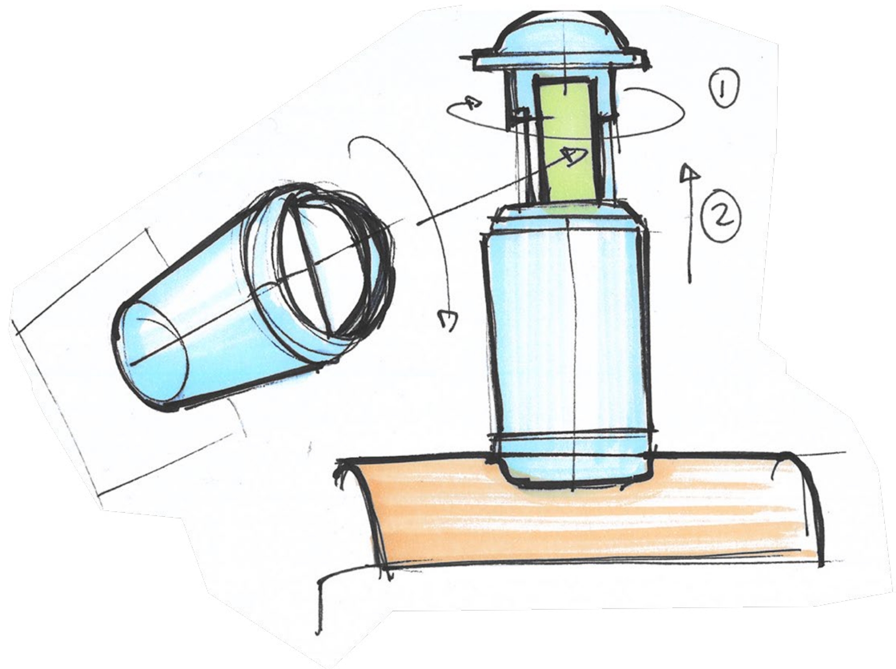


Figure 52: Quick extraction of battery from top

CONCEPT DIRECTIONS: IN FIELD REPAIR
The first direction (figure 53) that seems promising features a battery pack that can be pulled straight off similar to power tools. As the battery defines the size of the sensor node due to its relative size, an external battery would be easy to remove with gloves. This configuration is probably the fastest battery replacement possible.

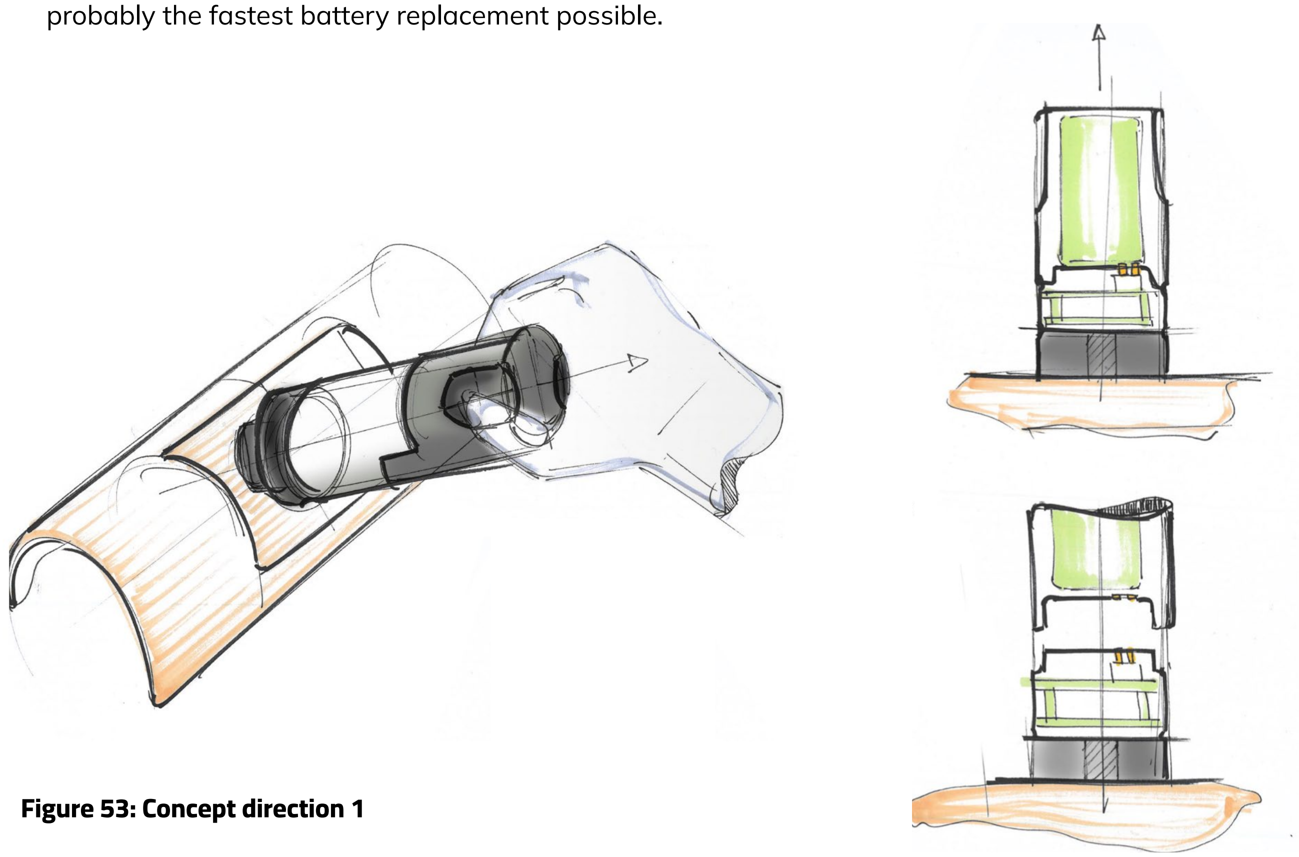


Figure 53: Concept direction 1

The second direction (figure 54) for in field repair has an internal battery that is accessed from the top. By screwing off a large 'wing nut' like cap, the battery can be pulled out. This avoids the challenge of protecting the battery terminals from corrosion.

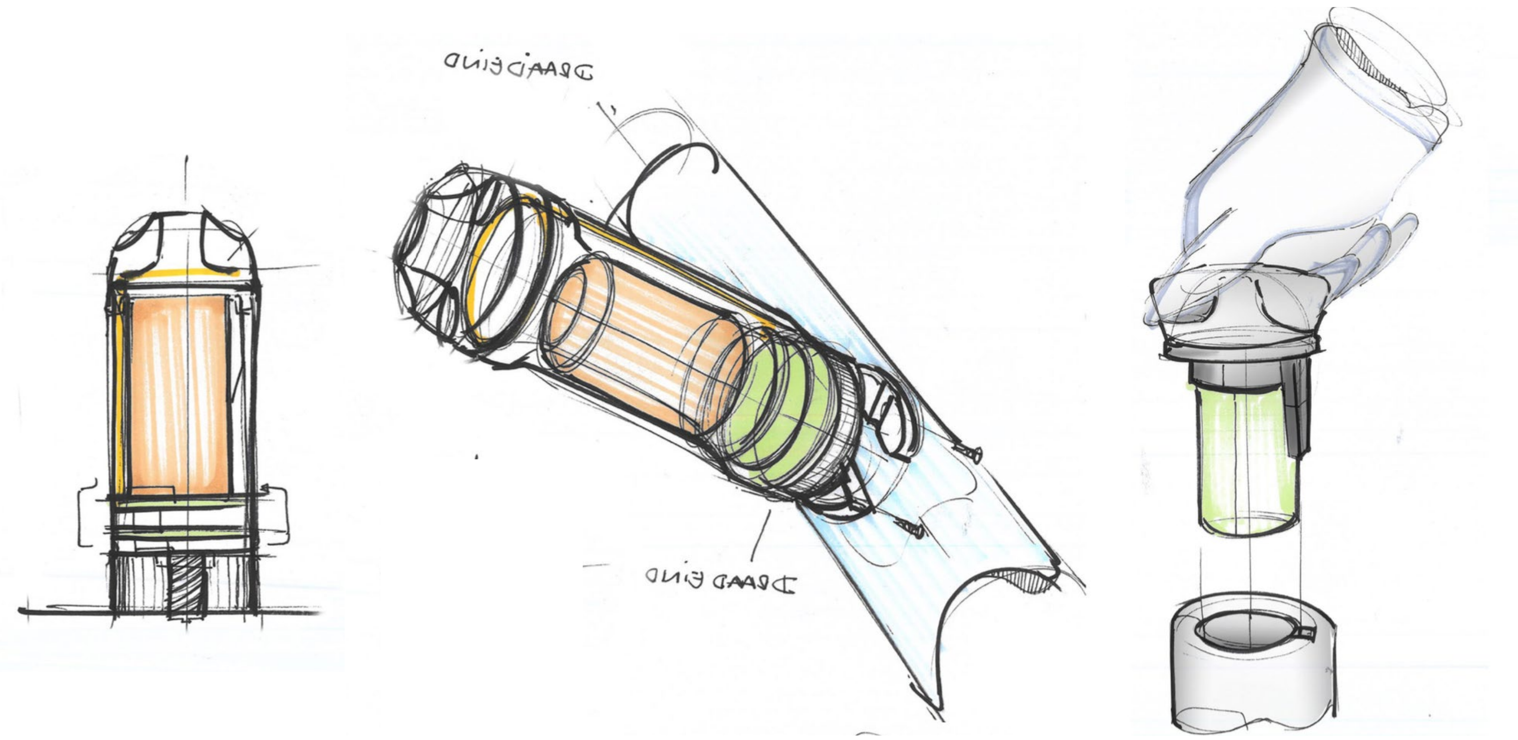


Figure 54: Concept direction 2

SCENARIO: REPAIR IN CONTROLLED ENVIRONMENT
Repairing sensor nodes elsewhere after exchanging them in field for a working sensor node comes with a different emphasis. Repair facilities back at an on-site maintenance centre or at Edge Dynamics can be considered an operating room (figure 55), where a controlled environment is created for either general maintenance. Here, sensor nodes can be disassembled and repaired without the unpredictability of an industrial environment. Moreover, a technician can make use of his or hers fingers without the inhibiting effect of gloves. The operating room can also be specifically oriented at sensor nodes, at Edge Dynamics' own facilities. Just as a surgeon would use specially tailored tools for specific operations, Edge Dynamics could use special tools to ease the disassembly of sensor nodes (figure 56).

Figure 55: Controlled environment (Brainlab, n.d.)

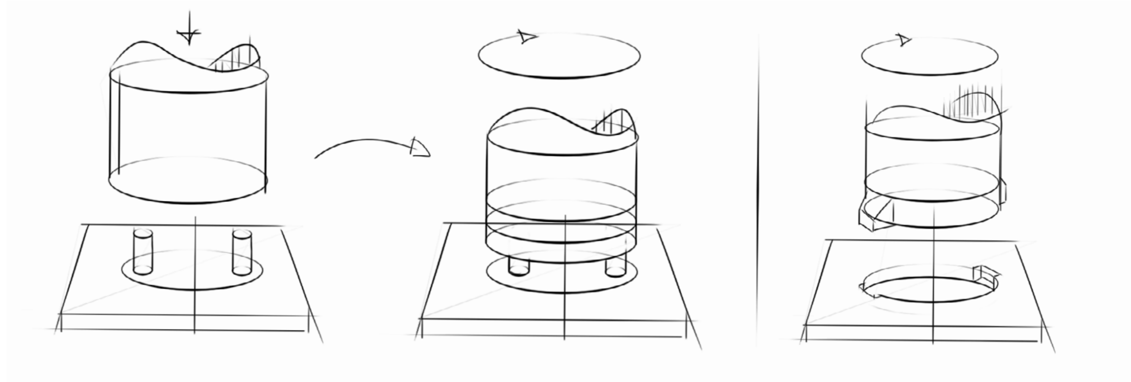


Figure 56: Tool idea for loosening the base; pins that fit the base on the bottom (left); notches on the base that fits a cut-out

Besides quick access to the battery, ideation in this scenario can be more focused on the optimisation of the current sensor node's architecture, as the intricacies mentioned in chapter 5.2 are of importance here as they hamper disassembly even in a controlled environment. The following page shows exploration of ideas for a repair in a controlled environment.

Organising clusters of components inside the sensor node can make it easier to focus the repair job. When components that are in the way of the battery are clumped together, they can be removed at once, revealing the battery (figure 57). An insert that separates the different component clusters could prioritise the components. The battery is accessed first, if the rest needs to be accessed a dedicated tool can be used to remove a skeleton structure holding the remaining components.

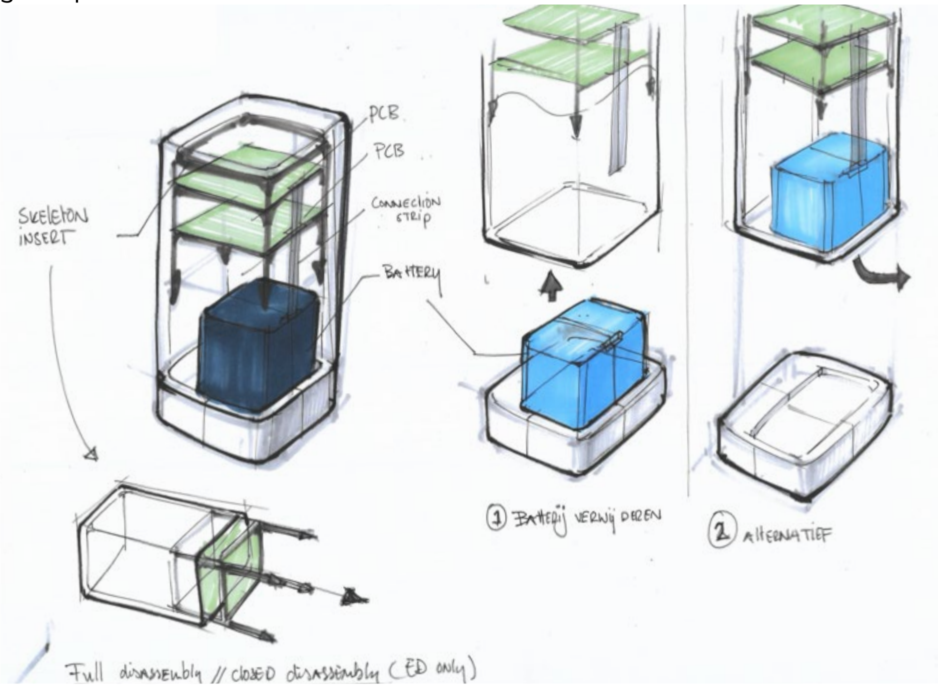


Figure 57: splitting the sensor node into separable modules can make repair quick

The product assessment showed cables are inhibiting disassembly. This idea shows the battery and PCB cards that can be inserted in slots and are powered and communicate through a rail (figure 58). This practically eliminates the use of cables and speeds up replacement.

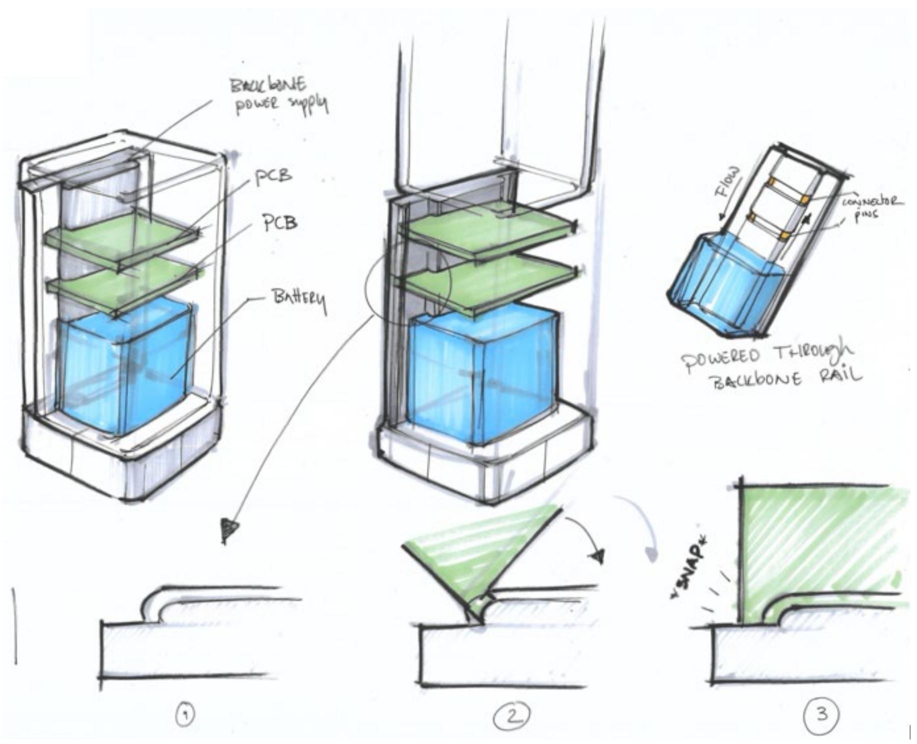


Figure 58: A general battery slot could be used in the future for varying add-ons

CONCEPT DIRECTIONS: CONTROLLED ENVIRONMENT

The most promising ideas or combinations of idea elements are pursued. The first concept extracts the battery from the top unscrewing and removing the casing first. Inside, the components are secured by a structure form fitting the battery and PCBs (figure 59). The battery is connected on the outside through the structure with the PCBs. The antenna increased in length slightly to be wide enough for the battery to pass through.

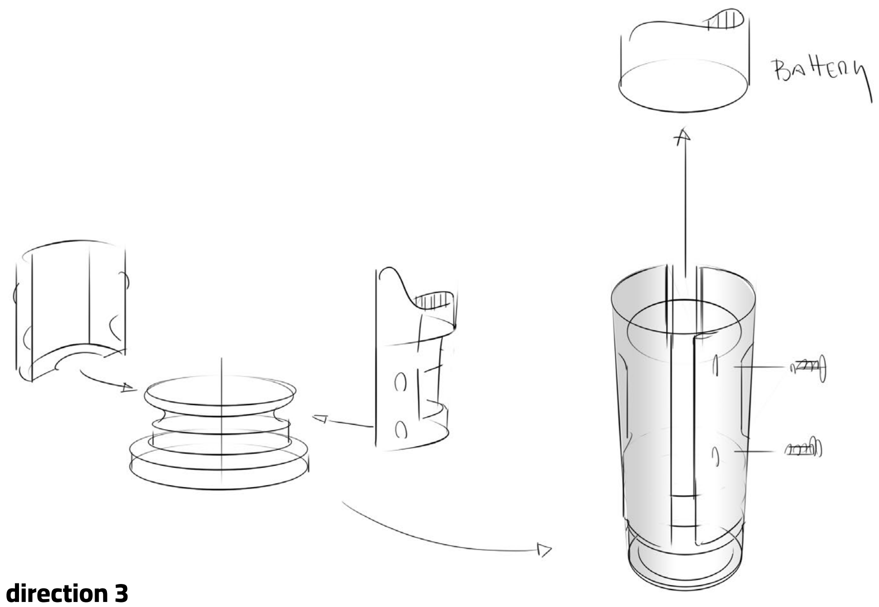


Figure 59: Concept direction 3

The second concept is again accessed in a similar fashion as the original sensor node, by unscrewing the casing from the base. This reveals a structure that holds the battery on one side and the PCBs on the other. A clip secures the battery in place. Removing the clip and the connected battery cable releases the battery (figure 60). This concept takes a few extra steps compared to the previous concepts but does not require adjustments to the antenna or risks contact with it.

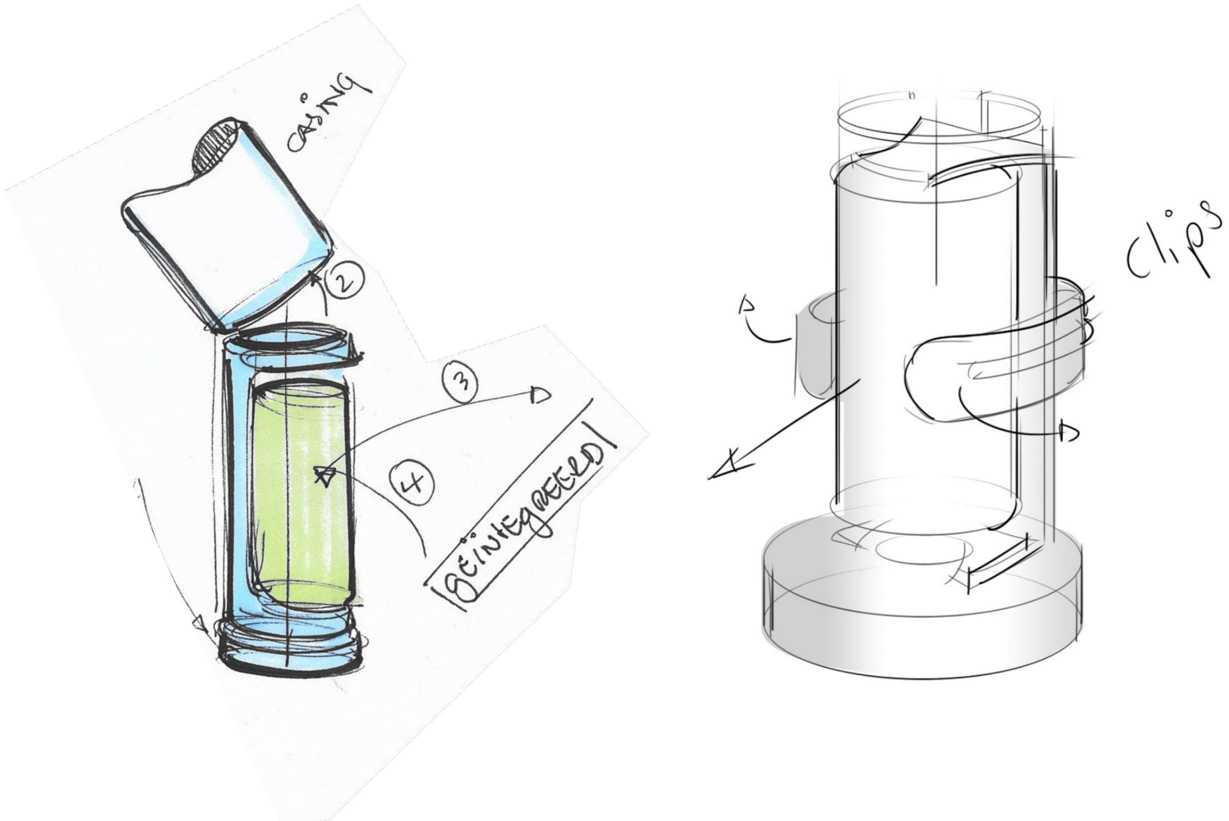


Figure 60: Concept direction 4

6.3 Conceptualisation

From the ideation, four concept directions seemed the most promising. In order to compare them sufficiently, their probable configurations are explored and determined. With the use of 3D mock-ups, a rough approximation can be made of the parts necessary to compile each concept. This way I can estimate the possible increased impact and complexity that comes with a redesign targeted at quick access to the battery. This also forces me to think on their feasibility.

CONCEPT 1: BIN
The first concept has an externally accessible battery pack (figure 61). Due to the positioning of the antenna, the battery is located on the side. To make it more comfortable, extended 'wings' protruding from the pack could increase the surface area to grip (figure 62). This pack is secured in place on both sides by spring pressured clips similar to that of a power drill's battery pack. By grabbing the battery pack and depressing the clips can it be removed in a single movement. Alternatively, the battery could be friction fitted with rubber pads and the battery terminals to reduce the complexity of the product housing.

As the battery pack should be tightly secured, a significant force is likely exerted on the sensor node. Pulling perpendicular to the mount of the node could put unwanted forces and moments on the mount. A lip on top of the casing could be used to grab and exert a counter force.

This concept emphasises the ease and speed of exchanging the battery in field.

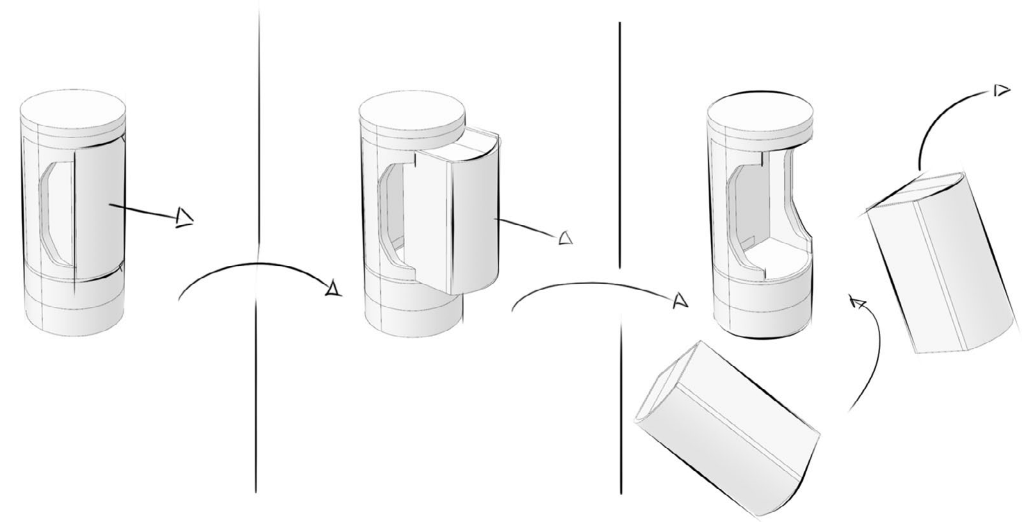


Figure 61: Battery swap sequence concept 1

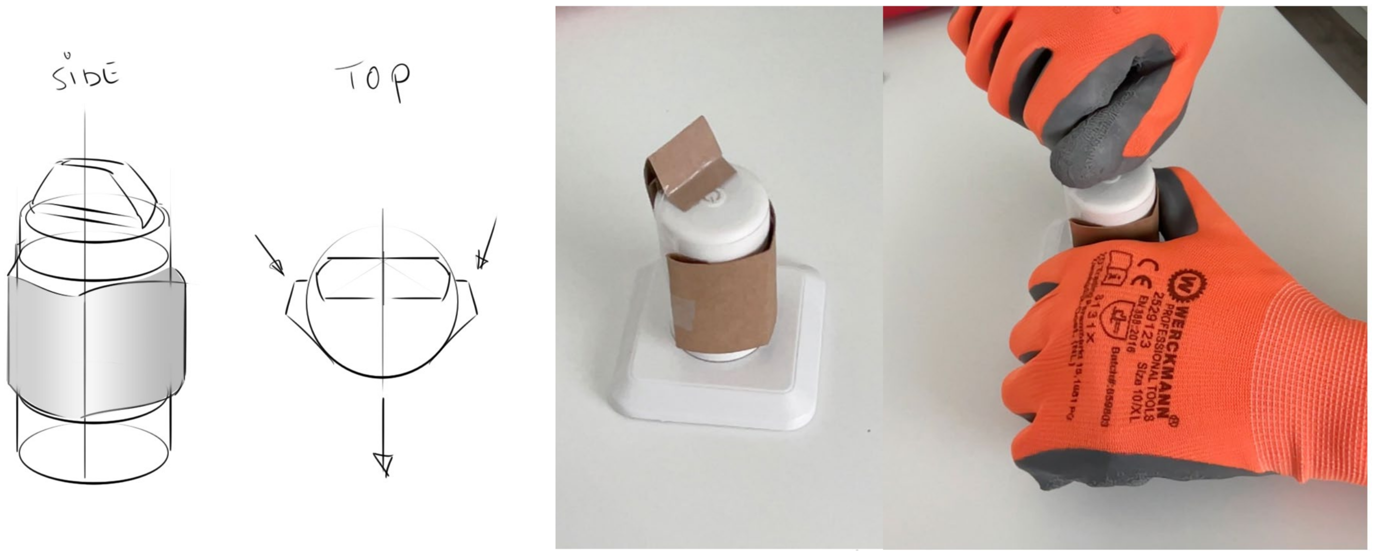


Figure 62: Enlarged surface area for improved grip; notch to provide counter-force

An estimation is made of the product's components required to realise the concept. This is shown in figure 63, with the accompanying part count.

With an external battery pack, additional waterproof housing is required and increases the part count extensively. Using reversible fasteners increases the amount of screws necessary. Moreover, the many seals required to keep internal components from water ingress (elastomers) increases the use of non-recyclable materials.

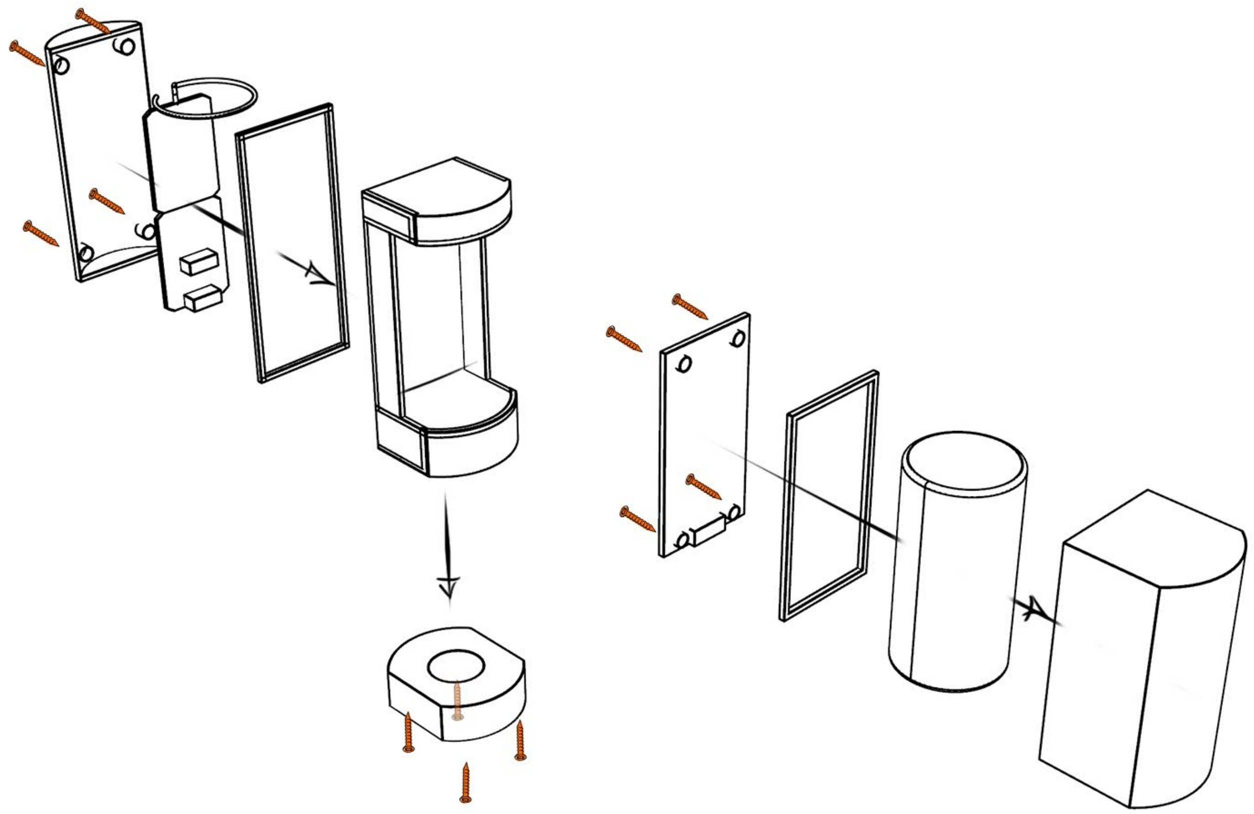


Figure 63: Exploded view of concept 1

Table 10: Probable component count concept 1

	Amount	Material / type
Screws	4	Steel
Cables	1	JST
Seals	3	Elastomer
Product-specific components	5	Polymer (PBT/ABS); stainless steel

CONCEPT 2: REACTOR
The second concept is accessed from the top by unscrewing a sealed cap (figure 64). This cap is connected by the seal so it's secured to the product and cannot be lost by dropping it. Once removed, the cap reveals a bow that can be grabbed and pulled straight up in order to remove the battery. As the battery can only be inserted through a key hole, it is made sure this is done correctly. The plane with the key hole cutout also limits the battery insertion preventing the battery from being pushed farther than necessary.

By encapsulating the battery 'key', there is no need for exposed battery terminals as is the case with the first concept. A threaded cap is a reliable and simple way to seal the sensor node. To comfortably and effectively pull the battery from the node, sufficient grip area needs to protrude from the top after unscrewing the cap (figure 65). This increases the length of the sensor node. The rest of the node's housing provides ample surface area to comfortably grip while removing the battery.

The concept emphasises ease and speed of exchanging the battery in field.

Figure 66 shows an estimation of the required components. The various components that make the battery replacement sequence effective increase the product-specific part count significantly. This would require additional tooling and increases the use of polymers.

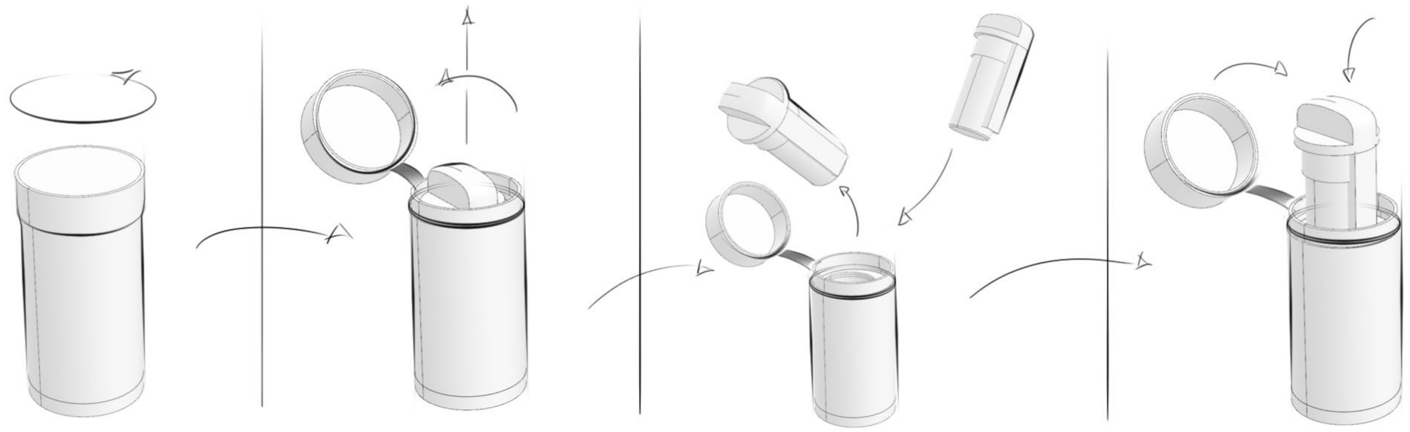


Figure 64: Battery swap sequence concept 2

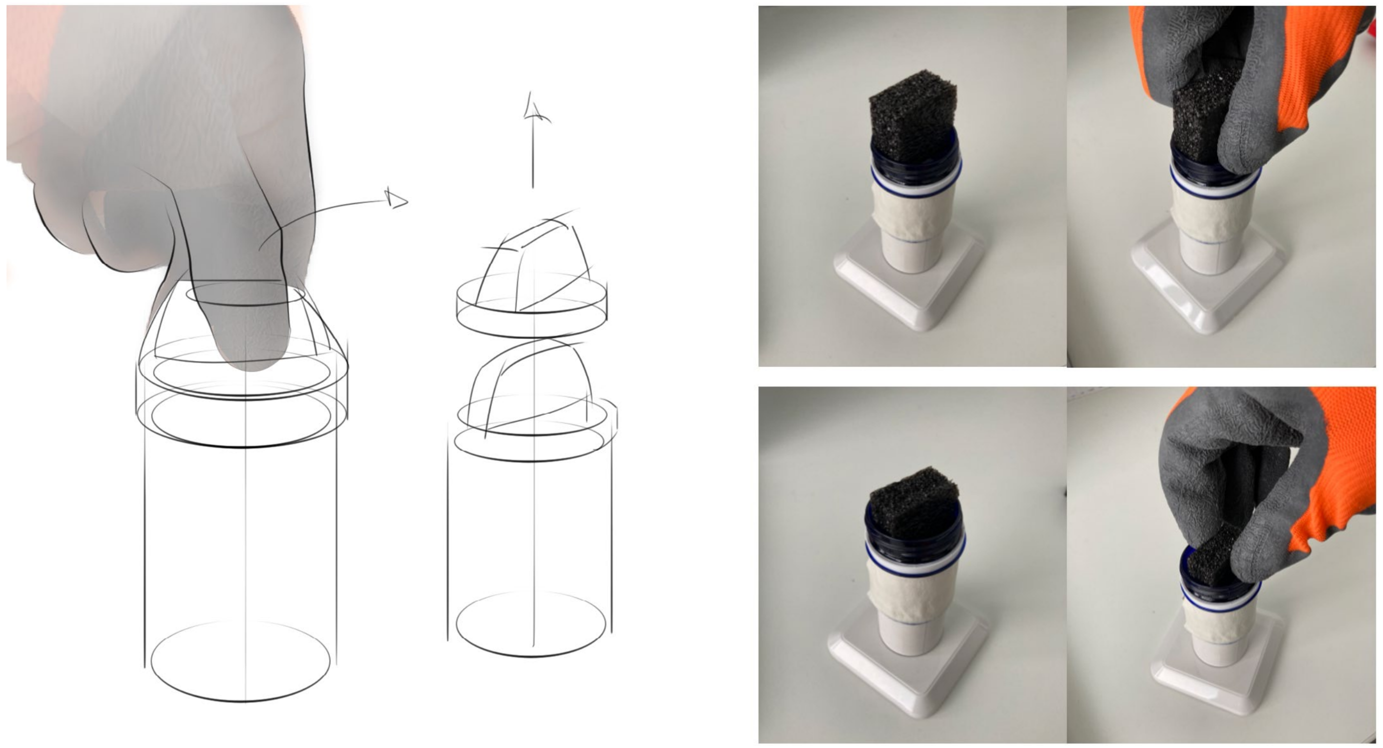


Figure 65: Large surface area for grabbing the battery

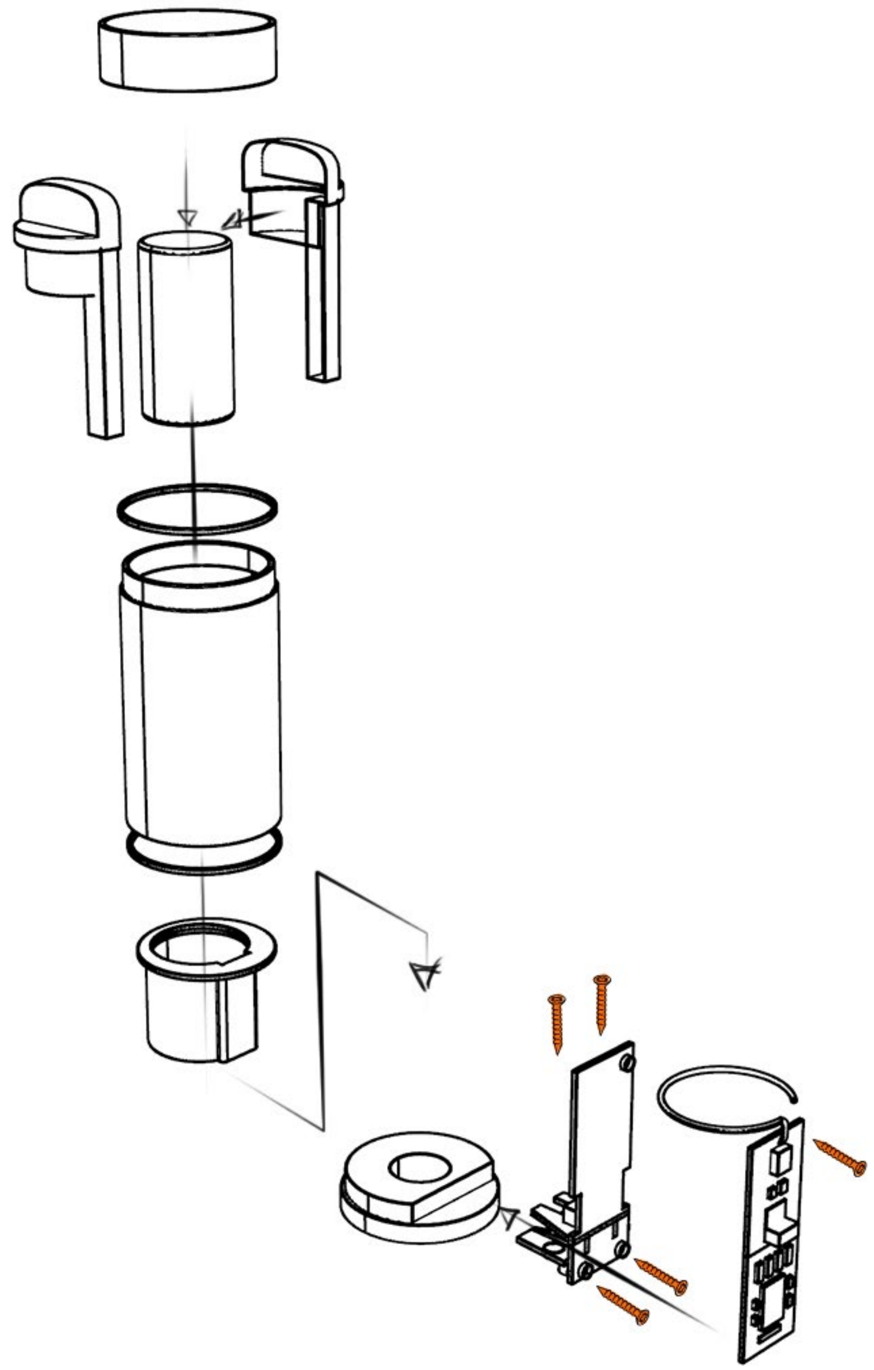


Figure 66: Exploded view of concept 2

Table 11: Probable component count concept 2

	Amount	Material / type
Screws	4	Steel
Cables	1	JST
Seals	2	Elastomer
Product-specific components	7	Polymer (PBT/ABS); stainless steel

CONCEPT 3: PLUNGER
The third concept is a sensor node that is accessed in the same way as Edge Dynamics' current sensor node, by unscrewing the casing. Inside, a structure is fastened to a notch on top of the base (figure 67). This structure houses the battery and PCB module. The battery is kept in place by a notch on the inside of the casing, exerting a force from above. This way, only the battery cable needs to be disconnected before removing it upwards through the antenna. The structure creates a slot on the outer side in which the PCB module can be slid. Securing this module on top with a screw prevents it from moving.

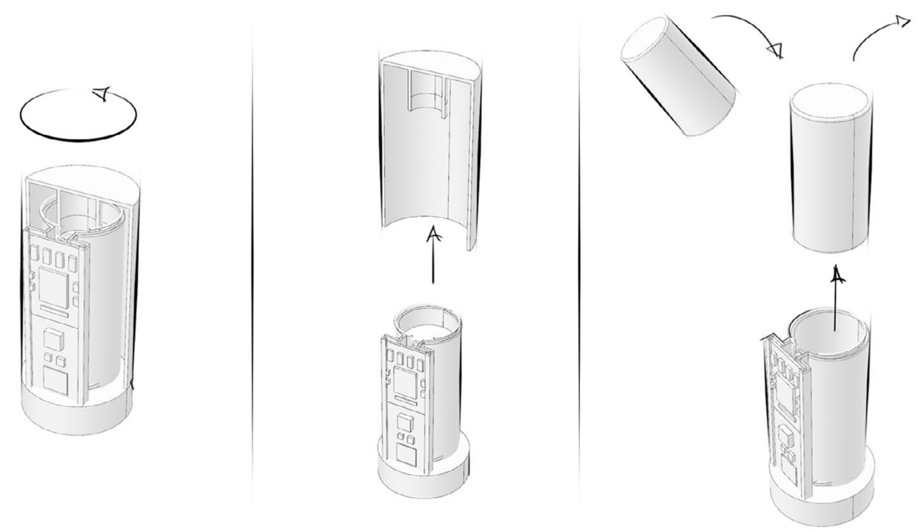


Figure 67: A general battery slot could be used in the future for varying add-ons

The two structure parts clamp together onto the base notch. This prevents the need for screws in fastening the structure onto the base.

This concept emphasises the reduction of components that hamper the accessibility of key components. Figure 68 shows an exploded view of the third concept.

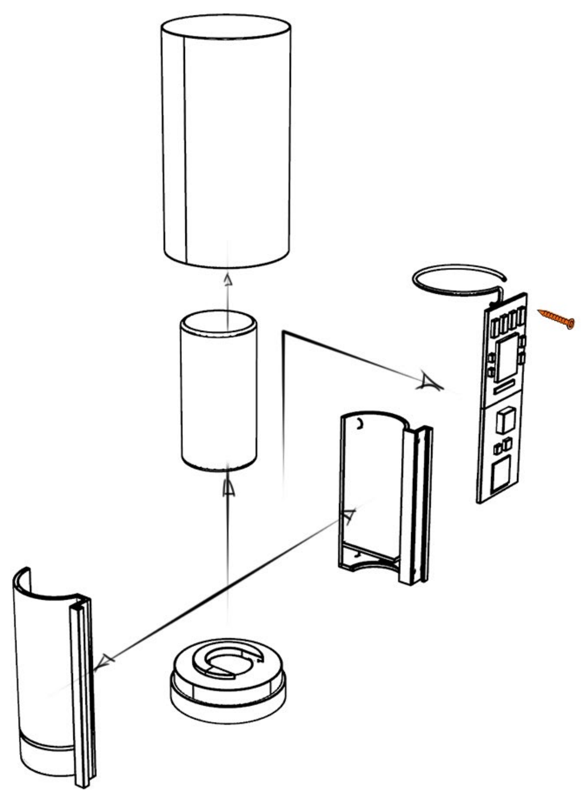


Figure 68: A general battery slot could be used in the future for varying add-ons

Table 12: Probable component count concept 3

	Amount	Material / type
Screws	4	Steel
Cables	2	JST
Seals	1	Elastomer
Product-specific components	4	Polymer (PBT/ABS); stainless steel

CONCEPT 4: CLIP
The last concept is accessed in the same fashion as the current sensor node as well. Unscrewing the casing gives access to the inside components. Here, a polymer structure is fastened by screws to the base of the node (figure 69). This structure provides space on one side for the battery that is secured in place by a clip. On the other side of the structure, the PCB module is secured. As the battery is removed from the side, the antenna stays out of the way of movement. Moreover, a wall protects the antenna from snagging onto anything when removing the battery.

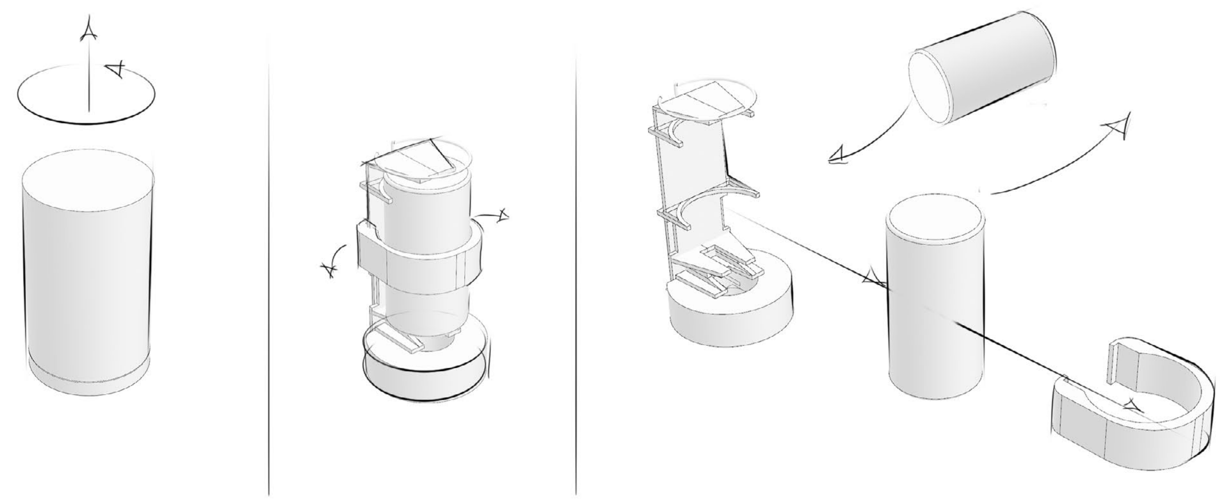


Figure 69: A general battery slot could be used in the future for varying add-ons

This concept emphasises the reduction of components that hamper the accessibility of key components. Figure 70 shows an exploded view of concept 4.

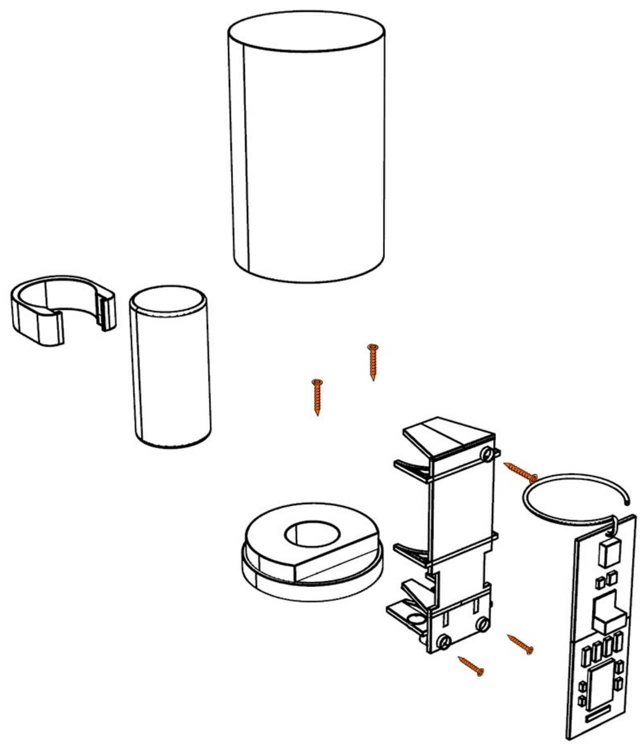


Figure 70: A general battery slot could be used in the future for varying add-ons

Table 13: Probable component count concept 4

	Amount	Material / type
Screws	4	Steel
Cables	2	JST
Seals	1	Elastomer
Product-specific components	4	Polymer (PBT/ABS); stainless steel

6.4 Concept choice

To make an educated guess which concept is best suited to continue, product profiles are made of each concept. This way, the concepts can be compared without fully detailing them. In a product profile, the concepts are ranked on several criteria, ranging from -2 to +2 points. The criteria are ranked from most important to least important and have a pre-defined standard. After assessing each concept on the defined criteria, the product profile can be established (see table 14). The product profile that scores highest on the upper criteria is picked as the most appropriate design to pursue (Roozenburg & Eekels, 1998).

The criteria are based on the list of requirements and wishes established in chapter 5.6. Concepts are not compared on their disassembly time or steps for the battery. As each concept is designed to minimise these aspects, it is assumed the differences will be negligible. Component count is based on tables 10-13.

The following criteria are used:

- **Impact: Are additional components required? Are they standardised or unique components? How many components is the concept composed of? An increase in the amount of components will both increase the concept's environmental and economic impact, where product-specific components are less favourable than standardised components.**

-2: High impact, 5 or more product-specific components, 20> total components
-1: Medium impact, 5 or more product-specific components, 15-20 total components
+1: Low impact, 3-5 product-specific components, 10-15 total components
+2: Similar impact as original, >3 product-specific components, >10 Total components

- **Complexity: Is the complexity of the concept higher than the original? Complexity in this case is the use of fasteners and cables that likely will negatively influence the (dis) assembly of the concept.**

-2: Highly complex: 10 or more fasteners and cables
-1: Complex: 8-10 fasteners and cables
+1: Average complexity: 5-7 fasteners and cables
+2: Low complexity: 4 or less fasteners and cables

Modularity: Are clustered components addressing the same role (functional grouping)? Are components that are subjected to change easily exchanged without influencing the rest of the product (component coupling)? Here, the PCBs, battery and base (insert) are determined to be subject to change.

-2: Poor: the concept is inflexible and its components are not functionally grouped
-1: Average: the concept has low flexibility and some components are functionally grouped
+1: Good: the concept has flexibility and most components are functionally grouped
+2: Excellent: the concept is flexible and all components are functionally grouped

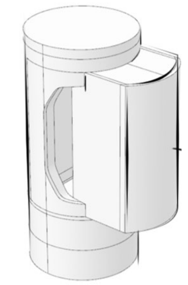
- **Recyclability: Are aspects of the concept hampering recycling? Are materials used that are suitable to be recycled?**

-2: Poor: the concept uses mainly non-recyclable materials and materials are tough to separate
-1: Average: the concept uses some recyclable materials and materials can mostly be separated
+1: Good: the concept uses mainly recyclable materials and materials can all be separated
+2: Excellent: the concept uses only recyclable materials and materials can all be separated

Table 14: Product profiles of concepts 1 - 4

Concept 1

	-2	-1	1	2
Impact		■		
Complexity	■	■		
Modularity			■	
Recyclability		■		



Concept 2

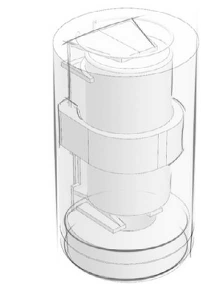
	-2	-1	1	2
Impact	■	■		
Complexity			■	
Modularity		■		
Recyclability		■		

Concept 3

	-2	-1	1	2
Impact			■	
Complexity			■	
Modularity		■		
Recyclability			■	

Concept 4

	-2	-1	1	2
Impact			■	
Complexity		■		
Modularity		■		
Recyclability		■		



From the product profiles can be concluded that concept 3 will have the lowest impact on the sensor node's architecture in terms of complexity and material. The configuration of this concept keeps the amount of components and total (dis)assembly steps not only low, but reduces them even. This is in contrast with the concepts intended for in field repair. These concepts facilitate quick in field repair at the cost of increased amount of components and material use.

In order to make a comparison with the original sensor node, the final concept needs to be worked out to the point it can be assessed in a similar fashion. The assessment will be elaborated on in the next chapter.

By making a prototype, the effectiveness of the proposed disassembly sequence can be tested (figure 71). At the same time this gives the opportunity to tweak the concept (figure 72).

Figure 71: Mock-up concept 3

From the prototype, the following can be learned:

- The battery wire collides with the antenna when it is inserted through the back seam. A slot for the battery wire on the front side can likely avoid this. At the same time will this position the battery wire closer to the PCBs, mitigating the bushing of the casing passed the battery wire.
- The Antenna is now hanging more or less free and could bend easily by brushing against it. Integrating a ridge in the top of the structure could keep the antenna in place and protect it.
- The structure halves are clamped surprisingly well in place. This gives confidence that the structure could be clamped and held together by snap-fits only, reducing the need for screws.

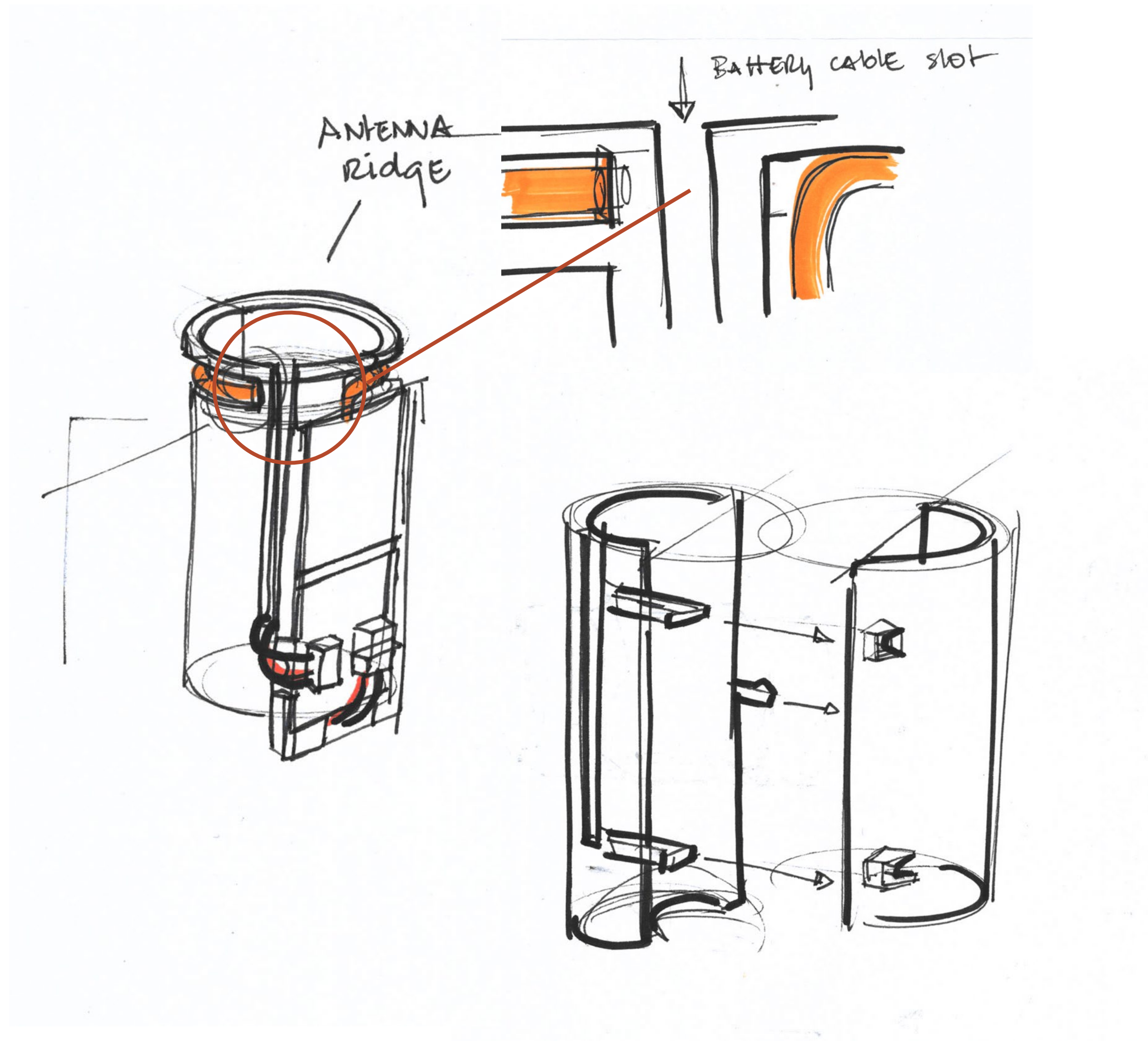
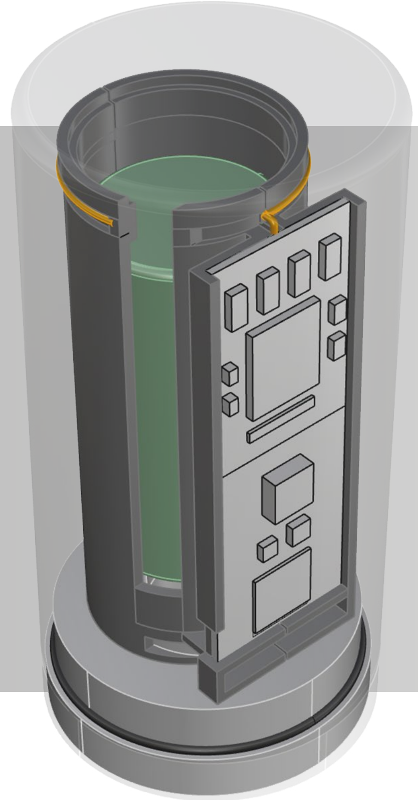
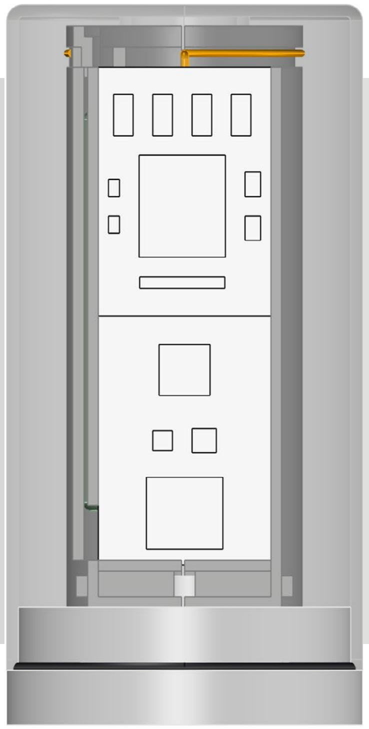


Figure 72: iteration sketches of concept 3

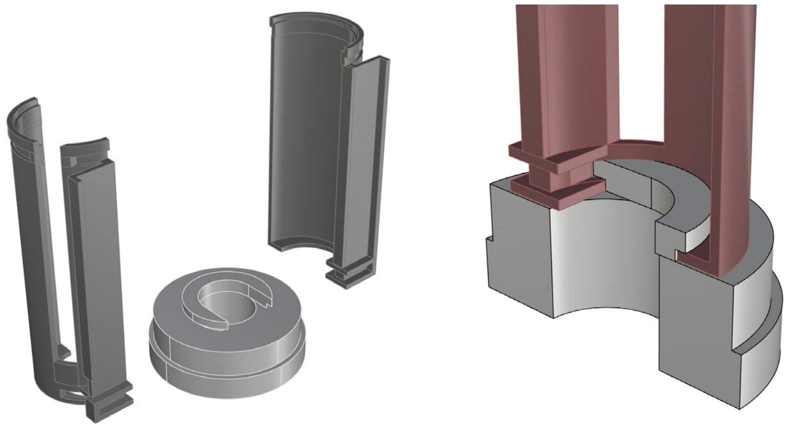
FINAL CONCEPT
The final design is based on the third concept and is a sensor node featuring fast access to the battery, while simplifying the product architecture. By creating a shape fit between the inside the casing and the battery from the top, only removing the casing and disconnecting the cable is enough to free up the battery. By turning the sensor upside down, the battery will simply fall out of the sensor.



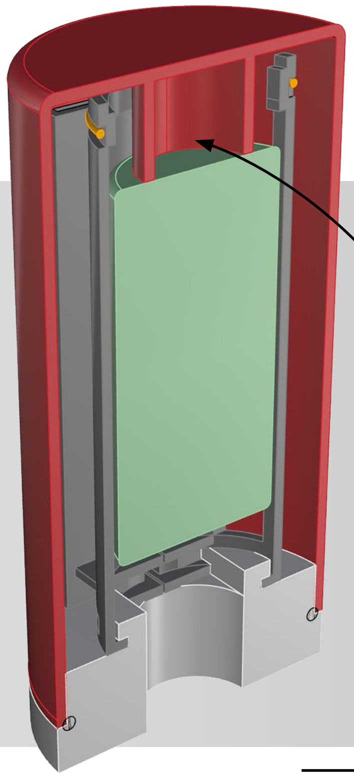


The PCBs are clustered as module, using integrated connectors. This avoids the use of a cable for data transfer.

The two structure halves can be injection moulded using a single mould. No undercuts are necessary, resulting in a simple component.

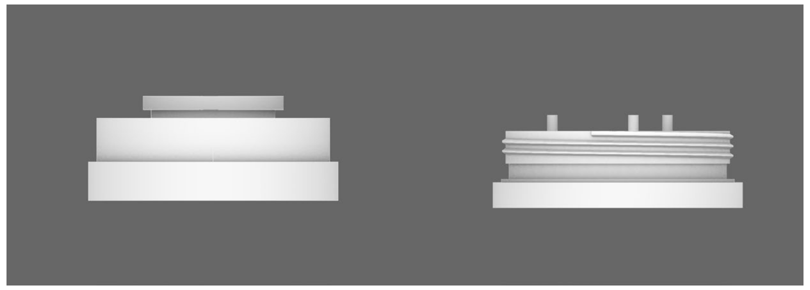


The redesigned base has a ridge that when sandwiched by both structure halves create a sturdy assembly.

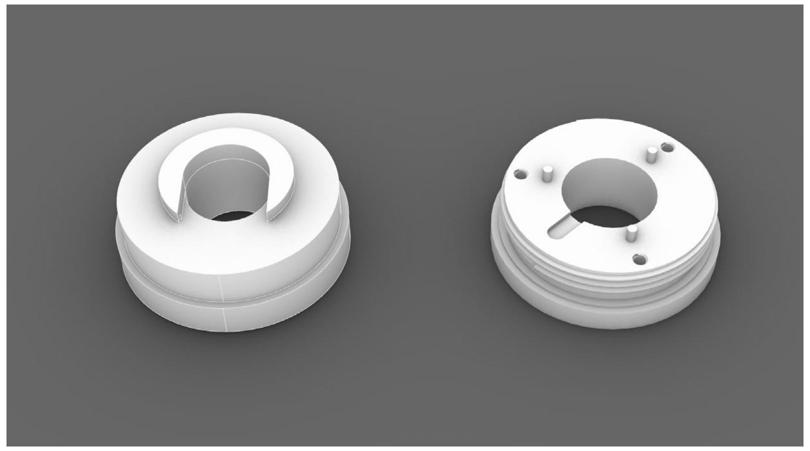


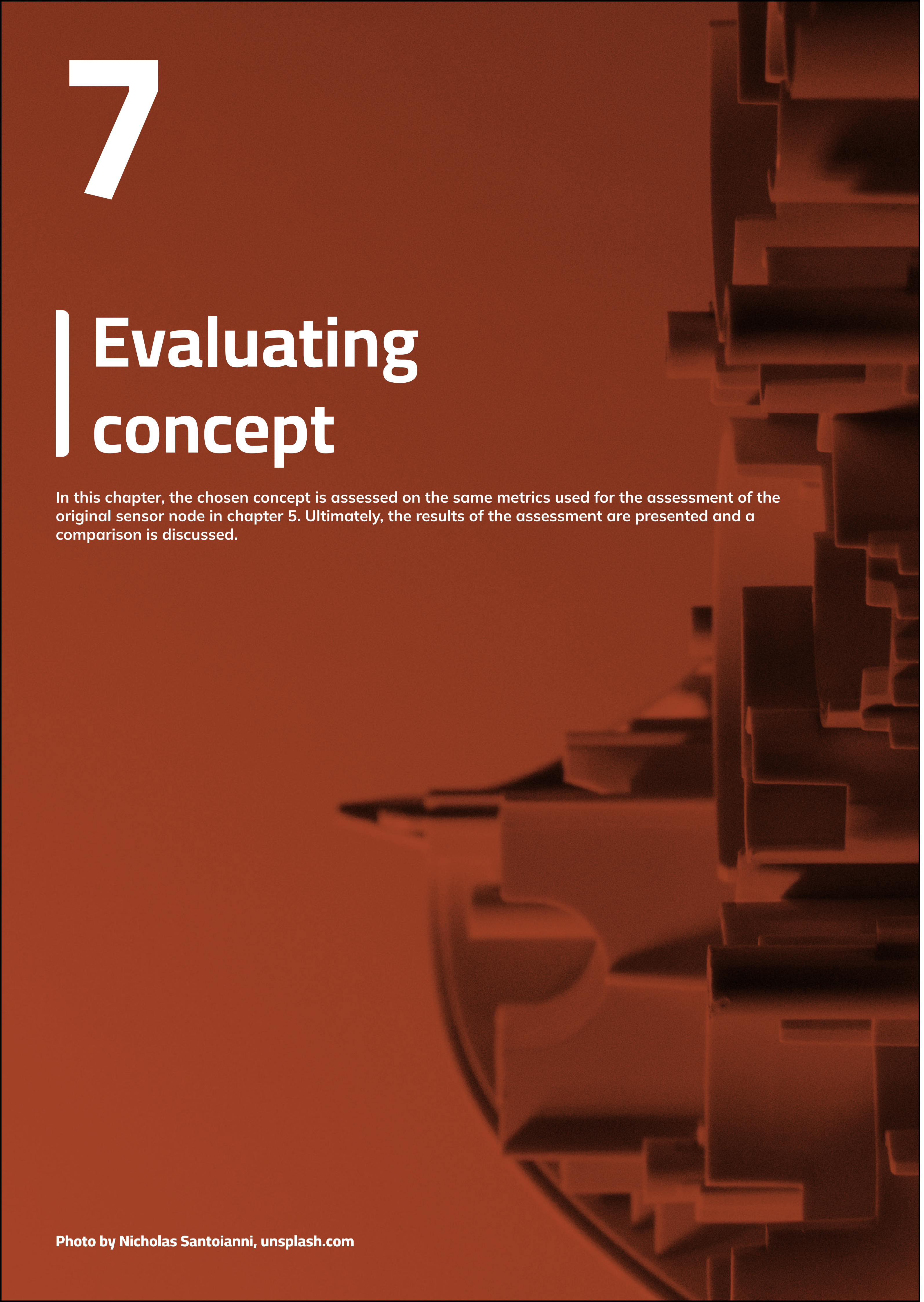
The casing now has an additional function of securing the battery in place. A flange is extruded from the ceiling of the casing, pressing down on the battery. This way, the battery is locked in position.

The new base has a taller exposed rim that creates a larger surface area. This makes it easier to unscrew the casing from the base.



The base of the final concept has been adjusted as it no longer requires threaded holes and positioning pins which are glued in place by the manufacturer.





7

Evaluating concept

In this chapter, the chosen concept is assessed on the same metrics used for the assessment of the original sensor node in chapter 5. Ultimately, the results of the assessment are presented and a comparison is discussed.

Photo by Nicholas Santoianni, unsplash.com

7.1 Accessibility and dis- & reassembly

In chapter 5.1, the PCBs and battery were designated as key components, where the battery is considered a priority part due to its high frequency of failure compared to other components. The PCBs contain toxic substances and valuable materials and are as such considered environmental and economic key components. The role of these components remains the same in the pursued concept, but their position has changed compared to the current node's architecture. Assessing the concept node on the same disassembly parameters as in chapter 5 can tell if the key components are now more accessible.

In order to assess the node, time estimates for each step were made based on either timing the disassembly steps using a prototype by analysing video recordings (figure 73), or they are projected from the times recorded of the original sensor node if the component is removed in a similar fashion. In Appendix H, the times are shown.

Figure 73: (Clockwise, starting top left) assembled prototype; disassembly of battery, full disassembly

ACCESSIBILITY: FINDINGS
The mean times of the individual disassembly steps show two steps that take significantly longer than other steps to perform. These two steps are not part of any target disassembly and are not needed for carrying out most circular activities.

The results (figure 74) show that removing the battery of the concept node takes a mean time of 17,0 seconds with an SD of 1,00 s. The PCBs are now removed together in one step as a sub-assembly. Disassembling the PCB module takes a mean time of 32,7 seconds with an SD of 3,79 s. The PCBs can then be separated by hand or using a spudger. Now, the communication PCB and sensor PCB are liberated in a mean time of 35,7 seconds with an SD of 4,04 s. The total amount of time needed to carry out a full disassembly of the concept node requires a mean time of 79,7 seconds with an SD of 4,04 s. Figure 75 shows that only two disassemly steps take significantly more time than other steps. These steps are do not appear in target disassemblies.

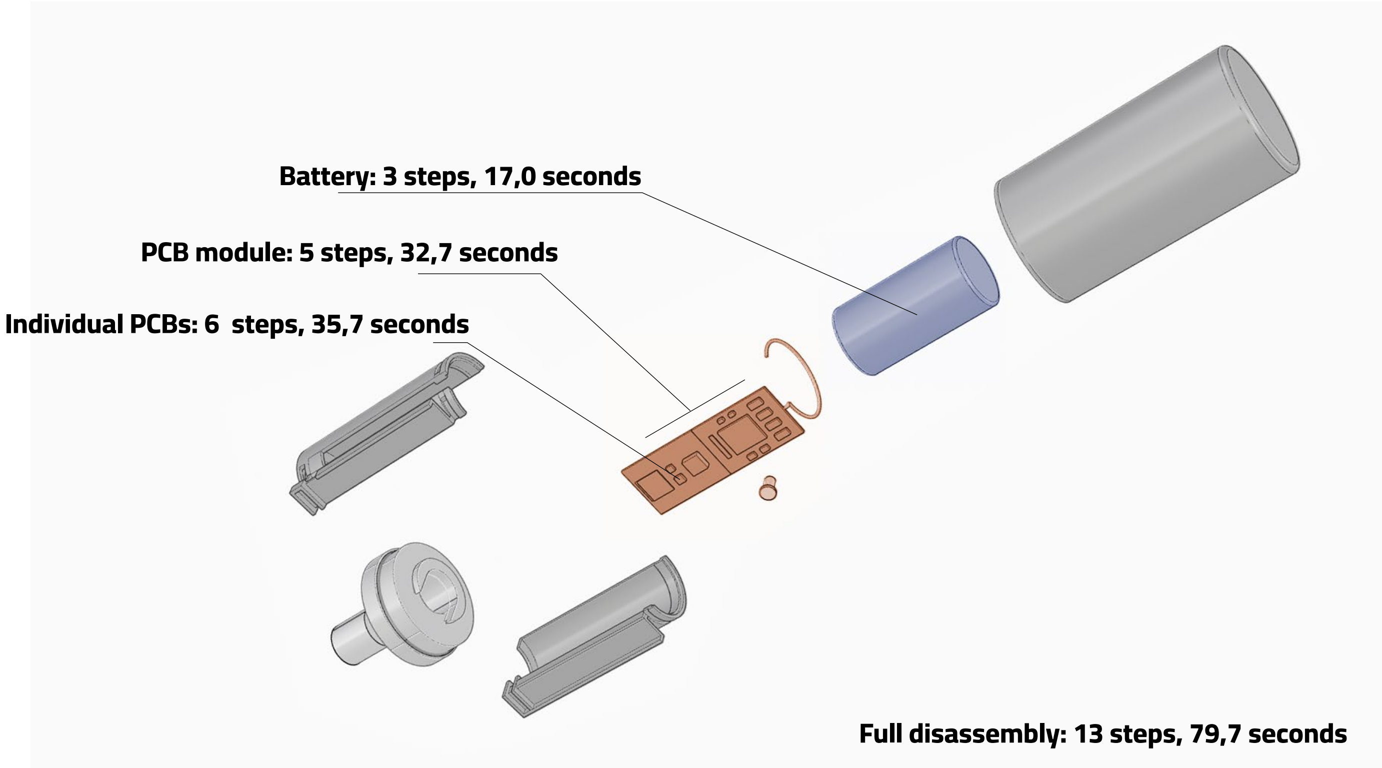


Figure 74: Accessibility of concept node; steps and time required for reaching key components

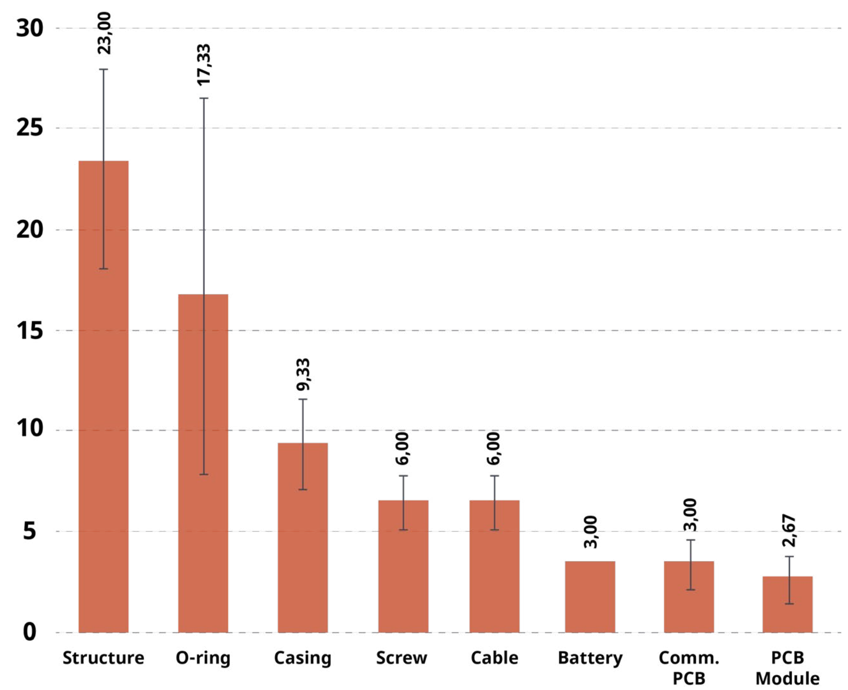


Figure 75: Mean times of disassembly steps

DISASSEMBLY: FINDINGS
Again, the disassembly sequence of the complete product is captured in a Disassembly Map (figure 76), to visualise the steps and actions needed. As can be noted, more tools are needed to disassemble the concept node; this is because of the use of a spudger to loosen the snap-fits fastening the inner structure. For now, the decision to use snap-fits instead of screws seems the better option as it avoids the use of more mechanical fasteners and mixing of materials. Moreover, it is assumed that after assembling the inner structure onto the base, this will not need to come apart anymore in the lifetime of the product.

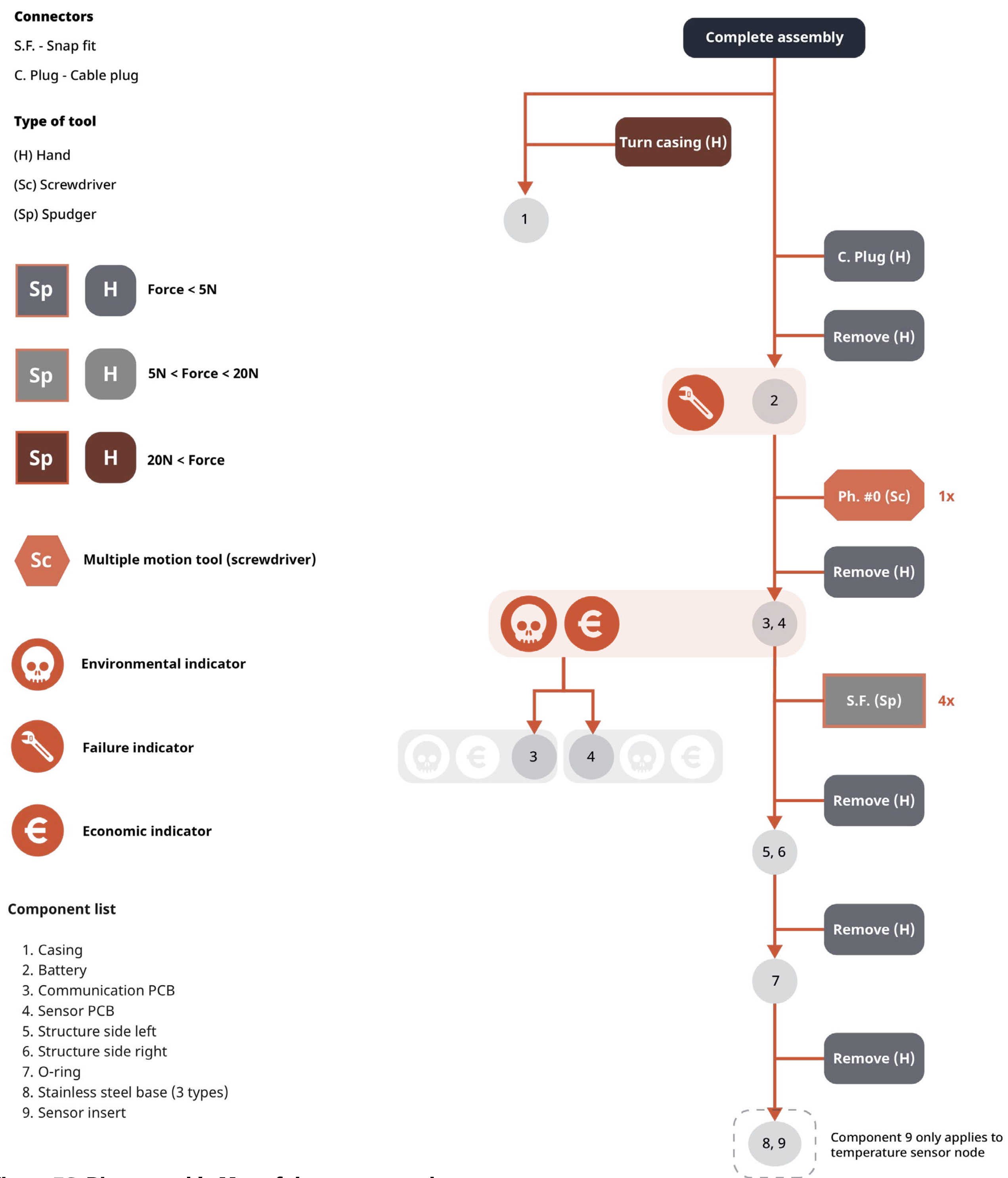


Figure 76: Disassembly Map of the concept node

Table 15: Comparison current sensor node an concept node

Compared on:	Current sensor node	Concept node	Decrease in %
Full disassembly time	160,3	79,7	50,3
Time removing battery	89,3	17,0	81,0
Time removing comm. PCB	86,7	35,7	58,8
Time removing sensor PCB	124,3	35,7	71,3
Number of tools	1	2	

Now, comparing the Disassembly Map (figures 77, 78) of the original sensor node to the concept node shows the battery has been surfaced; the position of this component is closer to the top of the full disassembly sequence and now takes 3 steps to remove. Several components, and therefore disassembly steps, have been trimmed and no longer appear in the Disassembly Map anymore. These are mainly fasteners and the ribbon cable. The PCBs have been clumped; the components can be removed together which reduces the required steps to extract each of the separate PCBs. Table 15 shows an overview of the decrease in time required for each disassembly sequence.

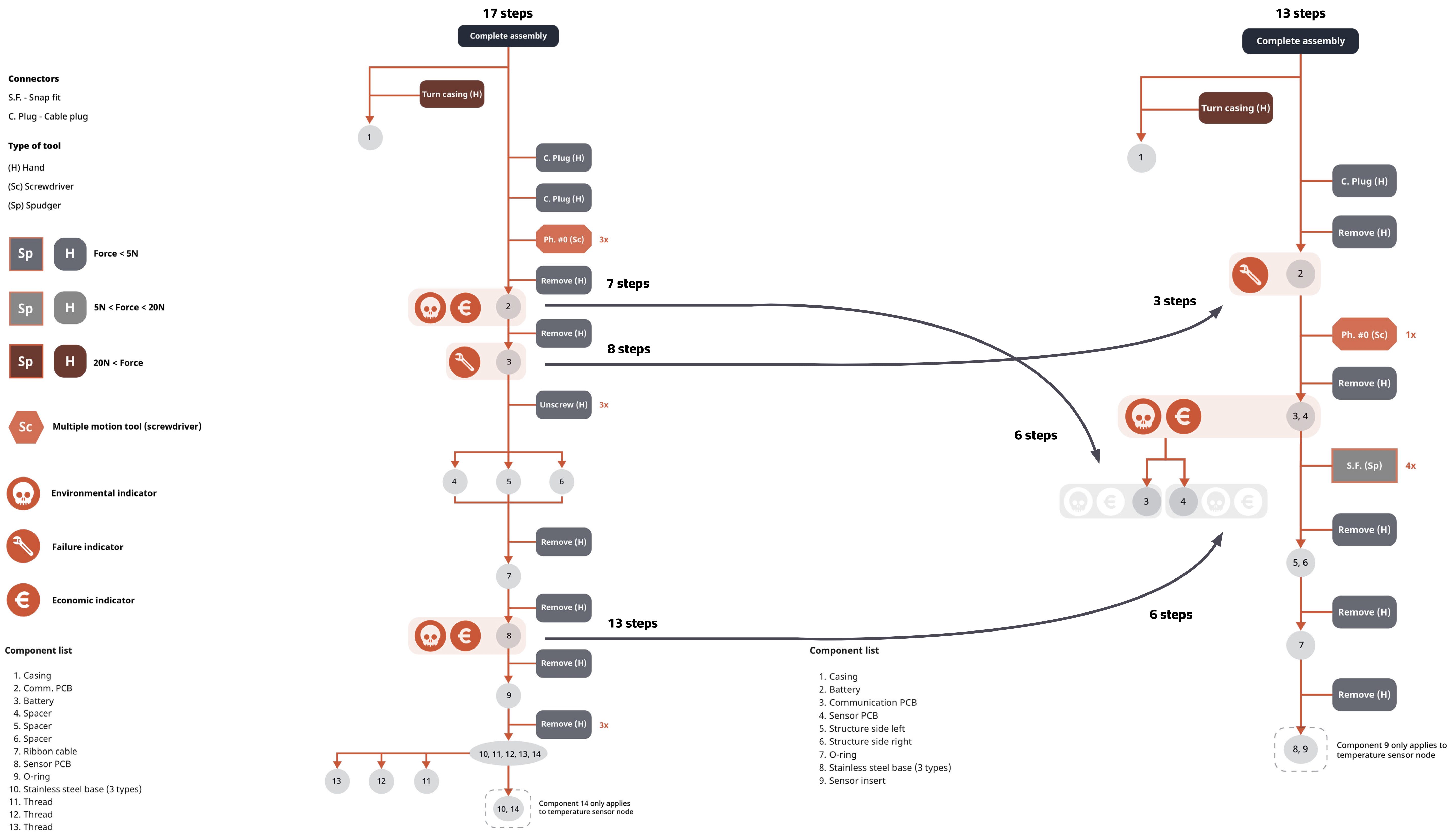


Figure 77: Dissassembly Map of the concept node

Figure 78: Dissassembly Map of the original node

7.2 Modularity

The current sensor node has been assessed on its modularity by looking at three underlying modular aspects, functional grouping, component coupling and standardisation. This showed that the sensor node already incorporates modular features. Still, some aspects could benefit from increased modularity.

The use of standard components has been reduced, from 13 to 3 components, and the use of product-specific (non-standard) components has been increased, from 6 to 8. This however is correlated as the new inner structure has assumed the functionality of the majority of standard components used in the original sensor node.

PCB MODULE
Bridging the PCBs in the current sensor node requires a ribbon cable as they are not spatially clustered. The concept node features a slot that fits both PCBs combined. This provides space for the PCBs to be grouped. Now, the PCBs can instead communicate through integrated board-to-board connectors (figure 79). This way, no ribbon cable is needed, a component that took a significant part of battery disassembly sequence.

BUTTON
In chapter 5, it was determined the button is coupled with the casing; in order to operate the button, the casing is required to be flexible at the top and with the right tolerances. To increase the modularity of the product, and make components more independent, this coupling can be lifted.

The button located on top of the communication PCB is used for a number of actions. It functions as on-off switch by pressing and holding the button and it can initiate the node to search for the nearest gateway when pressed shortly.

The easiest way to decouple the casing and button would be to leave out the physical button altogether and instead make use of the already available communication chip and saving the (minor) impact and costs of the button.

However, Edge Dynamics emphasises the need for a physical button. In case a sensor node requires an adjustment to its settings. Technically, this could be done over-the-air (submitted as task through the nearest gateway) or when connecting to a node in close proximity through for instance Bluetooth or near field communication (NFC), similar to Yokogawa's sensor nodes. In practice however, this is not always appropriate. Field technicians rarely can bring personal device along that support these types of communication due to ATEX zone restrictions. ATEX certified phones do exist but these come with a hefty price tag, meaning they are barely around on site (Hassan, personal communications, January 2022).

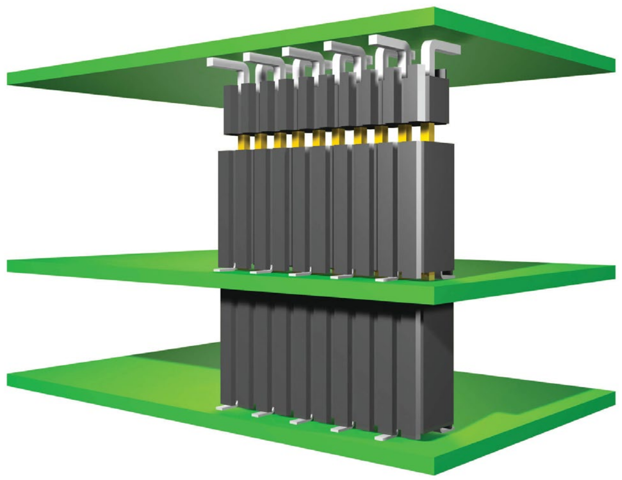


Figure 79: Board-to-board stacking configuration (Samtec, n.d.)

The concept node therefore features a physical button on the side of the PCB facing outside. In the unlikely event the sensor node needs attendance involving the button, the casing can be unscrewed revealing the button. Alternatively, disconnecting the battery could reset the sensor node's settings to default.

BASE COMPONENT
The component coupling between the base component and sensor insert remains in the redesigned sensor node. Therefore, the base and sensor insert still experience a functional coupling, meaning a change to either of these components would still force the other component to change as well.

7.3 Recycleability

Chapter 5.4 discussed the sensor node's recyclability based on the Design for Recycling guidelines (Appendix G).

On a material level, several things change. The amount of different materials can be reduced, if the inner structure and casing can both be made from PBT. As the aluminium spacers are not necessary anymore, this would reduce the amount of different materials. Still, other polymers are available that can be separated in recycling facilities with common techniques, such as ABS.

Moreover, expelling the threads, spacers and screws from the inner structure mitigates the compatibility problems that occurs with mixing ferrous and non-ferrous metals. With the threads and screws made of a steel alloy and the aluminium spacers fastened to a non-ferrous stainless steel base, either stream is likely polluted. Still, the stainless steel base contains press fitted magnets, likely polluting the ferrous stream.

The amount of fasteners and cables has been reduced in the concept node. This is beneficial to its recyclability. Still, a single screw is needed to block the PCB module in its only axis of freedom. This screw could be separated when shredded by securing it at the top instead of through the PCB (figure 80). This avoids the possibility of the PCBs ending up in ferrous waste streams.

On a product level, the accessibility improvements are also in favour of recyclability as the battery is now significantly easier to remove, an essential practice in recycling battery-powered devices.

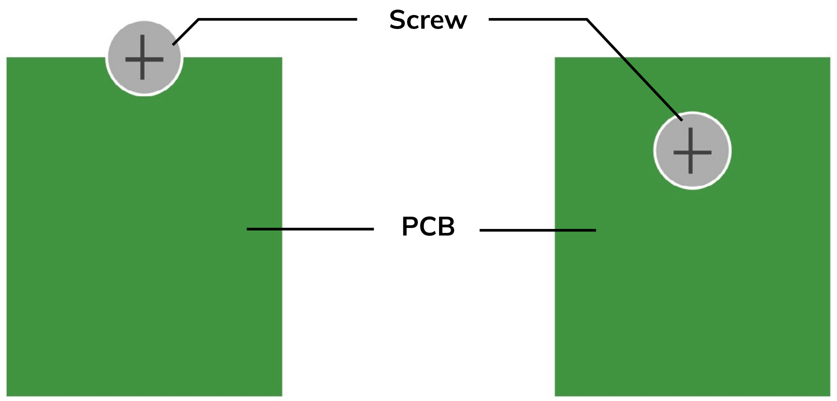


Figure 80: Front view of PCB module fastened by screws; locking in or tightening through PCB.

7.4 Cost reduction

Now the disassembly time for the battery is known, the cost estimation can be updated with the measured values. The estimated repair time of 30 seconds comes surprisingly close to the actual mean time of 34,0 seconds that is required to change the battery. Therefore, the estimated cost reduction for faster repair can be estimated at 0,40% in a scenario with 1500 sensor nodes (table 16) in operation, with a communication interval of 15 minutes.

Table 16: Comparison current sensor node an concept node

	10 year (1 hour Communication interval)	10 year (30 min. Communication interval)	10 year (15 min. Communication interval)
Cost difference (repair speed = 240 seconds)	14464,40	14577,33	14803,21
Cost difference (repair speed = 34 seconds)	14434,10	14537,38	14743,94
Difference in percentage (%)	100,21	100,27	100,40

In a scenario with 15000 sensor nodes in operation, with a communication interval of 15 minutes, the cost reduction for faster repair can be estimated at 2,16% (table 17).

Table 17: Comparison current sensor node an concept node

	10 year (1 hour Communication interval)	10 year (30 min. Communication interval)	10 year (15 min. Communication interval)
Cost difference (repair speed = 240 seconds)	24643,96	25773,33	28032,08
Cost difference (repair speed = 34 seconds)	24340,96	25373,77	27439,39
Difference in percentage (%)	101,24	101,57	102,16

8

Discussion & conclusion

The final chapter will discuss aspects that require future attention or that appeared in a limited way in this project. The thesis is ended with a conclusion revisiting the main research question and providing recommendations for Edge Dynamics to follow up on.

Photo by Maksym Kaharlytskyi, unsplash.com

8.1 Discussion

DISASSEMBLY MAP: PRECISION PENALTY

The Disassembly Map has been used during this project as an analysis tool. As the Disassembly Map is a standardised tool, it does not show product specific intricacies that occurred when taking apart the sensor node. These oddities are hampering the disassembly and reassembly of the product, yet this cannot be indicated according to the current method guidelines. An adjustment is proposed that could facilitate the communication of anomalies during disassembly and reassembly.

A penalty indicator (figure 81) could be added that indicates if precision is needed, a disassembly aspect that turned out to be slowing down the process. Disassembling the sensor node showed two occasions where this was an issue. The ribbon cable connecting the communication PCB and sensor PCB is connected on both sides using a ZIF (zero insertion force) connector. These are of small size and pose a challenge both during (re)assembly as disassembly.

Also the O-ring assembled on the base component requires precision to remove. This is underlined by the time recording showing a significant spread in time required.

Three precision penalty indicators are proposed, each indicating the 'direction' of the sequence. An arrow pointing up indicates going up the Disassembly Map, therefore (re)assembling the product, an arrow down would indicate precision is needed when disassembling this component. A two-sided arrow would indicate precision is needed either assembling or disassembling the component (figure 82).

A distinction between the different directions could be of interest as components might not need to be disassembled, therefore that could tell the priority of resolving the penalty. For instance, the O-ring is likely not disassembled at all and might in its lifetime only be separated from the base during shredding. Therefore addressing the ribbon cable connectors is of more importance in a repair scenario.

Figure 81: Precision penalty indicators

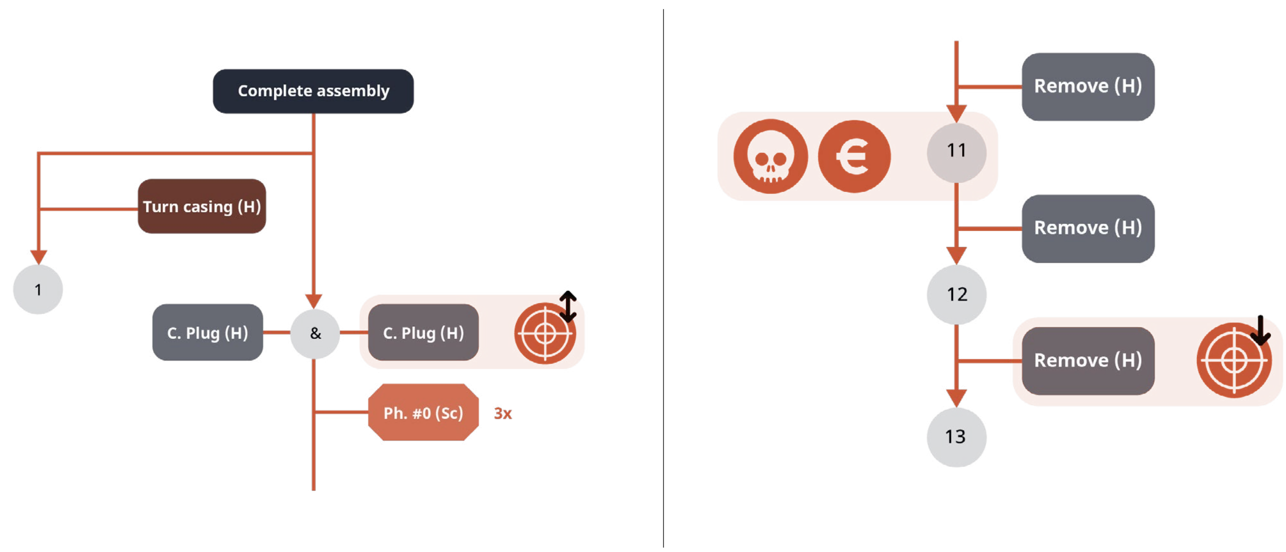


Figure 82: Precision penalty indicator ribbon cable (left), O-ring (right)

ENVIRONMENTAL IMPACT OF SENSOR NODE

Although the HotSpot Mapping tool identified the components with a significant environmental impact, this impact of Edge Dynamics' sensor node has not been quantified. As this metric is of major relevance to the a product's circularity, assessing the sensor node on its lifecycle's footprint can indicate where priority should lie for reduction of impact. Using a material database, (Granta EduPack) an eco-assessment has been performed on both the current sensor node and the concept node. The results show that the embedded footprint of the materials used in the product are by far the most significant (figure 83), as they account for 98,9% of the total lifecycle footprint. Among the material footprint, the PCBs make

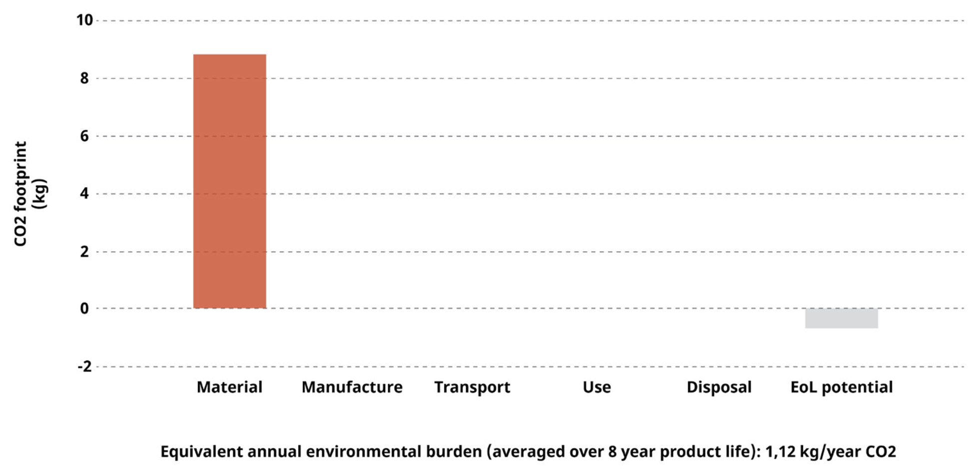


Figure 83: CO2 footprint fraction per lifecycle aspect

up most of the embedded CO_2 emissions of the product. With a combined footprint of 7,2 kg, they account for 81% of total material emissions (table 18). From this can be concluded that the prolonged use of the sensor nodes and thus the PCBs, will have the most significant impact reduction. Repairing sensor nodes is the lowest threshold strategy to achieve this. Remanufacturing sensor nodes can in turn achieve the reuse of PCBs by assessing their state and thus estimate the remaining lifetime.

Now, comparing the embedded footprint of the current sensor node with the concept node shows that there is virtually no difference in embedded footprint. The rearrangement of the architecture and replacement of structural components with a polymer inner structure reduces

Table 18: CO2 footprint per component, current node (left), concept node (right)

Component	CO2 footprint (kg)	%
Base	0,67	7,6
O-ring	0,0014	0,0
Sensor PCB	3,6	40,5
Thread / screw	0,02	0,2
Spacer	0,055	0,6
Battery	0,82	9,3
Comm. PCB	3,6	40,5
Cables	0,0034	0,0
Casing	0,1	1,2
Total	8,8	100

Component	CO2 footprint (kg)	%
Sensor PCB	3,6	40,4
Comm PCB	3,6	40,4
Base	0,67	7,6
Battery	0,82	9,3
Cables	0,0017	0,0
O-ring	0,0012	0,0
Structure	0,05	0,6
Screw	0,0034	0,0
Casing	0,15	1,7
Total	8,8	100

the use of a data cable and a variety of fasteners, but this has no noticeable impact on the embedded footprint. For both products a lifespan of 8 years and only the use of virgin materials is assumed.

Replacing the battery after 8 years effectively doubles the lifespan of the sensor node. Although the total embedded material footprint does increase due to the second battery (table 19), the annual footprint of a repaired sensor node declines with close to 84%, from 1,12 kg of CO_2 per year to 0,611 kg of CO_2 per year (figure 84. This shows that for Edge Dynamics, prolonging the product's lifespan is the most effective strategy for reducing the footprint of sensor nodes.

Table 19: CO2 footprint per component, current node (left), concept node (right), repair situation

Component	CO2 footprint (kg)	%
Base	0,67	7,0
O-ring	0,0014	0,0
Sensor PCB	3,6	37,0
Thread / screw	0,02	0,2
Spacer	0,055	0,6
Battery	1,6	17,1
Comm. PCB	3,6	37,0
Cables	0,0034	0,0
Casing	0,1	1,1
Total	9,6	100

Component	CO2 footprint (kg)	%
Sensor PCB	3,6	36,9
Comm PCB	3,6	36,9
Base	0,67	7,0
Battery	1,6	17,0
Cables	0,0017	0,0
O-ring	0,0012	0,0
Structure	0,05	0,5
Screw	0,0034	0,0
Casing	0,15	1,6
Total	9,7	100

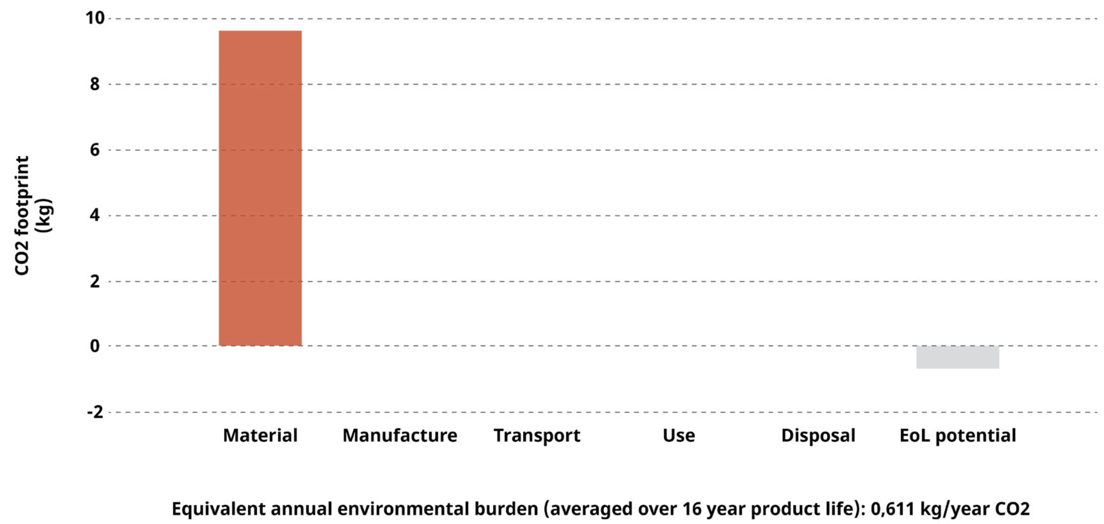


Figure 84: CO2 footprint fraction per lifecycle aspect - repair scenario

Using exlusively recycled materials can reduce the impact of the sensor node as significantly. Considering the use of 100% recycled materials for steel, aluminium and polymer components, a reduction of 18,5% of the embedded material footprint can be achieved compared to using only virgin materials (table 20, left).

However, if considering the typical recycled material fractions in the current supply of steels (around 50%), aluminium (around 45%) and PBT (0%) (Granta, 2021), the embedded material footprint can be lowered with 0,4 kg of CO_2 emissions, a reduction of 4,9%, when compared to the use of 100% recycled materials (table 20, right).

Table 20: CO_2 footprint of sensor node with ideal recycling rates (left), and typcial recycling rates (right)

Component	Recycled content (%)	CO2 footprint (kg)	%
Base	100,0%	0,12	1,5
O-ring	Virgin (0%)	0,0014	0,0
Sensor PCB	100,0%	3,6	43,8
Thread / screw	100,0%	0,006	0,1
Spacer	100,0%	0,011	0,1
Battery	Virgin (0%)	0,82	10,1
Comm. PCB	Virgin (0%)	3,6	43,8
Cables	Virgin (0%)	0,0034	0,0
Casing	100,0%	0,035	0,4
Total		8,1	100

Component	Recycled content (%)	CO2 footprint (kg)	%
Base	Typical %	0,39	4,6
O-ring	Virgin (0%)	0,0014	0,0
Sensor PCB	100,0%	3,6	42,0
Thread / screw	Typical %	0,013	0,2
Spacer	Typical %	0,035	0,4
Battery	Virgin (0%)	0,82	9,7
Comm. PCB	Virgin (0%)	3,6	42,0
Cables	Virgin (0%)	0,0034	0,0
Casing	0,0%	0,1	1,2
Total		8,5	100

The complete data tables can be found in Appendix I.

REMANUFACTURING OF SENSOR NODE

Retaining the functionality of sensor nodes has been limited to the repair, or replacement, of batteries. As a full battery can last 8 years or more depending on its communication interval, it is safe to assume other components will degrade and possibly fail within the extended lifecycle of a sensor node. Remanufacturing is a circular strategy mentioned in chapter 3.1 with the purpose of returning a used product back to at least the original state and performance and with a warranty that is similar or better than that of a new product. Here, this strategy clearly differentiates from repair as this process only brings back a product to a working state with no or only a limited warranty on its performance. In order to guarantee the entire product's prolonged performance, each component should be evaluated if it matches standards or should be replaced.

In case Edge Dynamics remains owner of the nodes, it is in their best interest to keep maintenance to a minimum and mitigate the possible malfunctioning of sensor nodes. When sensor nodes return, there is ample opportunity to perform the necessary tests and bring them back to an 'as new' state or better and install them elsewhere. This would be necessary to give any type of warranty on the performance of the nodes. Remanufacturing can be performed by Edge Dynamics or can be outsourced to any third party specialised in remanufacturing electronic equipment (figure 85).

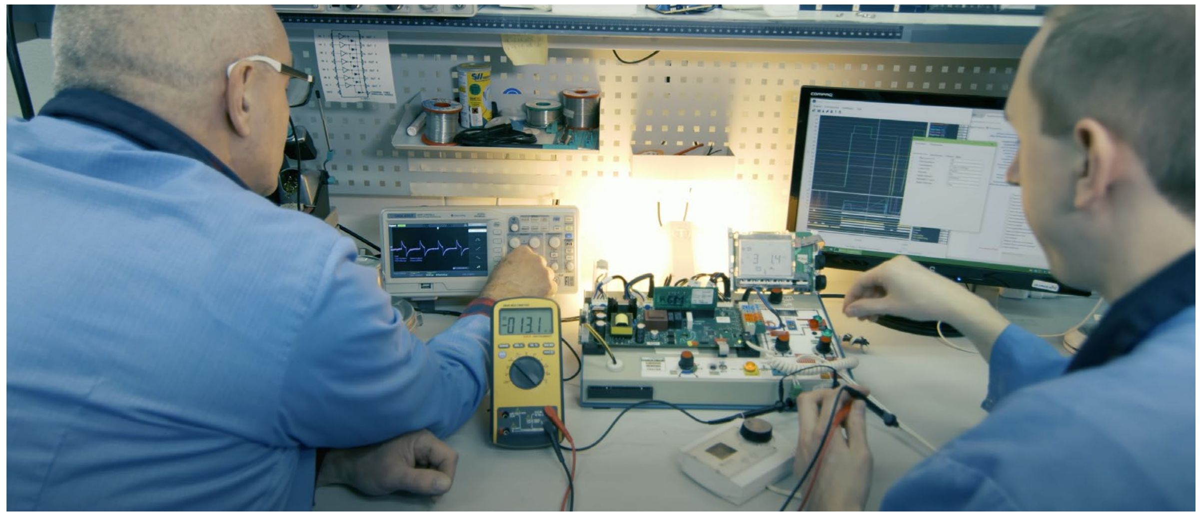


Figure 85: Inexeon, a Dutch electronics remanufacturing company offering boiler PCBs among other products

Mainly the sensor node's electronics are expected to require an assessment of their remaining lifespan in order to operate for a certain amount of years. As they are responsible for the vast majority of the embedded footprint, keeping the PCBs in a functional state can reduce the footprint of sensor nodes drastically. PCBs can have a design life (expected lifetime under normal specifications) of up to 60 years (Xiang et al., 2013) and can therefore with the right effort operate for decades. From an environmental point of view, remanufacturing is therefore an excellent and necessary strategy to reduce the impact of Edge Dynamics' sensor nodes.

A challenge of remanufacturing however is the establishment of an effective reverse logistics operation to make sure an appropriate amount of broken sensor nodes are recovered to support the circular strategy. Naturally, Edge Dynamics would need a stable influx of components and nodes to build new products in this scenario (Ijomah & Danis, 2012).

MODULAR BASE
The assessment of the sensor node showed that its modularity can be increased as the base component is coupled with the sensor insert (chapter 5.2). In practice, this means that the design of the base is dictated by the insert. As such, the base is different compared to the one used for the vibration version of Edge Dynamics' sensor node. This increases the amount of different components across the product family, currently there are three different base components (see figure 86). Ideally, the same base could be used for every version of the sensor node and possibly future versions. This would support the reuse of components in circular strategies as they can be used for any newly introduced sensor node. A low hanging fruit solution in this case could be the use of a (standardised) polymer thread plug (figure 87), to seal off the insert mount which would expose the intervals of the node when left open. This would avoid the need for a dedicated base for the vibration sensor (figure 86, left).

Figure 86: Current assortment of base components in Edge Dynamics sensor node family

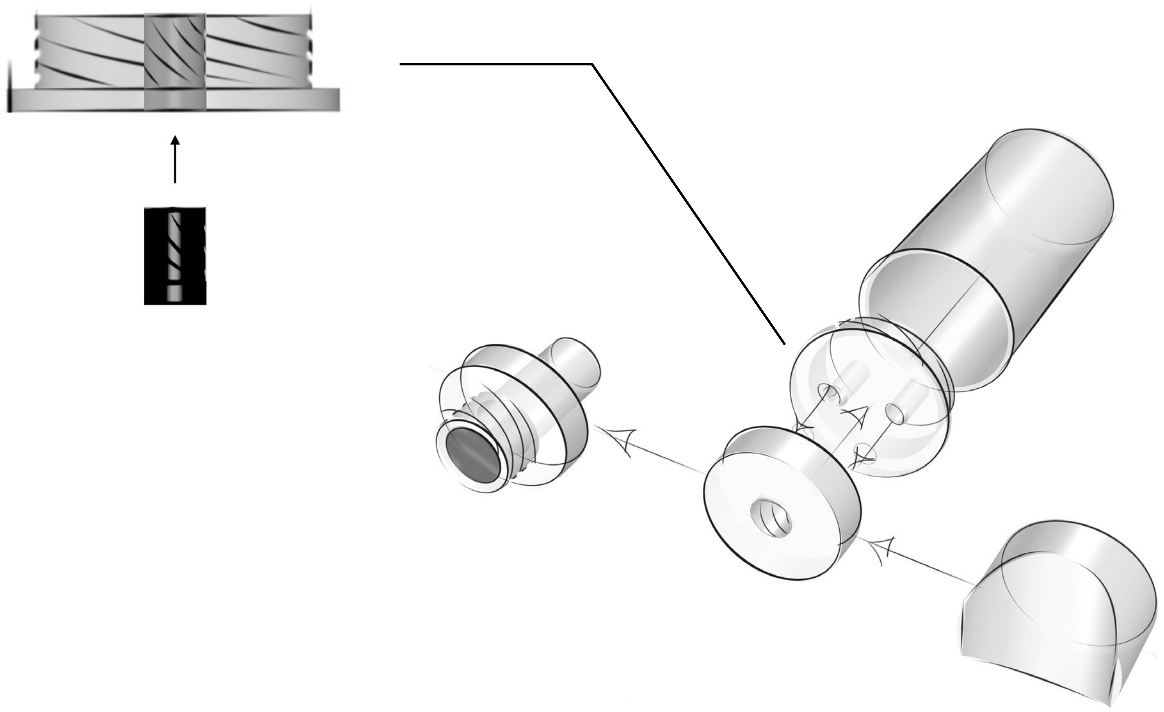


Figure 87: General base component that can facilitate multiple (future) mounts

8.2 Recommendations

DESIGN ADJUSTMENTS
Reviewing the concept proposal with Edge Dynamics led to several design alterations. In order to protect the components assembled on the PCBs, the PCB module could be flipped to face inwards. This needs to be adjusted in the node's structure to create additional space. Now, there is plenty of space to add the 2-pins JST connector required for the battery, and 3-pins and 4-pins JST connectors for sensor peripherals.

The structure can also be adjusted to facilitate two versions; a full length and a 'cuttable' short length. This way, the use of a smaller battery can make it possible to end up with a smaller product without the need for additional tooling.

ENERGY HARVESTING
The dependability of sensor nodes on battery life has been made clear in this thesis. As mentioned in chapter 3, energy harvesting is an alternative form of powering wireless devices. Instead of a battery, energy harvesting sensor nodes make use of a capacitor that gets charged by any form of locally generated power. If for instance light is abundant, a solar cell can be used for power, but if a sensor node would be place in a concealed location, a different approach is required. Therefore, these type of sensor nodes require to be tailored to the environment they will operate in. This makes them to a lesser degree 'plug-and-play'. Another significant difference is the predictability of failure. Critical failure of energy harvesting nodes will happen later than battery powered sensor nodes, but are not easy to predict. In contrast, it is effortless to receive information of a sensor node's remaining battery life (Broadhead, personal communications, December 2021).

Still, energy harvesting is a technology that is continuously improved and will become an adequate alternative to batteries (Everactive, n.d.). Especially avoiding the use of consumables (batteries) and the likely reduction of operational costs make energy harvesting an interesting option for circular business models and associated strategies.

8.3 Conclusion

This project was intended as an exploration of possibilities for Edge Dynamics to transition their current product into the circular economy. By assessing the sensor node on product aspects and principles that are inherently beneficial to operating circular strategies and business models, the factors that are obstructing these can be tackled. These can be pinpointed using the disassembly map method and hotspot mapping tool. Revisiting the main research question gives the occasion to answer it;

how can product design improve the circularity of Edge Dynamics' IIoT products?

On the system level, circular strategies such as repair and remanufacturing can considerably reduce the environmental impact of the sensor nodes, as giving nodes a second or third lifespan will prevent the need to use virgin materials for the manufacturing of new products. Product architecture design has shown to be able to significantly reduce the time and effort required to reach the components deemed essential to the prolonging of product lifetime. This supports circular strategies and also recycling as it is crucial to liberate chemical batteries from electronic devices before they can be shredded.

On a product level however, if considered that sensor nodes will be repaired in a controlled environment, the current product's key components are sufficiently easy enough to reach and repair that a redesign will only make a significant difference in time savings, and thus costs, on a certain scale. Naturally, a reduction of operational costs is a high incentive for any company to dedicate to circular strategies.

On a material level, using exclusively recycled metals and polymers in the sensor node could reduce its carbon footprint with 4,9% compared to the use of materials containing typical recycling fractions. Moreover, the effectivity of recycling processes can be improved by avoiding the use of mechanical fasteners mixed with dissimilar metals.

This project has shown that through redesigning the product architecture with the aim of achieving a better fit for circular strategies, product design can improve the circularity of Edge Dynamics' sensor nodes. Practically speaking, a simpler product containing less components such as cables and fasteners, configured in a way that crucial components are the easiest to reach can improve the circularity of IIoT products.

For Edge Dynamics, the most ground can be gained towards circular IIoT products by combining the efforts that can be made on all levels. Embedding the proposed concept node into a business model revolving around repair, remanufacturing and recycling can be feasible with the right partnerships and logistics in place. This way the circular activity of preventative maintenance can be carried out in a sustainable way.

Edge Dynamics can take a leading role in the industry and be ahead of the competition with eyes on upcoming legislation preferring sustainable operations and tailoring to potential customers' request for sustainable products.

9 | References

Alibaba. (2022). Lithium Battery Er26500 9000mah 3.6v With Wire Connector Outlet Assembly. Retrieved 17 March 2022, from https://www.alibaba.com/product-detail/Lithium-battery-ER26500-9000mAh-3-6V_1600207247064.html

Abdelbasir, S. M., Hassan, S. S. M., Kamel, A. H., & El-Nasr, R. S. (2018). Status of electronic waste recycling techniques: a review. Environmental Science and Pollution Research, 25(17), 16533–16547. https://doi.org/10.1007/s11356-018-2136-6

Achterberg, E., Hinfelaar, J., Bocken, N. (2016). Master Circular Business with the Value Hill. Retrieved from: https://www.circle-economy.com/ resources/master-circular-business-with-the-value- hill

ARMSTRONG, T. J., PUNNETT, L., & KETNER, P. (1989). Subjective Worker Assessments of Hand Tools Used in Automobile Assembly. American Industrial Hygiene Association Journal, 50(12), 639–645. https://doi.org/10.1080/15298668991375290

Bakker, C. A. (2022). Productontwerp in een Circulaire Economie. Technische Universiteit Delft.

Bakker, C., & Balkenende, R. (2021). A renewed recognition of the materiality of design in a circular economy: the case of bio-based plastics. Materials Experience 2, 193–206. https://doi.org/10.1016/b978-0-12-819244-3.00020-x

Bakker, C., Hollander, M., Van Hinte, E., Zijlstra, Y., Den Hollander, M., & Van Hinte, E. (2014). Products that Last. TU Delft.

Boesing, D. (2019, May 13). Board Stacking Interconnects For Unusual Applications. The Samtec Blog. https://blog.samtec.com/post/board-stacking-interconnects-for-unusual-applications/

Biobrandstoffen uit afval. (n.d.). Shell. https://www.shell.nl/over-ons/shell-pernis-refinery/biobrandstoffen-uit-afval.html

CEN/CLC TC10 European Standard. (2017). General methods for the assessment of the ability to repair, reuse and upgrade energy related products. DRAFT DOCUMENT. In (Vol. prEN 45554).

Circular economy principles: Circulate products and materials. (2022). EllenMacArthurFoundation. Geraadpleegd op 14 maart 2022, van https://ellenmacarthurfoundation.org/circulate-products-and-materials

Critical raw materials. (2022). Internal Market, Industry, Entrepreneurship and SMEs. Geraadpleegd op 7 maart 2022, van https://ec.europa.eu/growth/sectors/raw-materials/areas-specific-interest/critical-raw-materials_nl

Cypress Semiconductor Corporation. (2018). Antenna Design and RF Layout Guidelines. https://www.infineon.com/dgdl/Infineon-AN91445_Antenna_Design_and_RF_Layout_Guidelines-ApplicationNotes-v09_00-EN.pdf?fileId=8ac78c8c7cdc391c017d073e054f6227

Dahlqvist, F., Patel, M., Rajko, A., & Shulman, J. (2020, 16 september). Growing opportunities in the Internet of Things. McKinsey & Company. Geraadpleegd op 12 maart 2022, van https://www.mckinsey.com/industries/private-equity-and-principal-investors/our-insights/growing-opportunities-in-the-internet-of-things

De Fazio, F., Bakker, C., Flipsen, B., & Balkenende, R. (2021). The Disassembly Map: A new method to enhance design for product repairability. Journal of Cleaner Production, 320, 128552. https://doi.org/10.1016/j.jclepro.2021.128552

De Ingenieur. (2017, November 4). Recycling elektronisch afval vergeet kostbare materialen. Retrieved 1 April 2022, from https://www.deingenieur.nl/artikel/recycling-elektronisch-afval-vergeet-kostbare-materialen

de Jong, R., Sr. (2022, March 9). Internet of Things op de Noordzee. Linkedin. Retrieved 18 March 2022, from https://www.linkedin.com/pulse/internet-things-op-de-noordzee-remy-de-jong-sr/?trk=pulse-article_more-articles_related-content-card&originalSubdomain=nl

den Hollander, M. (2018). Design for Managing Obsolescence: A Design Methodology for Preserving Product Integrity in a Circular Economy. https://doi.org/10.4233/uuid:3f2b2c52-7774-4384-a2fd- 7201688237af

Designing Electronics for Recycling in a Circular Economy | edX. (2022). edX. Geraadpleegd op 19 april 2022, van https://courses.edx.org/dashboard?access_response_error=Access%20to%20Designing%20Electronics%20for%20Recycling%20in%20a%20Circular%20Economy%20expired%20on%20Apr%2014,%202022

edX. (2022). Designing Electronics for Recycling in a Circular Economy. https://www.edx.org/course/design-electronics-for-recycling-in-a-circular-economy?index=product&queryID=259e5ee13b7d66544d7e202b48d11b19&position=1

Emerson 10 Years of Wireless Innovation. (2020, November 25). YouTube. https://www.youtube.com/watch?v=EX8CyAXycTY

Fluke. (n.d.). 3561 Vibration Sensor. https://www.fluke.com/en-us/product/condition-monitoring/vibration/3561-vibration-sensor#

European Commission, 2020. A new Circular Economy Action Plan For a cleaner and more competitive Europe. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN.

European Commission. (2022). Langetermijnstrategie voor 2050. Geraadpleegd op 20 februari 2022, van https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2050-long-term-strategy_nl

European Parliament. (2021). New EU regulatory framework for batteries: Setting sustainability requirements. Geraadpleegd op 1 februari 2022, van https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2021)689337

Everactive. (n.d.). 8 Reasons Batteries Fail in Industrial IoT. Geraadpleegd op 16 mei 2022, van https://everactive.com/whitepapers/overcoming-the-battery-obstacle-part-ii/

Expert Cafe: Design for Disassembly. (2022, February 15). [Video]. YouTube. https://www.youtube.com/watch?v=LmA6qQ5raBk&list=PLzpdeFEALVvVlhMBNlaJmB39z5j4ahLAE&index=3

Farmer, William (1944). Ordnance Field Guide. Military Service Publishing Company. p. 97.

Fluke. (2022). 3561 Vibration Sensor. Fluke Corporation. Geraadpleegd op 31 januari 2022, van https://www.fluke.com/en-us/product/condition-monitoring/vibration/3561-vibration-sensor

Fraga-Lamas, P., Lopes, S. I., & Fernández-Caramés, T. M. (2021). Green IoT and Edge AI as Key Technological Enablers for a Sustainable Digital Transition towards a Smart Circular Economy: An Industry 5.0 Use Case. Sensors, 21(17), 5745. https://doi.org/10.3390/s21175745

Goodman, P. (2002). Current and future uses of gold in electronics. Gold Bulletin, 35(1), 21–26. https://doi.org/10.1007/bf03214833

Granta EduPack. (2021). [Dataset - Thermoplastics].

Healy, M., Newe, T., & Lewis, E. (2008). Wireless Sensor Node hardware: A review. 2008 IEEE Sensors. https://doi.org/10.1109/icsens.2008.4716517

HEMMINGER, T. L. (2005). ANTENNA IMPEDANCE MATCHING WITH NEURAL NETWORKS. International Journal of Neural Systems, 15(05), 357–361. https://doi.org/10.1142/s0129065705000335

Hicks, C., Dietmar, R., & Eugster, M. (2005). The recycling and disposal of electrical and electronic waste in China—legislative and market responses. Environmental Impact Assessment Review, 25(5), 459–471. https://doi.org/10.1016/j.eiar.2005.04.007 https://behrtech.com/blog/lpwan-antenna-placement/

Ijomah, W., & Danis, M. (2012). Refurbishment and reuse of WEEE. Waste Electrical and Electronic Equipment (WEEE) Handbook, 145–162. https://doi.org/10.1533/9780857096333.2.145

Jauch.com (2019). Advantages and Special Characteristics of Lithium Thionyl Chloride Batteries. Jauch Blog-Seite. Geraadpleegd op 28 februari 2022, van https://www.jauch.com/blog/en/advantages-and-special-features-of-lithium-thionyl-chloride-batteries/

K. A. Reinhardt, W. Kern (2008). Handbook of Silicon Wafer Cleaning Technology,

Kiddee, P., Naidu, R., & Wong, M. H. (2013). Electronic waste management approaches: An overview. Waste Management, 33(5), 1237–1250. https://doi.org/10.1016/j.wasman.2013.01.006

Klushin, G., Fortin, C., & Tekic, Z. (2018). Modular Design Guideline for Projects from Scratch. Proceedings of the 29th International DAAAM Symposium 2018, 0829–0837. https://doi.org/10.2507/29th.daaam.proceedings.120

Landing Party Manual. United States Office of Chief Naval Operations. 1960. p. 623.

Leading digital technologies for industry. (n.d.). ABB Group. https://global.abb/group/enA. (2022, January 9). Parts Of Rifle Cal 5.56mm M16a1 -

Levy S.C., Bro P. (1994) Lithium/Thionyl Chloride Batteries. In: Battery Hazards and Accident Prevention. Springer, Boston, MA. https://doi.org/10.1007/978-1-4899-1459-0_10

L. Delva, K. Van Kets, M. Kuzmanovic, R. Demets, S. Hubo, N. Mys, S. De Meester & K. Ragaert (2019) An introductory review - Mechanical recycling of polymers for dummies.

LS, LSH, LSP. (2020, November 2). Saft | Batteries to Energize the World. Retrieved 31 March 2022, from https://www.saftbatteries.com/products-solutions/products/ls-lsh-lsp?text=&tech=84&market=&brand=&sort=newest&submit=Search

Martínez Leal, J., Pompidou, S., Charbuillet, C., & Perry, N. (2020). Design for and from recycling: A circular ecodesign approach to improve the circular economy. Sustainability, 12(23), 9861.

Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer. (2021, December 14). Windenergie op zee. Duurzame energie | Rijksoverheid.nl. Retrieved 18 March 2022, from https://www.rijksoverheid.nl/onderwerpen/duurzame-energie/windenergie-op-zee

Mois, G., Folea, S., & Sanislav, T. (2017). Analysis of Three IoT-Based Wireless Sensors for Environmental Monitoring. IEEE Transactions on Instrumentation and Measurement, 66(8), 2056–2064. https://doi.org/10.1109/tim.2017.2677619

Morris, Christopher. Academic Press Dictionary of Science and Technology. Gulf Professional Publishing. p. 825.

Nancy M. P. Bocken, Ingrid de Pauw, Conny Bakker & Bram van der Grinten (2016) Product design and business model strategies for a circular economy, Journal of Industrial and Production Engineering, 33:5, 308-320, DOI: 10.1080/21681015.2016.1172124

Accelerometer placement – where and why. (2012). NXP. Geraadpleegd op 18 april 2022, van https://www.nxp.com/company/blog/accelerometer-placement-where-and-why:BL-ACCELEROMETER-PLACEMENT

Patil, H. K., & Chen, T. M. (2017). Wireless Sensor Network Security. Computer and Information Security Handbook, 317–337. https://doi.org/10.1016/b978-0-12-803843-7.00018-1

Personal communications Bjorn Van Den Brule - Engagement Manager Nautische sensoren Offshore Expertise Centrum, Rijkswaterstaat

Over ons. (n.d.). Shell. https://www.shell.nl/over-ons/shell-pernis-refinery/shell-pernis.html

Ørsted.nl - Love your home. (n.d.). Orsted. https://orsted.nl/

Personal communications James Broadhead - PhD candidate Human-Computer Interaction

Personal communications Leon Dirrix - Communication officer EEW

Personal communications Job-Jan Klompe - Junior instrument Engineer Shell

Personal communications Khadar Hassan - Turnaround Engineer Shell

Personal communications Mohamed Danad - Operations Manager Edge Dynamics

Peeters J.R., Tecchio P., Ardente F., Vanegas P., Coughlan D., Duflou J., eDIM: further development of the method to assess the ease of disassembly and reassembly of products — Application to notebook computers, EUR 28758 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79- 73189-1, doi:10.2760/864982, JRC107773

Pittroff, T. (2021, November 5). Mock Operating Rooms: The Real-life Blueprint that Every New Operating Room Project Needs. Brainlab. https://www.brainlab.com/es/journal/mock-o-r-s-the-real-life-blueprint-that-every-new-operating-room-project-needs/

Recycling of plastics from electronic waste. (z.d.). TNO. Geraadpleegd op 23 april 2022, van https://www.tno.nl/en/focus-areas/circular-economy-environment/roadmaps/circular-economy/plastics/plastic-waste-from-electronics/

Recycling rates in Europe by waste stream. (2021). European Environment Agency. Retrieved 1 April 2022, from https://www.eea.europa.eu/data-and-maps/figures/recycling-rates-in-europe-by

Rijkswaterstaat. (n.d.). Werken voor Nederland. Retrieved 17 March 2022, from https://www.werkenvoornederland.nl/organisaties/rijkswaterstaat#tab-over-ons

Rifle 5.56MM M16 and M16A1. Bev Fitchett's Guns. https://www.bevfitchett.us/rifle-5-56mm-m16-m16a1/info-stm.html

Roozenburg, N., & Eekels, J. (1998). Productontwerpen, structuur en methoden (2de editie). Boom Lemma.

Samal, S., Acharya, B., & Barik, P. K. (2022). Internet of Things (IoT) in agriculture toward urban greening. AI, Edge and IoT-based Smart Agriculture, 171–182. https://doi.org/10.1016/b978-0-12-823694-9.00015-3

Schischke, K., Proske, M., Nissen, N. F., & Schneider-Ramelow, M. (2019). Impact of modularity as a circular design strategy on materials use for smart mobile devices. MRS Energy & Sustainability, 6(1). https://doi.org/10.1557/mre.2019.17

Services – Edge Dynamics. (2020). Edge Dynamics. Geraadpleegd op 31 januari 2022, van https://edgedynamics.eu/services/

Sharma, D. K., Bhargava, S., & Singhal, K. (2020). Internet of Things applications in the pharmaceutical industry. An Industrial IoT Approach for Pharmaceutical Industry Growth, 153–190. https://doi.org/10.1016/b978-0-12-821326-1.00006-1

Shell Pernis. (n.d.). Shell. Retrieved 17 March 2022, from https://www.shell.nl/over-ons/shell-pernis-refinery/shell-pernis.html

Snuffelrobots en slimme helmen: 5G bij Shell Pernis. (2019). KPN.com. Retrieved 17 March 2022, from https://www.kpn.com/zakelijk/blog/snuffelrobots-en-slimme-helmen-5g-bij-shell-pernis.htm

Summary document of the Waste electrical and electronic equipment rates and targets. (n.d.). European Commission. https://ec.europa.eu/eurostat/documents/342366/351758/Target-Rates-WEEE

Tassoul, M. (2012). Creative Facilitation. VSSD.

The "Gelbe Tonne (Plus)". (n.d.). Alba. Retrieved 1 April 2022, from https://www.alba.info/en/business-areas/waste-management/trade-and-industry/recyclable-company-waste/

TLI series. (n.d.). Tadiran Batteries. https://www.tadiranbat.com/tli-rechargable.html

Tukker, A., Van den Berg, C., & Tischner, U. (2006). Product-services: a specific value proposition. In A. Tukker and U Tischner (Eds.), New Business for Old Europe - Product-service development, competitiveness and sustainability (pp. 22-34). Sheffield, UK: Greenleaf Publishing Ltd.

TWTG. (2021, August 31). Press Release - wins Shell Tender for Wireless Sensor - News. Retrieved 18 March 2022, from https://www.twtg.io/insights/news/press-release-twtg-wins-shell-tender/

TWTG. (2020, December 8). Webinar - LoRaWAN & Industrial Sites - News. https://www.twtg.io/insights/news/webinar-lorawan-industrial-sites/

United States Bureau of Naval Personnel (1970). Military Requirements for PO 1 & C. Bureau of Naval Personnel. p. 75.

Unsplash (n.d.). Various photos. Retrieved from: www.unsplash.com

van Boeijen, A., Daalhuizen, J., van der Schoor, R., Zijlstra, J., van Boeijen, A., & van der Schoor, R. (2014). Delft Design Guide. Macmillan Publishers.

Van Turnhout, K., Hoppenbrouwers, S., Jacobs, P., Jeurens, J., Smeenk, W., & Bakker, R. (2013). Requirements from the Void: Experiences with 1:10:100. International Working Conference on Requirements Engineering (REFSQ). Essen. Retrieved from https://www.researchgate.net/publication/263807351_Requirements_from_the_Void_Ex periences_with_110100

Van Turnhout, K., Leer, S., Ruis, E., Zaad, L., & Bakker, R. (2012). UX in the Wild: on Experience Blend & Embedded Media Design. The Web and Beyond. Amsterdam. Retrieved from https://www.researchgate.net/publication/263807038_UX_in_the_Wild_on_Experience_ Blend_Embedded_Media_Design

Vanegas, P., Peeters, J. R., Cattrysse, D., Tecchio, P., Ardente, F., Mathieux, F., Dewulf, W., & Duflou, J. R. (2018). Ease of disassembly of products to support circular economy strategies. Resources, Conservation and Recycling, 135, 323–334. https://doi.org/10.1016/j.resconrec.2017.06.022

Vanegas P., Peeters J.R., Cattrysse D., Duflou J.R., Tecchio P., Mathieux F., Ardente F., 2016. Study for a method to assess the ease of disassembly of electrical and electronic equipment - Method development and application in a flat panel display case study. EUR 27921 EN. doi:10.2788/130925

Vibration sensor - product manual. (z.d.). Github - TWTG. https://github.com/TWTG-R-D-B-V/neon-product-documentation/blob/main/VB/Installation%20%26%20Use/6008_AB_Product-Manual-NEON-Vibration-Sensor_D.pdf

Viola, N., Corpino, S., Fioriti, M., & Stesina, F. (2012). Functional Analysis in Systems Engineering: methodology and applications.

Viola, N., Stesina, F., Fioriti, M., Corpino, S., & Cogan, B. (2012). Functional Analysis in Systems Engineering: Methodology and Applications. IntechOpen.

Waste statistics - electrical and electronic equipment. (2022). European Commission. Retrieved 1 April 2022, from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Total_collection_rate_for_waste_electrical_and_electronic_equipment_(EEE),_2019_(%25_of_the_average_weight_of_EEE_put_on_the_market_in_the_three_preceding_years_(2016–2018)).png

Wu, Z., Yuan, W., Li, J., Wang, X., Liu, L., & Wang, J. (2017). A critical review on the recycling of copper and precious metals from waste printed circuit boards using hydrometallurgy. Frontiers of Environmental Science & Engineering, 11(5). https://doi.org/10.1007/s11783-017-0995-6

Xiang, D., Pang, Z. F., Long, D. F., Mou, P., Yang, J. P., & Duan, G. H. (2013). The Disassembly Process and Apparatus of Waste Printed Circuit Board Assembly for Reusing the Components. Applied Mechanics and Materials, 457–458, 474–485. https://doi.org/10.4028/www.scientific.net/amm.457-458.474

Xu, L. D., He, W., & Li, S. (2014). Internet of Things in Industries: A Survey. IEEE Transactions on Industrial Informatics, 10(4), 2233–2243. https://doi.org/10.1109/tii.2014.2300753