10 | Appendix

Appendix A: 1/10/100 method

The 1/10/100 method is considered useful for open ended projects that are oriented at opportunity finding instead of problem solving. It is also possible to apply this project when the client does not know of any preferable solution space. This project appears to agree with these characteristics. The overal idea of this method is to go through the entire project three times, taking a varying amount of days each time. The first design cycle would take one day, basically a pressure-cooker. The second cycle takes ten days and has an increased fidelity. The last cycle takes the remaining time available for this graduation project (van Turnhout et al., 2012).

The point of the first two cycles is simply to fail or at least not to put value on the outcome. Instead, the ideas and concept directions should “guide discussions about underlying desires, needs and requirements” (van Turnhout et al., 2013). Moreover, “there is a buildup of knowledge about the problem and its possible solutions during the project because the research and exploration of the design space ‘sticks’ with the designers” (van Turnhout et al., 2012).

According to Koen van Turnhout et al., the process benefits from risk taking in the first two cycles. Coming up with farfetched ideas makes it easier to challenge the stakeholders to look at the problem from a novel perspective.

CYCLE 1: 1 DAY

Redefine the problem statement

The problem definition is still quite broad. By narrowing down the problem it will be easier to come up with an adequate solution.

Context
Huidige situatie: vb. 1000 sensoren in bezit van bedrijf X. Levensduur van 1000 sensoren is 10-15 jaar. Aanname is dat de eerste sensoren het begeven na 10 jaar en de laatste sensoren na 15 jaar. Dit betekent dat na 10 jaar, voor 5 jaar lang (5*365=1825 dagen / 1000 sensoren) gemiddeld ongeveer om de dag (elke 44 uur) een sensor vervangen moet worden. Dit voelt als een significante taak, waarvan aangenomen wordt dat bedrijf X deze vermeden, of gereduceerd, wil zien worden.

Paradox: ook al verhogen we de levensduur van 10-15 jaar naar bijv. 20-25 jaar, het probleem blijft bestaan: na 20 jaar zal elke 44 uur een sensor vervangen of opgehaald moeten worden.

De vraag/ goal is : hoe kan je het economisch gerechtvaardigd maken om ‘wireless network nodes’ ‘in the wild’ van onderhoud te voorzien?
Hoe deal je met onderhoud / collection van ‘vast networks of wireless sensing nodes’?
Hoeveel tijd kost het onderhoud / ophalen van een wireless node?
Hoeveel tijd mag het kosten om een wireless node te repareren?
Modulair in batterij grootte; afhangend van toepassing/bereikbaarheid maar ook aantal in gebruik kan de batterij groter of kleiner gemaakt worden
Zodra de eerste sensoren aangeven dat ze leegraken, komt Edge Dynamics ze allemaal ophalen / vervangen voor nieuwe/repurposed sensoren.

According to Dwayne Spradlin (hbr.org, 2012), the following steps should be taken to come to the right problem statement:

Step 1: establish the need for a solution

What is the basic need?
Everlasting sensors; economically viable maintenance of sensors

What is the desired outcome?
Uninterrupted monitoring of industrial assets

Who stands to benefit and why?
The client benefits as they do not need to worry/ deal with down-time of sensors;

Edge Dynamics does not benefit as they their current business model relies on sales

Step 2: Justify the need

Is the effort aligned with our strategy?
Does not seem to be the case

What are the desired benefits for the company, and how will we measure them?
Increased revenue; attaining sustainability targets

Step 3: Contextualise the problem

What approaches have we tried?
More energy efficient software (firmware); solar powered sensors have been considered

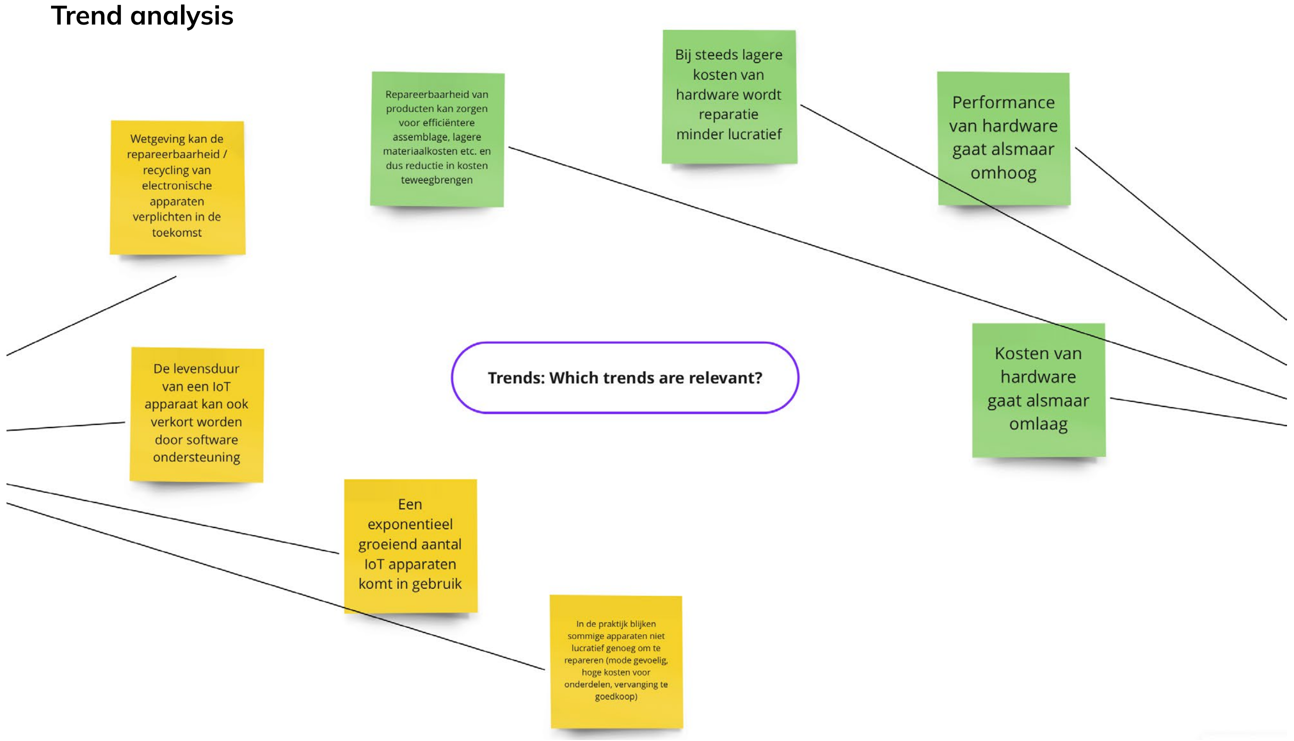
What have others tried?
Energy harvesting (solar; thermo-electric)

What are the internal and external constraints on implementing a solution?
Size; environment

Step 4: write the problem statement

Sensors currently have a finite life. It is as of now not economically feasible to repair the sensors. Sensors installed at the same time will more or less malfunction at the same time. This leads to logistical challenges for anyone having to repair the sensors.

Trend analysis



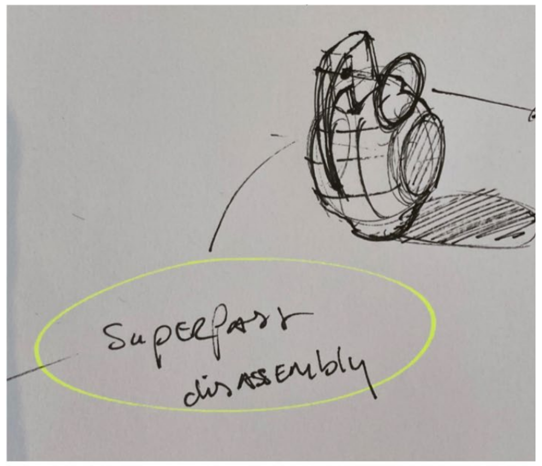
A quick trend analysis showed the most likely factors of relevance to the (future) development of industrial IoT. These were then clustered to form two design directions:

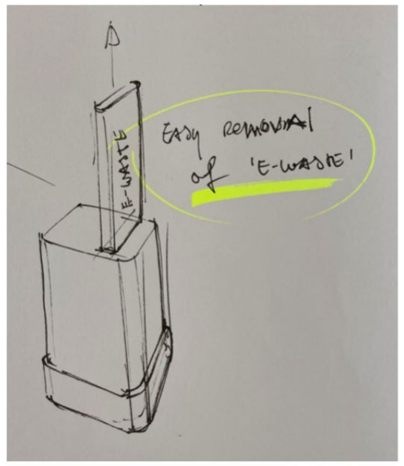
Almost infinite sensors future hardware will make sensors almost perpetual as computing power is ever increasing (Moore’s law), while at the same time less energy is required. (increasing energy efficiency for microchips; increasing energy density of batteries)

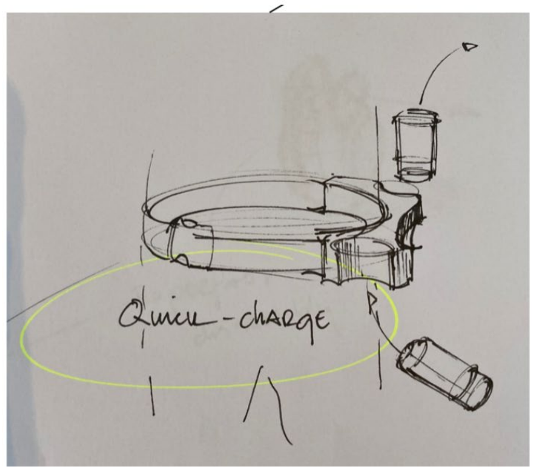
Consumable sensors wireless sensors will become so cheap to produce that it is not cost-effective to repair them: instead, sensors should be optimised for recycling.

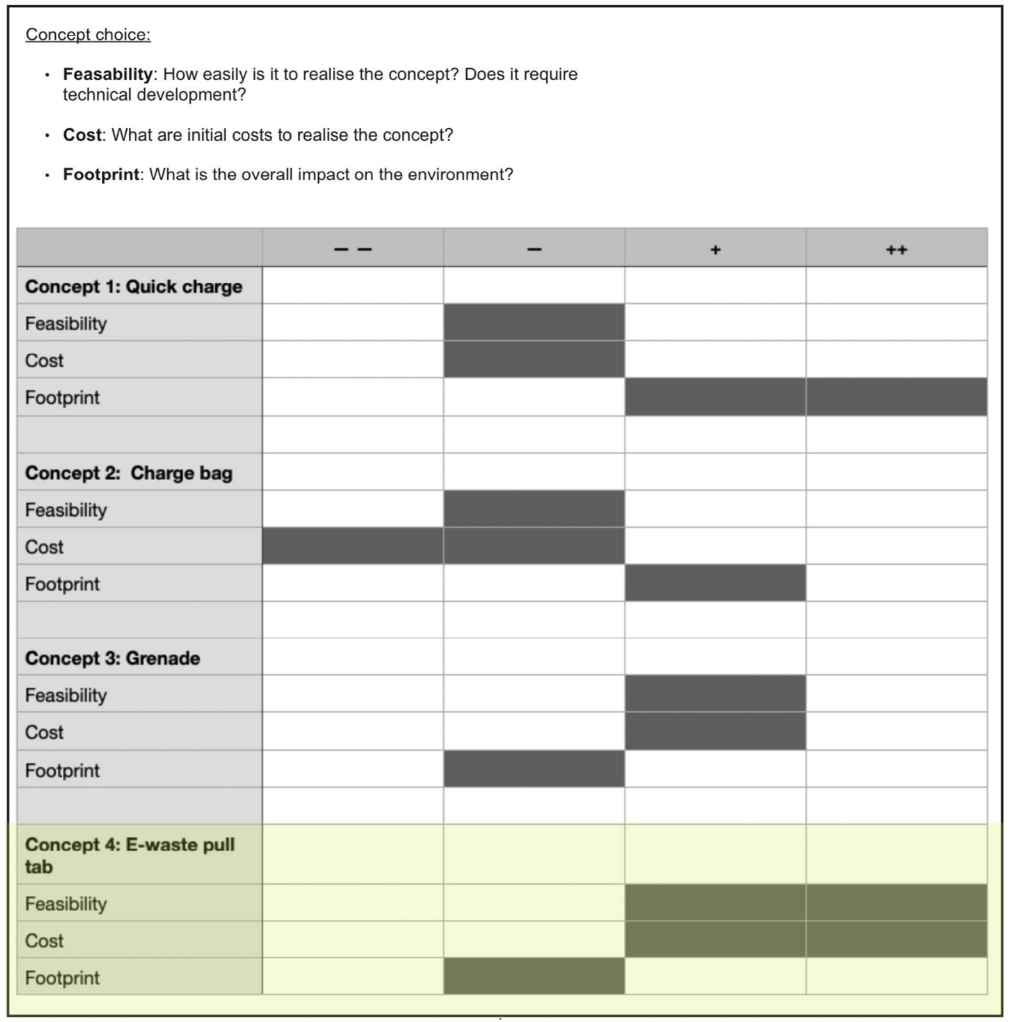
Ideation

By using How-tos, multiple Ideas were quickly generated. Based on the formulated design directions, the most promising ideas were chosen. Using a Harris profile, the most appropriate concept direction was chosen.









Concept choice:

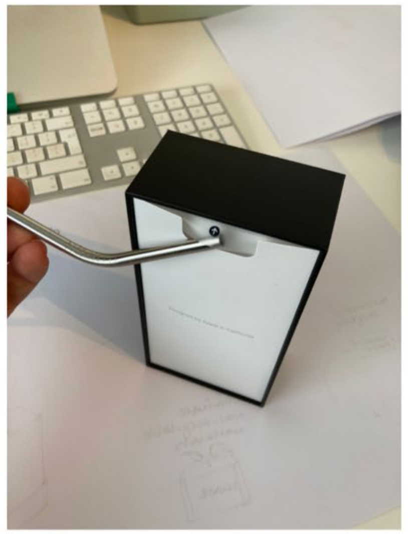
- **Feasability**: How easily is it to realise the concept? Does it require technical development?
- **Cost**: What are initial costs to realise the concept?
- **Footprint**: What is the overall impact on the environment?

	– –	–	+	++
Concept 1: Quick charge				
Feasibility		■		
Cost		■		
Footprint			■	■
Concept 2: Charge bag				
Feasibility		■		
Cost	■	■		
Footprint			■	
Concept 3: Grenade				
Feasibility			■	
Cost			■	
Footprint		■		
Concept 4: E-waste pull tab				
Feasibility			■	■
Cost			■	■
Footprint		■		

Prototyping

Quickly prototyping the concept further detailed the idea; a priming action should be done before recycling, as not to accidentally pull the device apart. This could require a special tool, proprietary to Edge Dynamics. Once the product becomes obsolete, the product can be separated with ease for recycling of its components.

MOCK-UP CHOSEN CONCEPT



Speciale tool voor priming

Pull tab verschijnt voor snel verwijderen van moeilijk te scheiden onderdelen

Onderdeel met geintergreerde PCB wordt verwijderd

Nu is batterij met pull tab tevoorschijn gekomen en kan verwijderd worden

Rest product kan met conventionele afval

Outcome

The first cycle aimed to include an analysis phase, an ideation phase and a validation phase. Starting off with the pressure cooker I revisited the problem definition. Using a structured problem-definition process, I tried to define the problem to be solved. Next, using mind-maps I quickly exhausted the topics I could think of surrounding the stated project goal. Combining this with a short trend analysis, I identified two future scenarios. Based on these design directions, I generated several ideas of which I picked the best option using the weighted objectives method. This lead to a concept direction, which I quickly prototyped to illustrate the idea.

Key insights

The following insights were revealed during discussion with Edge Dynamics:

- Edge Dynamics acknowledges that their current business model is not yet in line with the intended updated product.

With a sales oriented business model, it is hard to benefit from longer lasting products. A service or performance business model embraces product longevity, as the supplier remains the owner of the products they offer and can charge an annual fee, resulting in predictable and recurring revenue. This is likely a better and even necessary corporate pivot to reap the benefits from products that would be easy to maintain and repair.

- Edge Dynamics stresses the need for repair as their products retail for €300 - €500 a piece. This is a strong incentive for customers to keep using the sensors already bought.

This retail price incorporates development costs (hardware, software, certification), competitors' products retail for even higher prices due to higher overhead. Instead of coughing up the large investment upfront, providing the sensors as a service with a lower annual fee might be an easier decision to take for companies.

- A product-service system seems the way to go, as keeping sensors alive after sale is going to be complex by the looks of it.

Either the supplier or customer has to deal with the generation of drained primary batteries and malfunctioning hardware. Linked to the scale of implementation, this might be a significant problem. A holistic approach is likely required, taking into account spare parts, logistics and upgrades.

Reflection

Results from the pressure cooker were quite comfortable and obvious outcomes. This is unfortunately in contrast with the intention of the method. I believe I could have pushed for more farfetched, intangible ideas in order to deviate from the rather obvious design direction. However, I did get into valuable discussions with Edge Dynamics.

Discussion with my mentor came down to trying different methods to break out of my comfort zone. We agreed on using analogies to project Edge Dynamic's design challenge onto different scenarios. In addition, visiting the scene where ED's sensor nodes are deployed should be at the top of my To-Do list. This can show obvious design aspects that are likely overlooked from afar.

CYCLE 2: 10 DAYS

The second cycle takes up ten working days, and started off with the conclusions from reflecting on the first cycle.

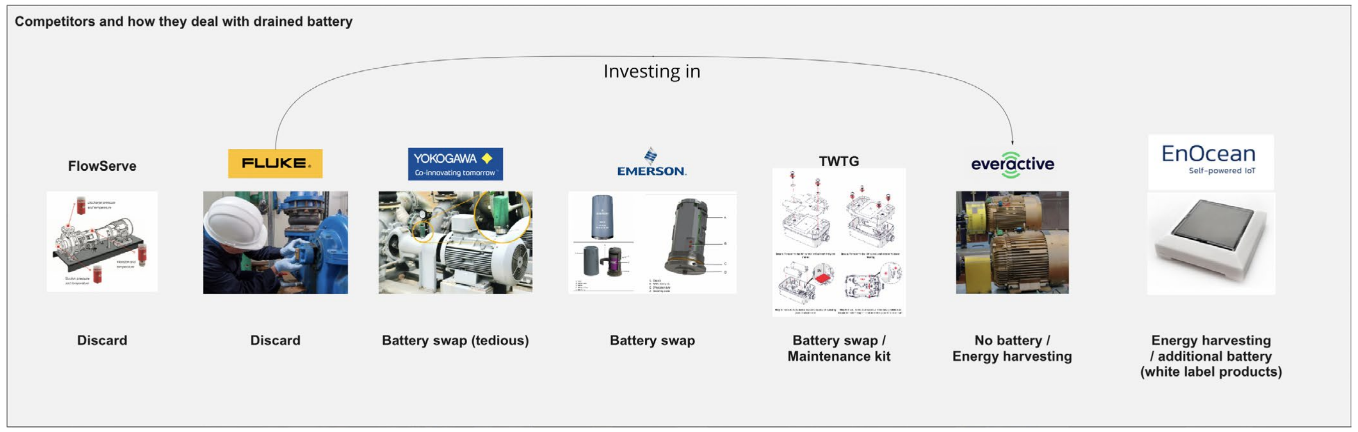
Analysis

How are other players in the market dealing with the stated problem?

Concluded from cycle 1 was that Edge Dynamics' business operations are still malleable. To get a feeling for the problem I am wondering how and if others are dealing with the same challenge. Therefore, I took a look a competitors and more specifically the way they deal with maintenance of their products.

Most competitors offer their products as a service, in some combination with their proprietary cloud service and platform. Still, many offer only hardware with installation services or even hardware only. Everactive (energy-harvesting) only offers service based machine monitoring.

Competitor products either make use of a primary battery as well or utilise energy harvesting. Looking at product manuals, some competitor products are not meant to repaired, they are single use (Fluke). Another competitor does offer replacement batteries, but opening up the sensor is a tedious process (Yokogawa). Emerson and TWTG seem to have dedicated effort to make their products' batteries at least swappable.



Competitors and how they deal with drained battery

Competitors that offer energy harvesting sensors (Everactive) make it clear how it is a benefit over battery-powered sensors, stating no maintenance is required after instalment and no harmful waste is generated (primary batteries).

Energy harvesting could be an interesting pivot in Edge Dynamics' corporate direction. Trend analysis from cycle 1 shows that wireless electronics are becoming faster and more energy efficient.

However, Edge Dynamics is promising battery life of 15 years or more, which likely means battery life will not be the bottleneck as other components degrade as well.

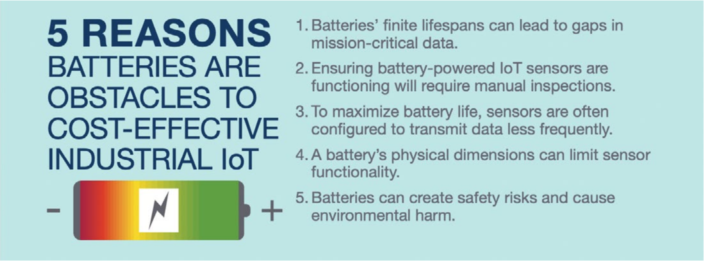
TU Delft has a research group led by Przemyslaw Pawelczak on battery free IoT. Interviewing him could answer what the potential of energy harvesting in IIoT could be.

Interview James Broadhead - answers

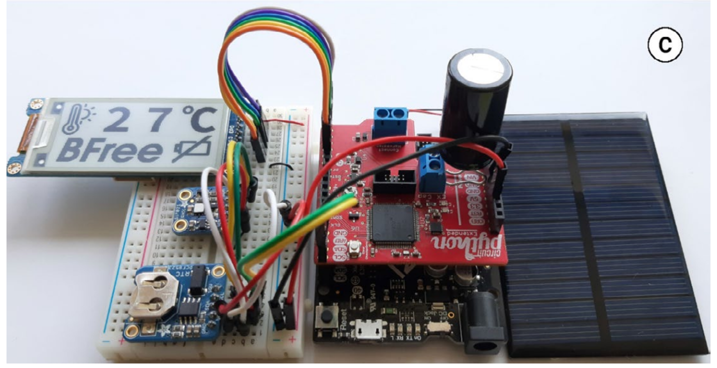
- Most important are the situational aspects, where is the device going to operate, what energy can be harvested at location (what type of EH is possible), how often are measurements needed
- Bottlenecks of EH are the volatility of energy levels (e.g. cloudy or night time for solar panels. This could results in a delay of data measurements.
- Legislation likely towards reduction of harmful materials (in terms of ecology but also mining conditions), but batteries won't go away.
- Research on sustainable IoT is increasing, this is an indicator for its future.
- Battery technology is also advancing, so we're likely going to see a mix of both BP and EH in

(https://s3.amazonaws.com/everactive-media/content/uploads/2019/06/17103828/EverActive_Infograph_1.pdf)

https://www.tudelft.nl/2021/tu-delft/iedereen-kan-nu-batterijloze-apparaten-bouwen



1. Batteries' finite lifespans can lead to gaps in mission-critical data.
2. Ensuring battery-powered IoT sensors are functioning will require manual inspections.
3. To maximize battery life, sensors are often configured to transmit data less frequently.
4. A battery's physical dimensions can limit sensor functionality.
5. Batteries can create safety risks and cause environmental harm.



the future.

- Companies offering energy harvesting sensors cannot claim 20 years of maintenance free operation as they do not exist this long yet.
- Critical failure of EH device will happen on a later moment in time than BP, but will not be easily predictable.
- In case the type of energy harvesting is related to the parameter that is measured, losing connection can be the indication something is wrong with the monitored asset.

Battery powered IoT will have its place in the IoT market as its reliable, cheap (economy of scale) and can operate in a variety of harsh conditions (industrial environments).

How would maintenance be incorporated with E.D.'s current practice?
When a long lasting product is completely dependent on a replaceable part with a limited lifespan, the supplier is utilising a hybrid business model. The main product is offered at a reduced price and recurrent revenue is generated by replaceable part (Products That Last, 2014).

Risks:

- The user should be prepared to regularly pay for a refill (what is regular? >10 year battery life might be too long for a replacement)
- The 'refill' could be bypassed as primary batteries are sold by others (the current battery is a standard component)

Service based business model
By offering access to sensors as a service, a high upfront capital investment is avoided, which makes it a lower-threshold decision for customers. At the same time, the supplier keeps ownership of the products, which opens up the possibility for reverse logistics and valuable feedback on their products.

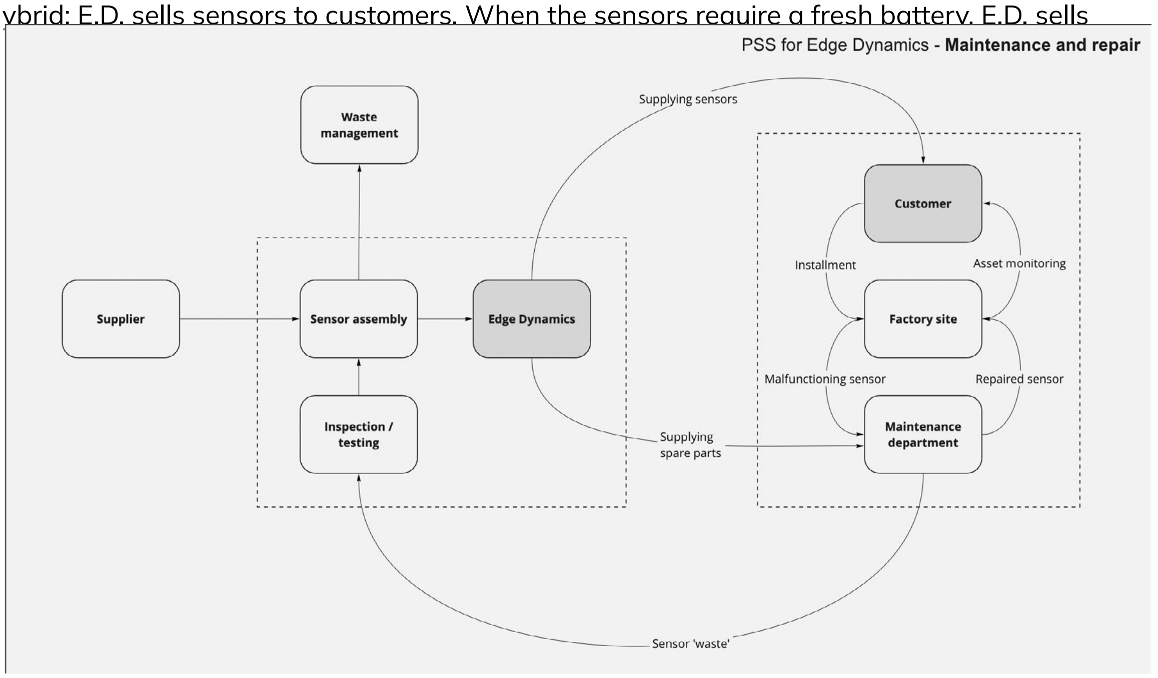
Risks:

- Relative affordability. The service has to offer a significant benefit or be affordable enough where simply buying the sensors would make less sense.

Exploration of possible business models gave light to the following options. They range from closest to farthest from current business practice:

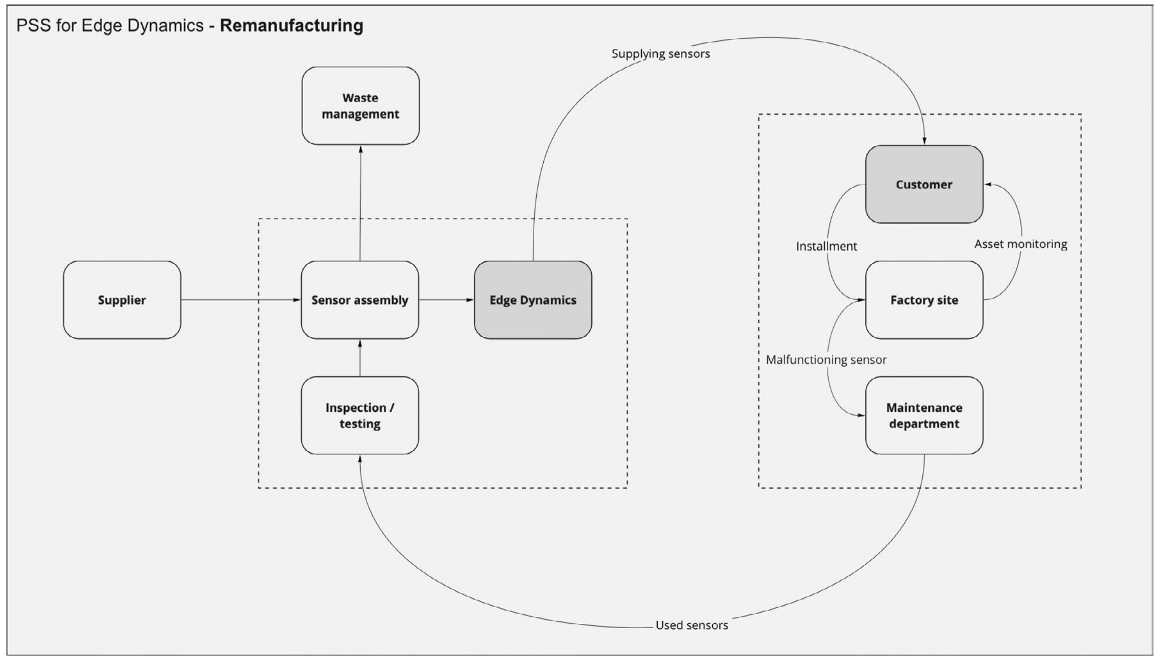
Hybrid / Service model - Maintenance and repair

Hybrid: E.D. sells sensors to customers. When the sensors require a fresh battery, E.D. sells replacement batteries to the customer. This involves little responsibility for E.D.



Service: E.D. supplies sensors to customers for a recurrent rate (e.g. monthly, annually). When the sensors require a fresh battery, E.D. supplies replacement batteries to the customer. The cost for replacement batteries are incorporated in the recurring flat rate.

Service / performance model - Remanufacturing (pay-as-you-go)



Service: E.D. supplies sensors to customers for a recurrent rate (e.g. monthly, annually). When the sensors are low on battery, E.D. recollects sensors from the customer and provides new ones.
Performance: E.D. supplies and installs sensors at customer facilities. The customer pays per minute of monitoring. When sensors are running low on battery, E.D. either installs new batteries or replaces sensors.

Design direction

The business models require a redesign of the current sensor. This redesign has to follow either design for repair guidelines or design for remanufacturing guidelines, although there is significant overlap.

Design for repair has the benefit of giving customers the option to prolong their products themselves, by providing them with spare parts. No maintenance has to be provided by the supplier.

Design for repair:

- On the spot repair
- Easy access to the product parts that are most likely to fail
- No (or few) tools needed to open the product and replace battery, therefore no use of screws, adhesives and glues

Risks:

- The sensors are long lasting products. They are likely prone to technological obsolescence and might be outdated by the time of battery replacement.
- Just replacing the battery is not a guarantee for 'infinite' operation. Other hardware components are degrading over time as well.

Design for remanufacturing has the benefit of bringing every product back to a 'good as new' state; the customer can be assured the product works just like it did the first time.

Design for remanufacturing:

- Integrate modules in the product; for instance communication module, power module, computing module.
- In case of screws use as few different types as possible and no exotic types
- Tracking and identification of modules or parts
- No (or few) tools needed to open the product, no use of adhesives and glues

Risks:

- E.D. has customers worldwide, which makes it currently for E.D. a challenge to execute proper recovery of sensors destined for remanufacturing. Replacing sensors is likely time sensitive as well. This can be mitigated by premature / preventative replacement.
- Operating remanufacturing of sensors is a significant cost. This could be mitigated by cost savings due to reverse logistics.

scope / mission

I want to future proof E.D.'s sensors by preparing them for inevitable hardware improvements and alternative power supplies. This will lead to a strengthening of Edge Dynamic's value proposition of uninterrupted machine health monitoring with circular sensors.

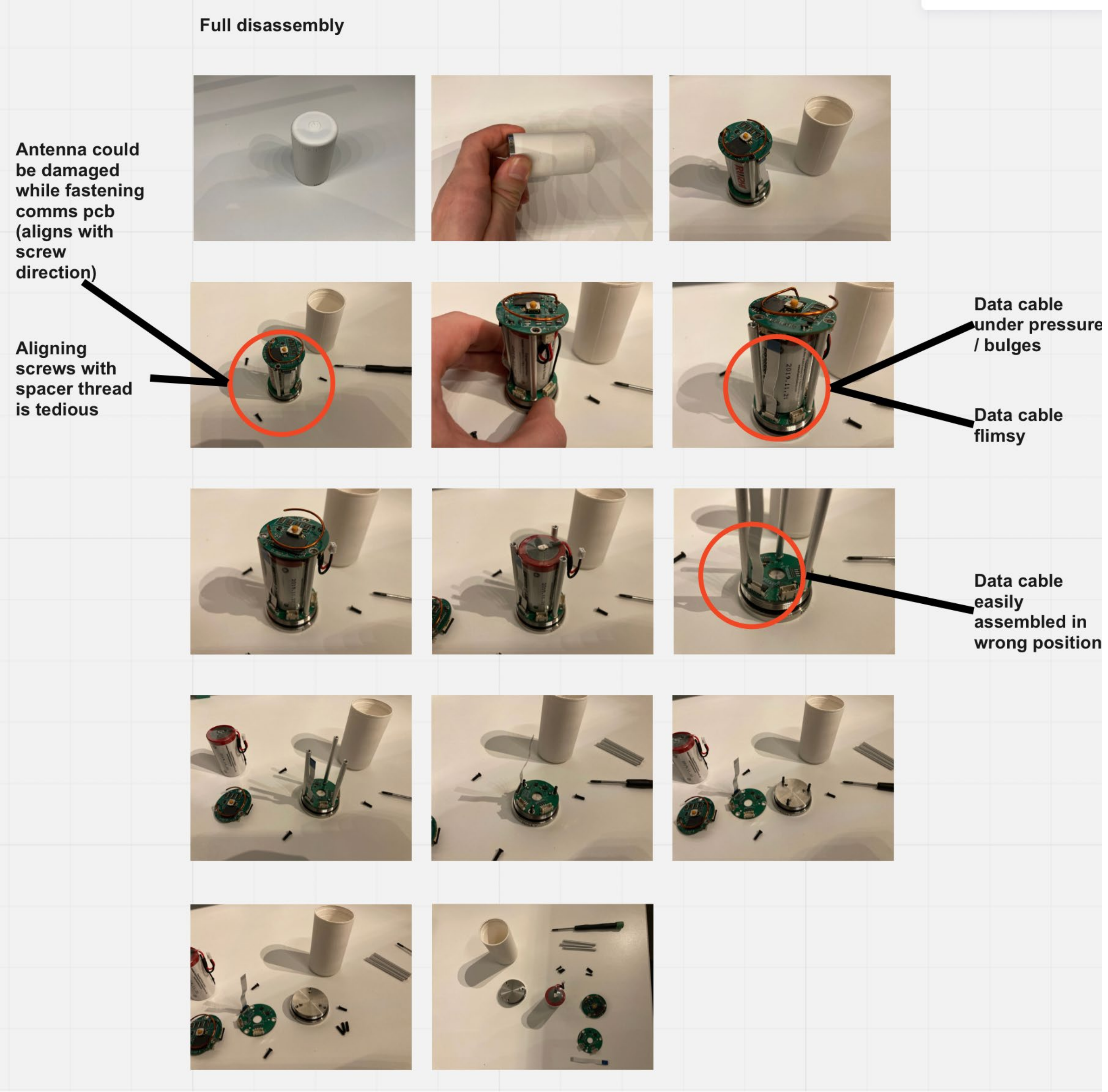
Therefore I need to answer the following questions:

- RQ: How can the repairability of electronic / IoT devices be assessed?
- sub-RQ: How can repairability of electronics / IoT devices be optimised?

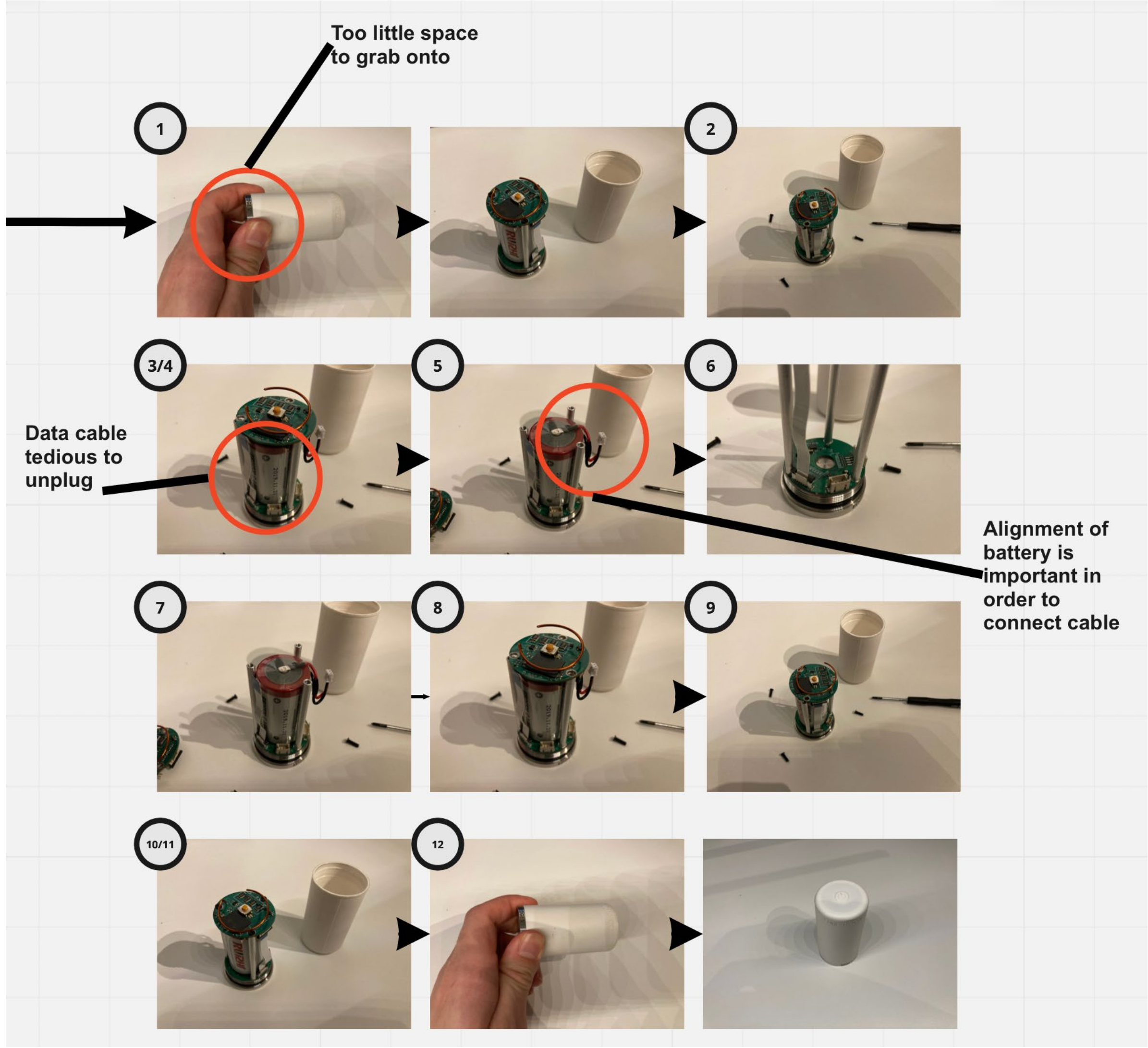
Analysing the current product

- What is the current product's assembly architecture?

Full disassembly of the product shows the following issues:



Performing maintenance (replacing the battery) on the current product goes as follows:



Too little space to grab onto

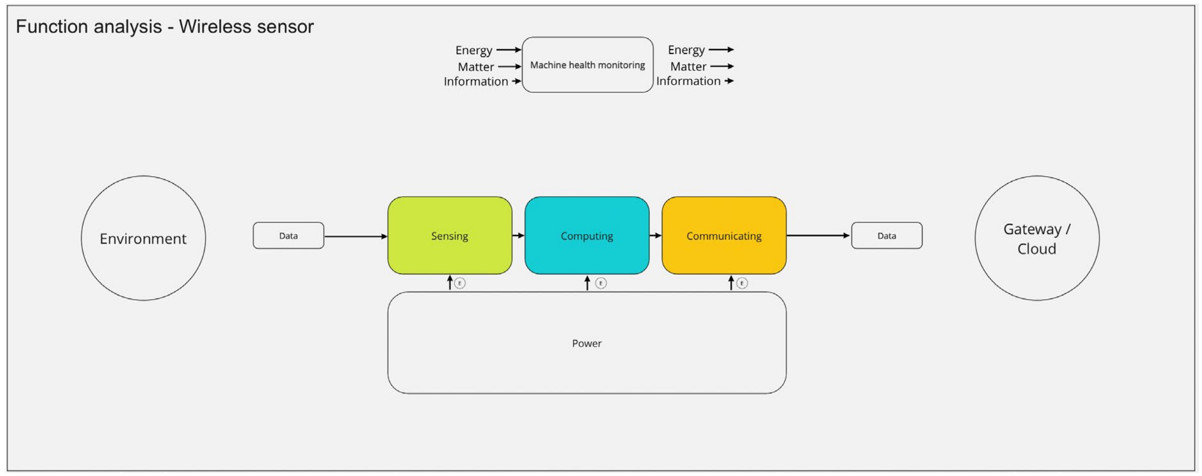
Data cable tedious to unplug

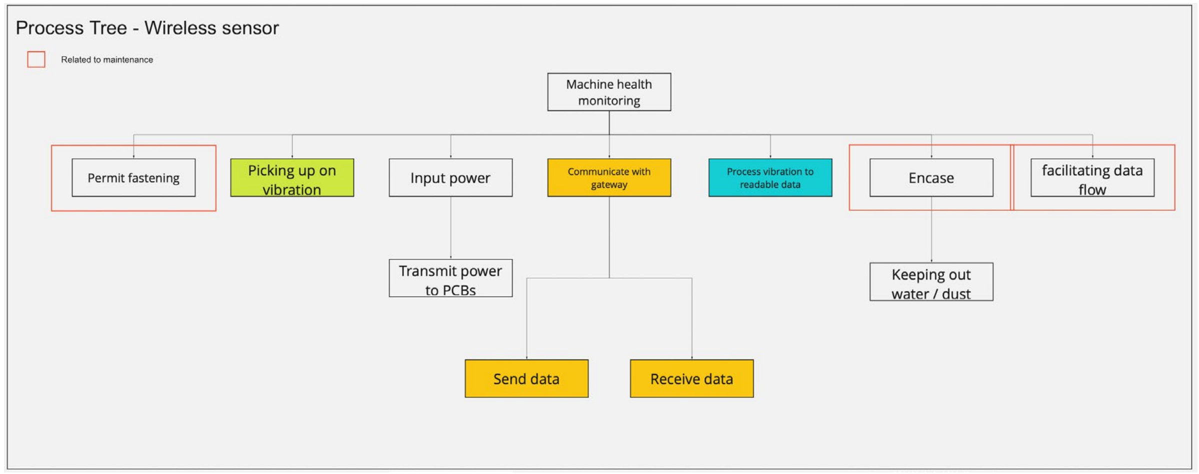
Alignment of battery is important in order to connect cable

In order to assess the repairability of the current sensor node, I will map the product architecture using a function analysis.

What are the product’s (sub)functions?

- The product’s essential and core functions are:
- Sensing: hardware that can pick up and transform environmental energy to digital data
- Computing: hardware that can compute and process the data provided by the sensing hardware for it to be transmittable
- Communicating: hardware that can transmit and receive data to and from the nearest gateway





Which functions are essential in supporting maintenance (red square in image)?

- Encasing: in the current product architecture the case is solely meant for protecting the essential hardware from environmental effects such as moisture, dust and fall damage. The case is also the first thing that stands in between anyone considering maintaining the product.
- Connections: bridging hardware components, be it wiring or soldering, can be essential for (easier) maintenance.
- Fastening: making sure every component stays where it has to be, fasteners are essential to a product but can be a significant hindrance to anyone maintaining the product

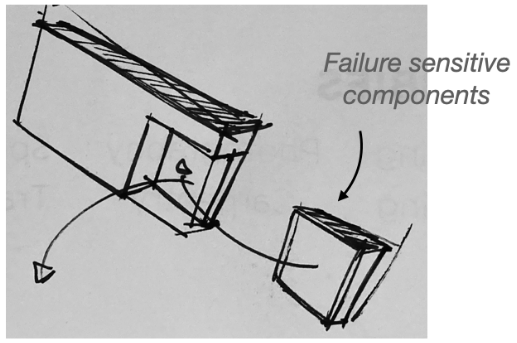
What sensor node components need to repaired?

- Battery as it drains over time; this is currently the bottleneck of the sensor's lifespan
- PCBs because they either degrade or become outdated
- Casing due to (fall) damage; this could lead to weathering damage and violation of certification

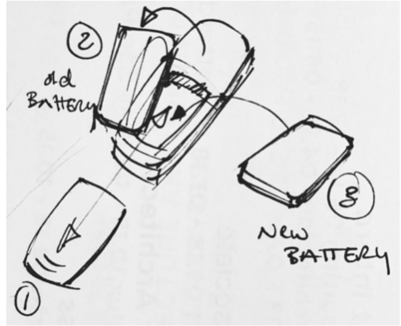
Ideation

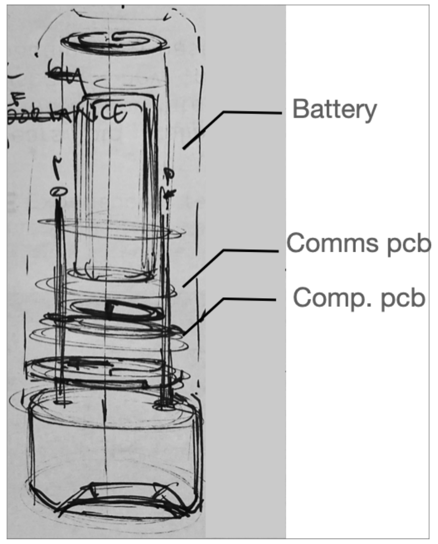
How can repair be facilitated? Figure below shows several design directions how barriers to repair can be lowered.

Swappable
unit

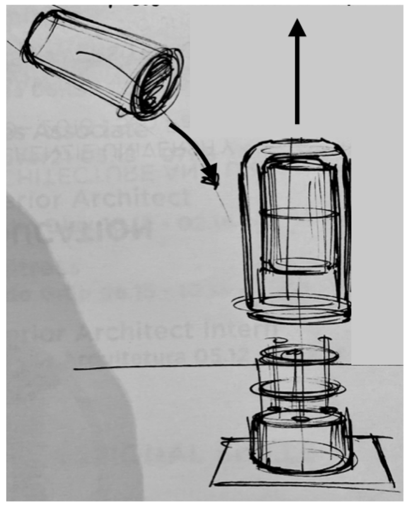


Swappable
battery





Components stacked by increasing importance; first access to part that is most likely to fail

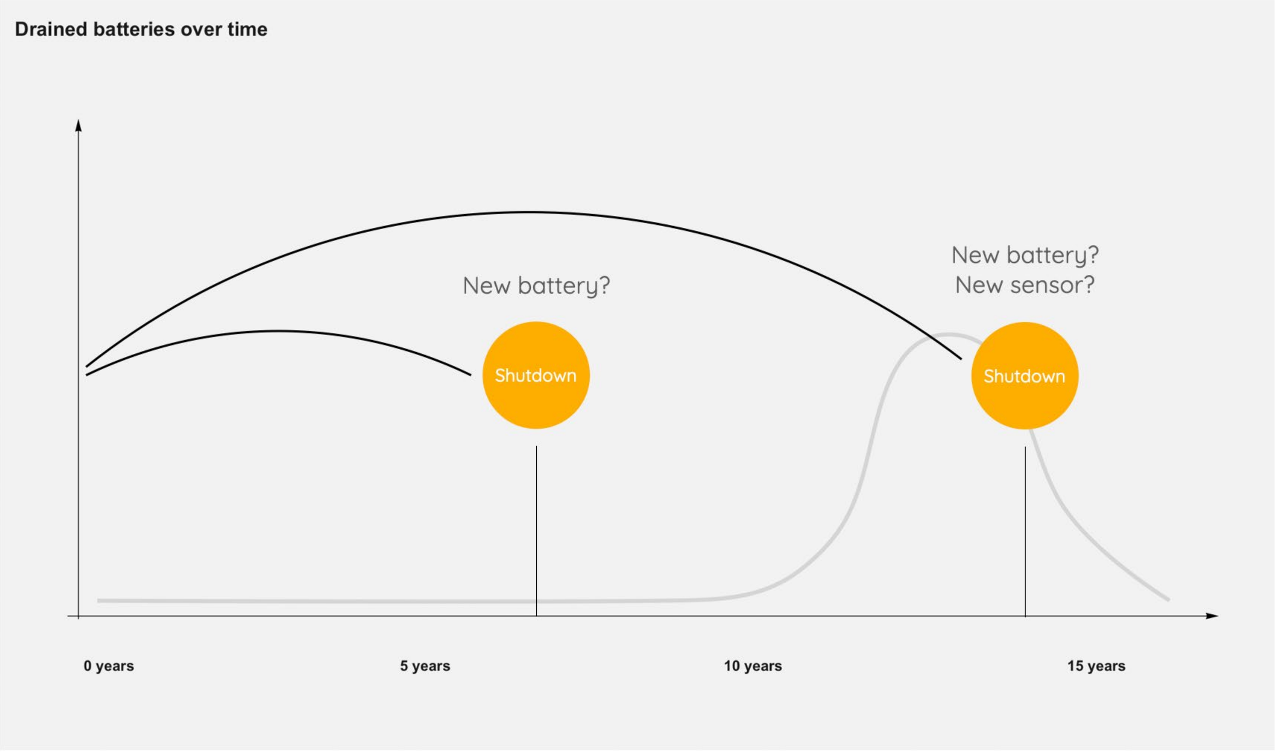


Reduce the current amount of steps for disassembly from 10 to just 2 steps by integrating the battery into the case; removing the case will remove the battery as well

Outcome

After diving deeper into the IIoT market through a market / competitor analysis, I stumbled upon what seemed to me to be the key challenge of this project in the second cycle; the accumulation of dead sensor node batteries around more or less the same time. This conundrum seemed to be a case of which situation would be less bad; either the sensors are installed in batches, spreading the load of replacement over time, or a massive amount of batteries needs to be replaced at the same time. Either way, it would be a huge stand alone undertaking.

Discussing this surface the concept of a shutdown; the systematic maintenance run already in place and occurring every several years. This could be an opportunity to tune the sensor implementation and maintenance to.



In addition, Edge Dynamics revealed their corporate colours; the reasoning for a redesign were touched upon and showed a different direction that seems valuable. Therefore, the problem statement could be refined once more.

Problem statement
The current product family does not match the corporate goals of Edge Dynamics. The product family does not support an EoL scenario. The product family is difficult to match individual customer requirements.

Refined assignment
I will apply modular design principles and generate a variety of alterations for the current product's architecture. By prototyping these and comparing them with the original design will show if the desired outcome has been achieved.

Key insights

Why does Edge Dynamics want repairable sensors?

They want to keep sensors running that are already in use, because this reduces costs for the customer and would reduce costs for Edge Dynamics in case of a PSS, a mode of operations the industry is shifting towards and they want to follow suit. In addition, it reduces the environmental footprint of a sensor, which would lead to a greener image for Edge Dynamics and offers customers the choice to work with sustainable partners, something which is specifically asked for.

Why does Edge Dynamics aim for sensors that run for 15 years?

Every factory site has a recurrent maintenance period called a shut-down. For smaller sites this moment could happen every 3 or 4 years, large sites could carry out shut-downs every 7 or 8 years. A shutdown is a perfect moment to also maintain sensors, especially when they are installed in hard to reach locations. A battery life of 15 years (2 times 7 years + 1 year buffer) could account for two periods in-between shutdowns of large sites. Having sensors that are tuned to these shutdowns makes them efficient in use.

Why does Edge Dynamics want a modular sensor?

Customer requirements can differ a lot. Currently, this means sensors are almost tailor made to the needs of individual customers. Edge Dynamics wants to move ahead and offer flexibility up front. This would require a range of components or modules that are intended to be matched with each other based on customer preference. If for instance customer A works with communication protocol X and needs sensor type Y with battery life Z, a modular product architecture would make it easier to compile this product.

Reflection

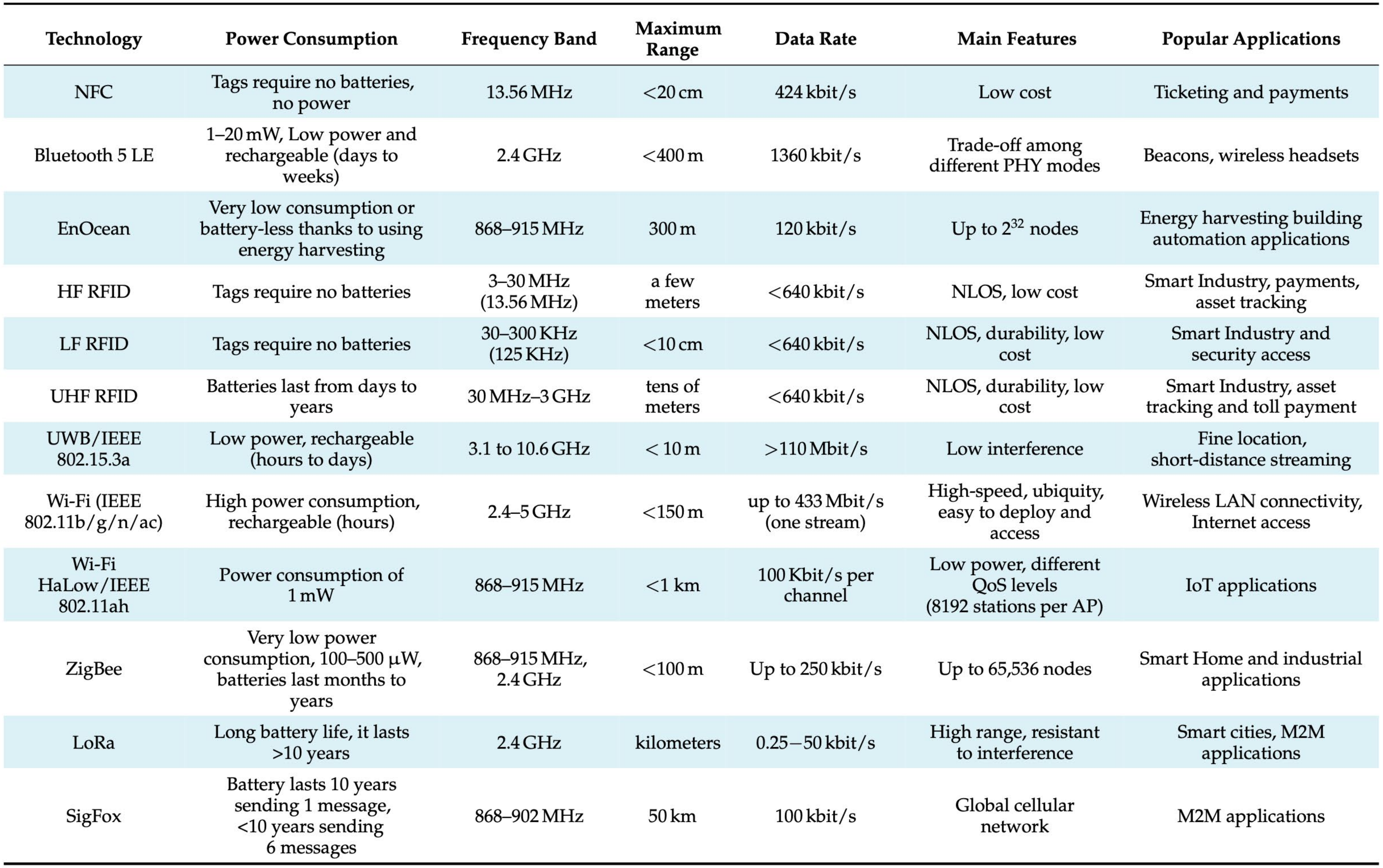
The second cycle started off on the right track; an analysis on the problem context showed interesting compromises between viability of any business model put in place and the technological possibilities of IoT sensors.

Towards the end of the cycle I did however deviate from the outline of the basic design cycle and got stuck in the analysis phase as it seemed like I got closer to finding the right problem. Here, I lost the purpose of the 1/10/100 method a bit out of sight, as the first cycles aren’t necessarily about the results, but emphasise the discussions that should arise from any possibly farfetched design directions. Instead, I jumped right to the third cycle. Together with my supervisors I agreed on pursuing the corporate goals as input for the product redesign.

Appendix B: Comparison main competitors

	Image	Size	Sensor types	Power	Communication	Battery life	Battery life (corrected 1 hour)	Certification	Special notes	IP protection
Edge Dynamics		70 x 38 (dia.) mm	Temperature Pressure Vibration Humidity	**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	ATEX zone 0	-	IP67
Yokogawa		Vibration: 97 × 46 (dia.) mm Pressure, temperature: 188 × 68 (dia.) mm	Temperature Pressure Vibration	**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	ATEX zone 1	Features NFC chip combined with phone app to adjust settings	IP67
TWTG		96 x 64 x 40 mm	Temperature Vibration Valve position	**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)**	ATEX zone 1	Offers battery replacement kit (two batteries, four o-rings and gasket)	IP65
Fluke		60,5 x 24 (dia.) mm	Vibration sensor	**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)	-	-	Requires glue for mounting on equipment	IP67
Emerson		-	Vibration sensor	**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	ATEX zone 0	Batteries are replaceable in an explosive atmosphere	IP67
Flowserve		132 x 64 (dia.) mm	Temperature Pressure Vibration	**3.6V, 4800mAh** primary battery (lithium-thionyl chloride) Note: **Non-repaceable battery**	LoRaWAN 900 MHz	4 years (update time: 0,5 hour)	8 years	ATEX zone 0	-	IP67
ABB		100 x 36 (dia.) mm	Vibration sensor + temperature combined	**3.6V, 2600mAh** primary battery (lithium-thionyl chloride) Note: **Non-repaceable battery**	WirelessHART 2.4 GHz	3-5 years (Update time: unknown)	-	ATEX zone 0	Communicates battery life solely on temperature operating range	IP66

Appendix C: General overview characteristics communication protocols



Technology	Power Consumption	Frequency Band	Maximum Range	Data Rate	Main Features	Popular Applications
NFC	Tags require no batteries, no power	13.56 MHz	<20 cm	424 kbit/s	Low cost	Ticketing and payments
Bluetooth 5 LE	1–20 mW, Low power and rechargeable (days to weeks)	2.4 GHz	<400 m	1360 kbit/s	Trade-off among different PHY modes	Beacons, wireless headsets
EnOcean	Very low consumption or battery-less thanks to using energy harvesting	868–915 MHz	300 m	120 kbit/s	Up to 2^{32} nodes	Energy harvesting building automation applications
HF RFID	Tags require no batteries	3–30 MHz (13.56 MHz)	a few meters	<640 kbit/s	NLOS, low cost	Smart Industry, payments, asset tracking
LF RFID	Tags require no batteries	30–300 KHz (125 KHz)	<10 cm	<640 kbit/s	NLOS, durability, low cost	Smart Industry and security access
UHF RFID	Batteries last from days to years	30 MHz–3 GHz	tens of meters	<640 kbit/s	NLOS, durability, low cost	Smart Industry, asset tracking and toll payment
UWB/IEEE 802.15.3a	Low power, rechargeable (hours to days)	3.1 to 10.6 GHz	< 10 m	>110 Mbit/s	Low interference	Fine location, short-distance streaming
Wi-Fi (IEEE 802.11b/g/n/ac)	High power consumption, rechargeable (hours)	2.4–5 GHz	<150 m	up to 433 Mbit/s (one stream)	High-speed, ubiquity, easy to deploy and access	Wireless LAN connectivity, Internet access
Wi-Fi HaLow/IEEE 802.11ah	Power consumption of 1 mW	868–915 MHz	<1 km	100 Kbit/s per channel	Low power, different QoS levels (8192 stations per AP)	IoT applications
ZigBee	Very low power consumption, 100–500 µW, batteries last months to years	868–915 MHz, 2.4 GHz	<100 m	Up to 250 kbit/s	Up to 65,536 nodes	Smart Home and industrial applications
LoRa	Long battery life, it lasts >10 years	2.4 GHz	kilometers	0.25−50 kbit/s	High range, resistant to interference	Smart cities, M2M applications
SigFox	Battery lasts 10 years sending 1 message, <10 years sending 6 messages	868–902 MHz	50 km	100 kbit/s	Global cellular network	M2M applications

Main characteristics of communications technologies IoT nodes (Fraga-Lamas et al., 2021)

Appendix D: Antenna Design and RF Layout Guidelines

EFFECT OF ENCLOSURE AND GROUND PLANE ON ANTENNA PERFORMANCE
Antennas used in consumer products are sensitive to PCB RF ground size and the product's plastic casing. The antenna can be modeled as an LC resonator whose resonant frequency decreases when either L (inductance) or C (capacitance) increases. A larger RF ground plane and plastic casing increase the effective capacitance and thus reduce the resonant frequency.

EFFECT OF GROUND PLANE
As explained before, a monopole PCB antenna requires a ground plane for proper operation. Figure 25 shows an example where a MIFA is placed on a PCB with a different ground plane size. The PCB size varies from 20 mm × 20 mm to 50 mm × 50 mm.
The curves show that larger RF ground planes decrease the resonant frequency and better grounding provides better return loss. This is the key for a good PCB layout. The better the ground provided for the quarter-wave antenna, the better it will correlate with the theoretical behavior. This is a key concept in antenna design for small modules where there is hardly enough space for ground clearance.

EFFECT OF ENCLOSURE
Similar to the effect of the ground plane, to quantify antenna sensitivity to the product's plastic casing, experiments were performed on a wireless mouse as shown in Figure 26. The Cypress MIFA is placed inside the plastic casing of the wireless mouse, and then measurements are made for radiation pattern and return loss.

WIRE ANTENNAS
Wire Antennas are the classical antennas that are conductors of quarter-wave length. They are fixed on the PCB but rise from the PCB plane and protrude to free space over a ground plane.

They have excellent RF performance as they are exposed to space as a 3D antenna. They have the best range and have the most isotropic radiation pattern.

For BLE applications requiring a small form factor, they are not preferred as they take a lot of space and vertical height. However, if space is not a constraint, they can be the best antenna to use in terms of RF range, directivity and radiation pattern. In general applications such as a smart home controller that plugs into a wall can use this type of antenna. The wire shape and size need to be optimized for a particular industrial design (ID). The wire can be bent according to the enclosure. Special care should be taken for manufacturing of the wire antenna as they can be of various shapes according to the enclosure (Cypress Semiconductor Corporation, 2018).

Table 5. Comparison of MIFA, IFA, Chip, and Wire Antennas

Properties at 2.44 GHz	MIFA	IFA	Chip Antenna	Wire Antenna
Appearance				
Recommended Applications	Less Area (Mouse, Keyboard, Presenter)	Height Constrain (Heart Rate Monitor)	Small Area (Nano Dongle, BLE Module)	More Height (6 mm) (3D) (Sensor Hub)
Dimensions (mm)	7.2 × 11.1	4 × 20.5	3.2 × 1.6	6 × 30
Dimensions (mils)	284 × 437	157.5 × 807	126 × 63	250 × 1200
Gerber File	Web	Web	Refer to datasheet	
Cost (US$)	Minimal	Minimal	0.1–0.5	0.1
Bandwidth (MHz) ($S_{11} \le -10$ dB)	230	220	200	200
Gain (dBi)	1.6	1.1	0.5	2

Appendix E: Selection design principles

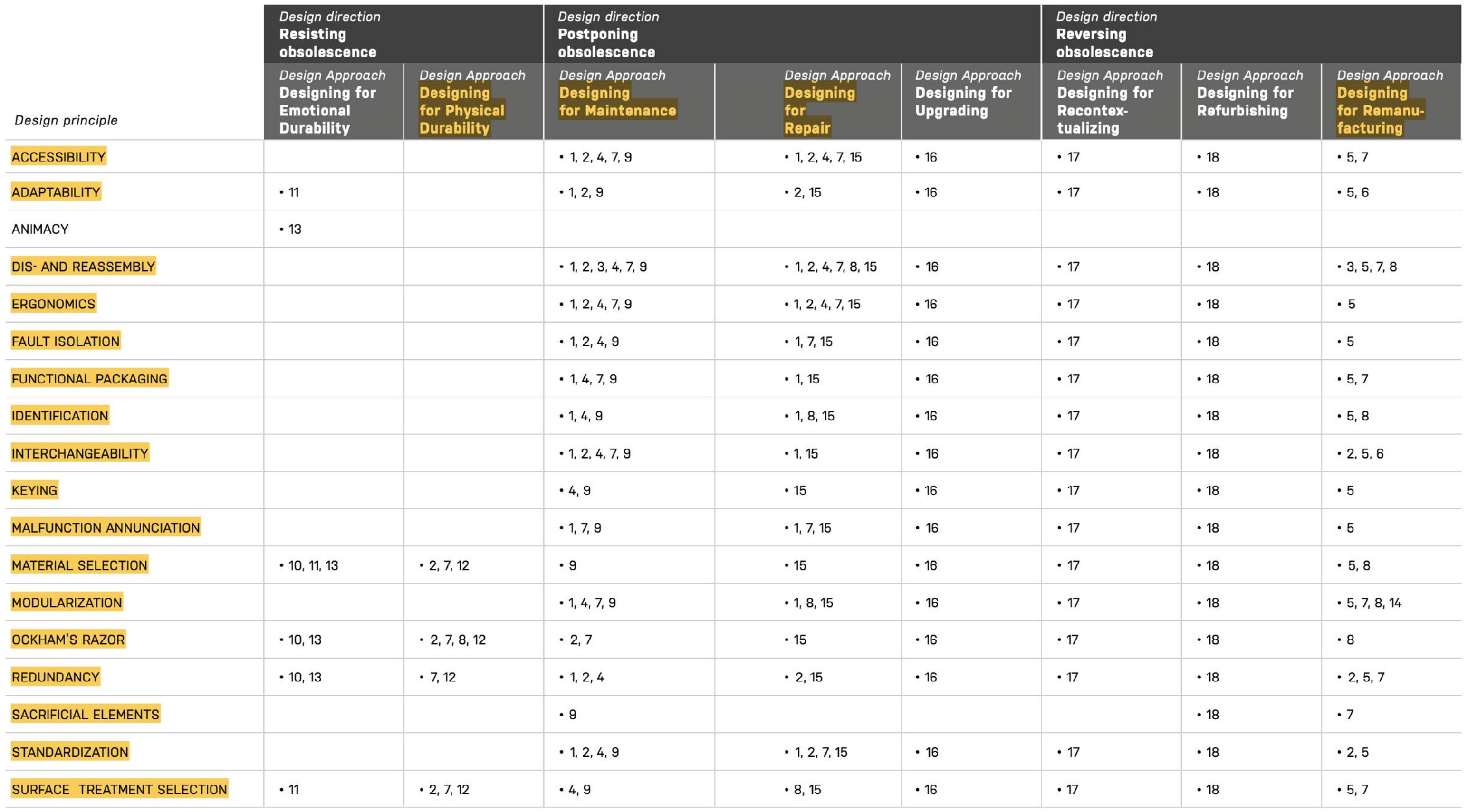
The selection of design principles is based on their relevance to the design strategies (top figure right). With one exception, this turned out to be the entire list. The remaining principles have been ordered on their apparent role in the assessment of Edge Dynamics' current sensor node. This is a subjective selection.

GREEN
The design principles highlighted in green are considered strongly related to and affecting the product architecture of the sensor node.

BLUE
The design principles highlighted in blue are considered general requirements and are considered supportive of but not essential aspects related the product architecture of the sensor node.

YELLOW
The design principles highlighted in yellow are at the moment of product assessment unclear if they are relevant to the assessment of the product architecture.

The product architecture will be assessed (if possible) on principles highlighted in green.



	Design direction **Resisting obsolescence**		*Design direction* **Postponing obsolescence**			*Design direction* **Reversing obsolescence**		
Design principle	*Design Approach* **Designing for Emotional Durability**	*Design Approach* **Designing for Physical Durability**	*Design Approach* **Designing for Maintenance**	*Design Approach* **Designing for Repair**	*Design Approach* **Designing for Upgrading**	*Design Approach* **Designing for Recontex-tualizing**	*Design Approach* **Designing for Refurbishing**	*Design Approach* **Designing for Remanu-facturing**
ACCESSIBILITY			• 1, 2, 4, 7, 9	• 1, 2, 4, 7, 15	• 16	• 17	• 18	• 5, 7
ADAPTABILITY	• 11		• 1, 2, 9	• 2, 15	• 16	• 17	• 18	• 5, 6
ANIMACY	• 13							
DIS- AND REASSEMBLY			• 1, 2, 3, 4, 7, 9	• 1, 2, 4, 7, 8, 15	• 16	• 17	• 18	• 3, 5, 7, 8
ERGONOMICS			• 1, 2, 4, 7, 9	• 1, 2, 4, 7, 15	• 16	• 17	• 18	• 5
FAULT ISOLATION			• 1, 2, 4, 9	• 1, 7, 15	• 16	• 17	• 18	• 5
FUNCTIONAL PACKAGING			• 1, 4, 7, 9	• 1, 15	• 16	• 17	• 18	• 5, 7
IDENTIFICATION			• 1, 4, 9	• 1, 8, 15	• 16	• 17	• 18	• 5, 8
INTERCHANGEABILITY			• 1, 2, 4, 7, 9	• 1, 15	• 16	• 17	• 18	• 2, 5, 6
KEYING			• 4, 9	• 15	• 16	• 17	• 18	• 5
MALFUNCTION ANNUNCIATION			• 1, 7, 9	• 1, 7, 15	• 16	• 17	• 18	• 5
MATERIAL SELECTION	• 10, 11, 13	• 2, 7, 12	• 9	• 15	• 16	• 17	• 18	• 5, 8
MODULARIZATION			• 1, 4, 7, 9	• 1, 8, 15	• 16	• 17	• 18	• 5, 7, 8, 14
OCKHAM'S RAZOR	• 10, 13	• 2, 7, 8, 12	• 2, 7	• 15	• 16	• 17	• 18	• 8
REDUNDANCY	• 10, 13	• 7, 12	• 1, 2, 4	• 2, 15	• 16	• 17	• 18	• 2, 5, 7
SACRIFICIAL ELEMENTS			• 9				• 18	• 7
STANDARDIZATION			• 1, 2, 4, 9	• 1, 2, 7, 15	• 16	• 17	• 18	• 2, 5
SURFACE TREATMENT SELECTION	• 11	• 2, 7, 12	• 4, 9	• 8, 15	• 16	• 17	• 18	• 5, 7

Overview of design principles, design directions and design approaches for preserving product integrity (den Hollander, 2018, p. 55).

Designing for Preserving Product integrity

Design principle	*Description*
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).
ADAPTABILITY	Allowing a product to be continually updated (Keoleian & Menery, 1993) or to "perform several different functions" (Keoleian & Menery, 1993, p. 64). Updating allows a product to keep performing the functions it was originally designed for in a changing environment whereas upgrading enhances the functionality of a product.
~~ANIMACY~~	~~Making the product look, move and behave if it is alive (Chandler & Schwartz, 2010; Mullaney, 2010; Bartneck et al., 2009, Chapman, 2009; Heider & Simmel, 1944; Scholl & Tremoulet, 2000).~~
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)
ERGONOMICS	"Designing and arranging things people use so that the people and things interact most efficiently and safely" (Merriam-Webster, 2016).
FAULT ISOLATION	Assuring "that an [approaching] equipment malfunction can be traced to the part of the assembly requiring replacement (Moss, 1985, p. 37).
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).
IDENTIFICATION	Utilizing "engraving, marking, or labelling for quick location of parts or assemblies" (Moss, 1985, p. 38).
INTERCHANGEABILITY	"Controlling dimensional and functional tolerances of manufactured parts and assemblies to assure that [a part that is expected to fail or has failed] soon can be replaced in the field with no physical rework required for achieving a physical fit, and with a minimum of adjustments needed for achieving proper functioning" (Moss, 1985, p. 37)
KEYING	Utilizing matching geometric features (e.g., matching sizes and shapes like holes and pins to ensuring correct positioning of connectors, components and parts. (Kuo et al., 2001).
MALFUNCTION ANNUNCIATION	Providing means "for indicating to the operator that the equipment is malfunctioning, in those cases where a malfunction is not readily evident" (Moss, 1985, p. 37).
MATERIAL SELECTION	Selecting the material that is best suited to the design requirements of the product under consideration.
MODULARIZATION	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).
OCKHAM'S RAZOR	"Given the choice between functionally equivalent designs, the simplest design should be selected" (Lidwell et al., 2003, p.142)
REDUNDANCY	Providing an excess of functionality and/or material in products or parts, for example to allow for normal wear or removal of material as part of a recovery intervention (Keoleian & Menery, 1993) or to prevent interruptions in the functioning of a product (Kuo et al., 2001)
SACRIFICIAL ELEMENTS	Introducing an inexpensive and easy to replace part that is "designed to be used up or destroyed in fulfilling a purpose or function" (Oxford, 2017), such as protecting more expensive and difficult to replace parts.
STANDARDIZATION	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).
SURFACE TREATMENT SELECTION	Selecting the type of surface treatment (for example anodizing, painting, plating or coating (Bijen (2003)) best suited to the design requirements of the product under consideration.

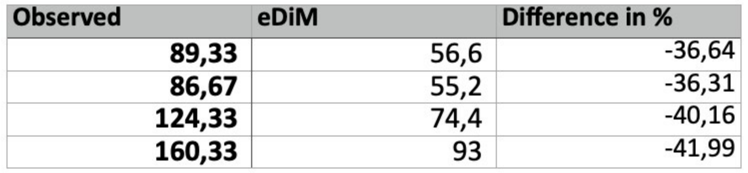
Overview of design principles for preserving product integrity (den Hollander, 2018, p. 57).

Appendix F: Assessment of current product

SET UP OF HOTSPOT MAPPING
To assess the sensor node on hotspots, the HSM spreadsheet was populated with the necessary information. For estimating disassembly time, the eDiM calculation tool was used used (Vanegras et al., 2016). In addition, the sensor node has been disassembled three times while recording the full disassembly. Disassembling as fast as possible was not the intent here, instead disassembling at a normal pace would approximate a real life scenario more. PCBs were considered one component and were not disassembled any further. While disassembling, recordings have been made with a Macbook Pro integrated camera. Afterwards, the recordings have been analysed on the amount of seconds spent on individual disassembly steps. The mean times were calculated and used to populate the time values in the HSM (see next pages). In addition, all components have been weighted with a brand-less kitchen scale with a minimum sensitivity of one gram. All components whose weight could not be registered were considered to have a weight of zero grams. All necessary information was finally inserted into the HotSpot Mapping excel sheet.

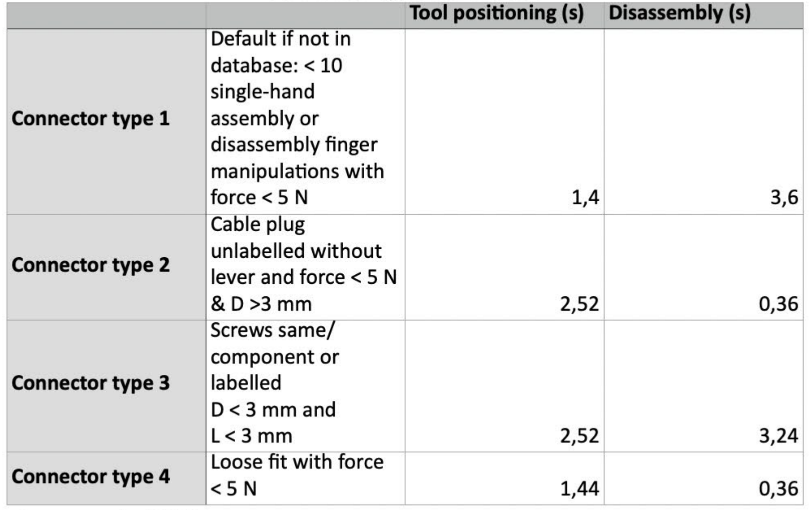
The HSM assesses the relative impact instead of providing absolute values. Red flags indicate components with the highest impact (90% or more for environmental impact and 80% or more for economic impact). The yellow flags indicate a moderate relative impact of 80% or more for environmental impact and 60% or more for economic impact (de Fazio, 2019).

Difference video analysis / calculated



Observed	eDiM	Difference in %
89,33	56,6	-36,64
86,67	55,2	-36,31
124,33	74,4	-40,16
160,33	93	-41,99

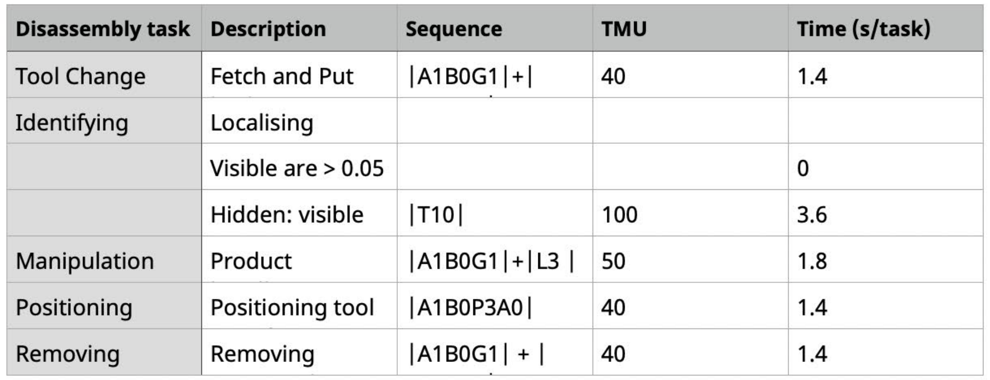
Connector type description



		Tool positioning (s)	Disassembly (s)
Connector type 1	Default if not in database: < 10 single-hand assembly or disassembly finger manipulations with force < 5 N	1,4	3,6
Connector type 2	Cable plug unlabelled without lever and force < 5 N & D >3 mm	2,52	0,36
Connector type 3	Screws same/ component or labelled D < 3 mm and L < 3 mm	2,52	3,24
Connector type 4	Loose fit with force < 5 N	1,44	0,36

Peeters et al., 2018)

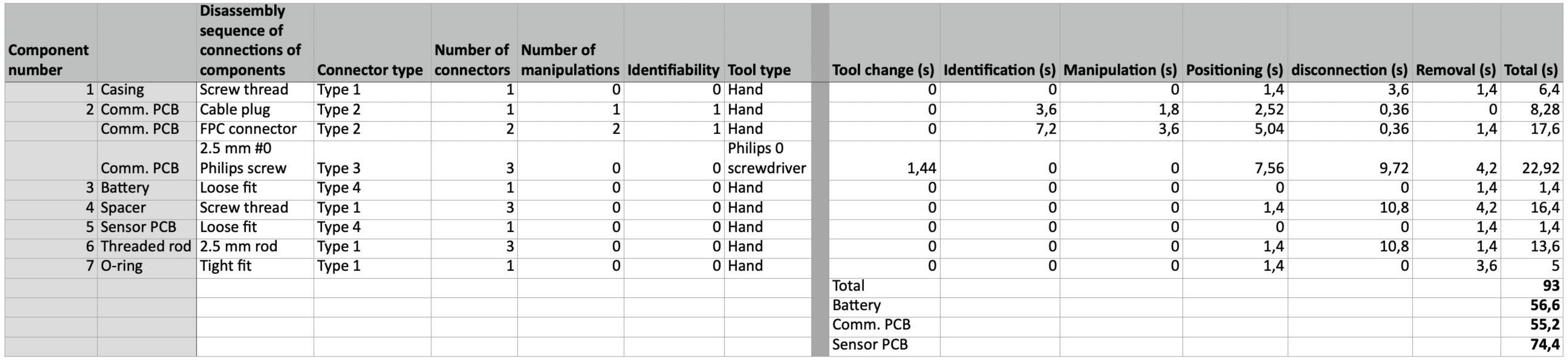
Standardised disassembly tasks



Disassembly task	Description	Sequence	TMU	Time (s/task)
Tool Change	Fetch and Put	|A1B0G1|+|	40	1.4
Identifying	Localising			
	Visible are > 0.05			0
	Hidden: visible	|T10|	100	3.6
Manipulation	Product	|A1B0G1|+|L3 |	50	1.8
Positioning	Positioning tool	|A1B0P3A0|	40	1.4
Removing	Removing	|A1B0G1| + |	40	1.4

Vanegras et al., (2016)

eDiM calculation for sensor node

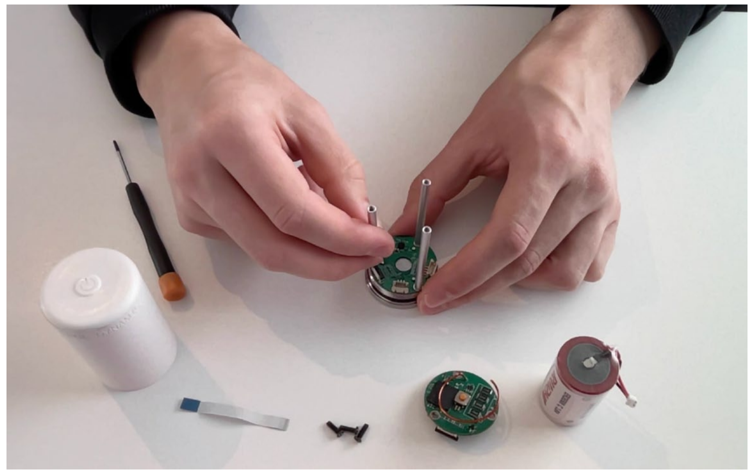


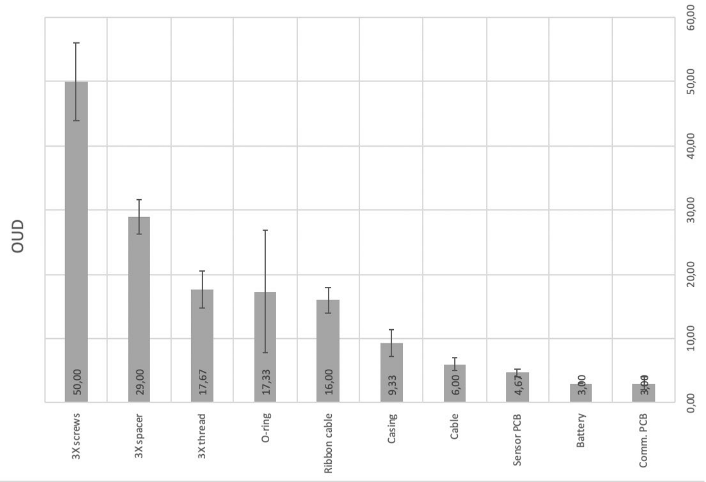
Component number		Disassembly sequence of connections of components	Connector type	Number of connectors	Number of manipulations	Identifiability	Tool type	Tool change (s)	Identification (s)	Manipulation (s)	Positioning (s)	disconnection (s)	Removal (s)	Total (s)
1	Casing	Screw thread	Type 1	1	0	0	Hand	0	0	0	1,4	3,6	1,4	6,4
2	Comm. PCB	Cable plug	Type 2	1	1	1	Hand	0	3,6	1,8	2,52	0,36	0	8,28
	Comm. PCB	FPC connector	Type 2	2	2	1	Hand	0	7,2	3,6	5,04	0,36	1,4	17,6
	Comm. PCB	2.5 mm #0 Philips screw	Type 3	3	0	0	Philips 0 screwdriver	1,44	0	0	7,56	9,72	4,2	22,92
3	Battery	Loose fit	Type 4	1	0	0	Hand	0	0	0	0	0	1,4	1,4
4	Spacer	Screw thread	Type 1	3	0	0	Hand	0	0	0	1,4	10,8	4,2	16,4
5	Sensor PCB	Loose fit	Type 4	1	0	0	Hand	0	0	0	0	0	1,4	1,4
6	Threaded rod	2.5 mm rod	Type 1	3	0	0	Hand	0	0	0	1,4	10,8	1,4	13,6
7	O-ring	Tight fit	Type 1	1	0	0	Hand	0	0	0	1,4	0	3,6	5
								Total						**93**
								Battery						**56,6**
								Comm. PCB						**55,2**
								Sensor PCB						**74,4**

Time recording based on video footage of three disassemblies

Step	Rec1	Rec2	Rec3	Gemiddelde	std
Time to battery	88	86	94	**89,33**	**4,16**
Time to comm.	86	83	91	**86,67**	**4,04**
Time to sensor.	122	117	134	**124,33**	**8,74**
Totaal dis.	158	162	161	**160,33**	**2,08**

Component	Dis1 (in seconds)	Dis2 (in seconds)	Dis3 (in seconds)	gemiddelde	std
Comm. PCB	3	4	2	3,00	1,00
Battery	3	3	3	3,00	0,00
Sensor PCB	5	4	5	4,67	0,58
Cable	6	7	5	6,00	1,00
Casing	7	10	11	9,33	2,08
Ribbon cable	18	16	14	16,00	2,00
O-ring	10	28	14	17,33	9,45
3X thread	16	16	21	17,67	2,89
3X spacer	31	26	30	29,00	2,65
3X screws	56	44	50	50,00	6,00

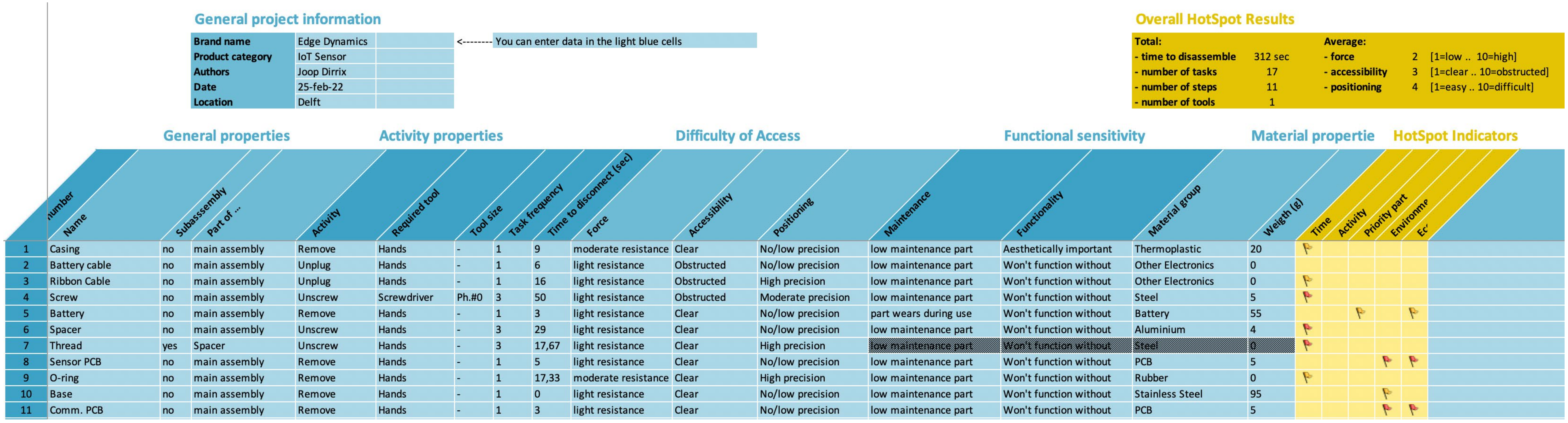




SET UP OF DISASSEMBLY MAP

Using the same recordings made for the HotSpot Mapping analysis, the steps are noted down and the tools and frequencies of use are specified. Notes have been made on anomalies that are not registered within the Disassembly Map tool. For the disassembly of the sensor node two tools are required; a pair of hands and a Philips #0 screwdriver.

Philips #0 screwdriver



General project information

Brand name	Edge Dynamics	
Product category	IoT Sensor	
Authors	Joop Dirrix	
Date	25-feb-22	
Location	Delft	

<-------- You can enter data in the light blue cells

Overall HotSpot Results

Total:		**Average:**		
- time to disassemble	312 sec	**- force**	2	[1=low .. 10=high]
- number of tasks	17	**- accessibility**	3	[1=clear .. 10=obstructed]
- number of steps	11	**- positioning**	4	[1=easy .. 10=difficult]
- number of tools	1			

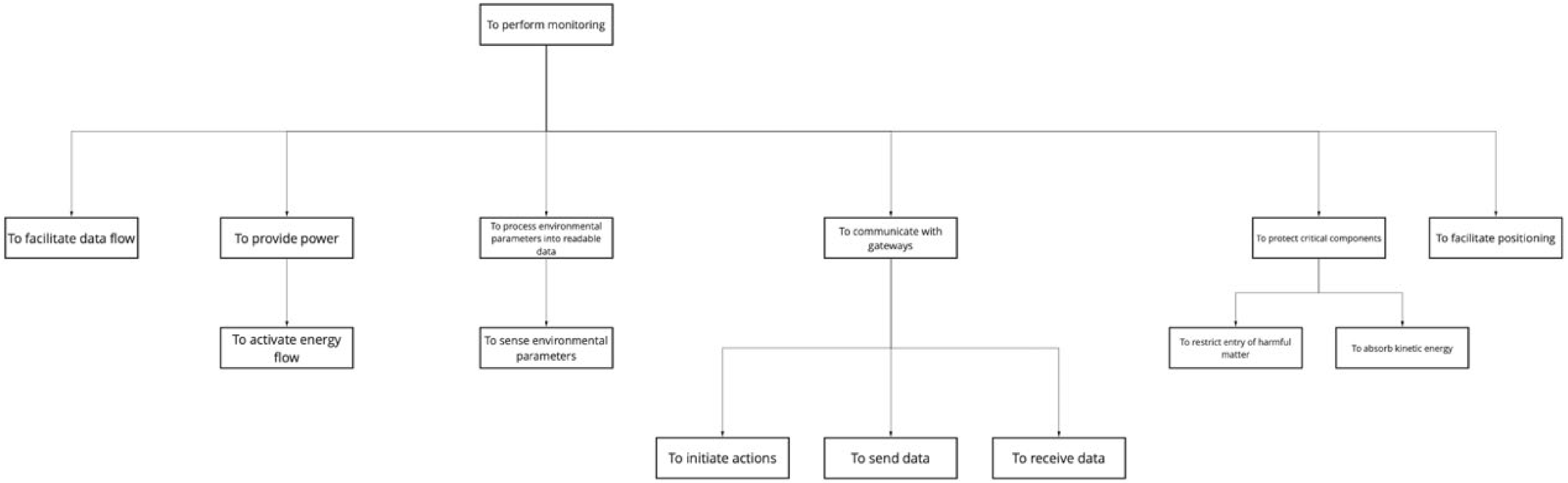
General properties | Activity properties | Difficulty of Access | Functional sensitivity | Material propertie | HotSpot Indicators

number	Name	Subasssembly	Part of ...	Activity	Required tool	Tool size	Task frequency	Time to disconnect (sec)	Force	Accessibility	Positioning	Maintenance	Functionality	Material group	Weigth (g)	Time	Activity	Priority part	Environme	Ec
1	Casing	no	main assembly	Remove	Hands	-	1	9	moderate resistance	Clear	No/low precision	low maintenance part	Aesthetically important	Thermoplastic	20	⚐				
2	Battery cable	no	main assembly	Unplug	Hands	-	1	6	light resistance	Obstructed	No/low precision	low maintenance part	Won't function without	Other Electronics	0					
3	Ribbon Cable	no	main assembly	Unplug	Hands	-	1	16	light resistance	Obstructed	High precision	low maintenance part	Won't function without	Other Electronics	0	⚐				
4	Screw	no	main assembly	Unscrew	Screwdriver	Ph.#0	3	50	light resistance	Obstructed	Moderate precision	low maintenance part	Won't function without	Steel	5	🚩				
5	Battery	no	main assembly	Remove	Hands	-	1	3	light resistance	Clear	No/low precision	part wears during use	Won't function without	Battery	55			⚐		⚐
6	Spacer	no	main assembly	Unscrew	Hands	-	3	29	light resistance	Clear	No/low precision	low maintenance part	Won't function without	Aluminium	4	🚩				
7	Thread	yes	Spacer	Unscrew	Hands	-	3	17,67	light resistance	Clear	High precision	low maintenance part	Won't function without	Steel	0	🚩				
8	Sensor PCB	no	main assembly	Remove	Hands	-	1	5	light resistance	Clear	No/low precision	low maintenance part	Won't function without	PCB	5				🚩	🚩
9	O-ring	no	main assembly	Remove	Hands	-	1	17,33	moderate resistance	Clear	High precision	low maintenance part	Won't function without	Rubber	0	⚐				
10	Base	no	main assembly	Remove	Hands	-	1	0	light resistance	Clear	No/low precision	low maintenance part	Won't function without	Stainless Steel	95				⚐	
11	Comm. PCB	no	main assembly	Remove	Hands	-	1	3	light resistance	Clear	No/low precision	low maintenance part	Won't function without	PCB	5				🚩	🚩

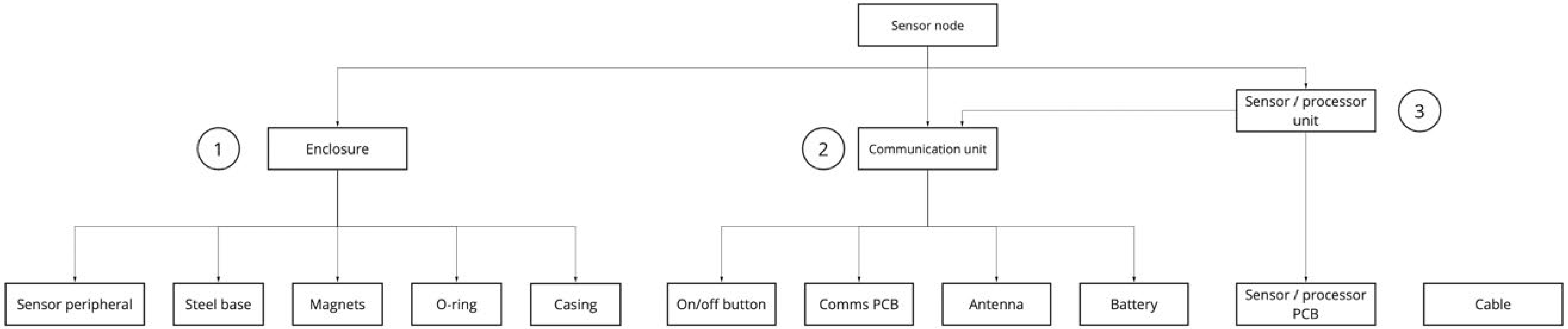
HotSpot Mapping overview

Adaptability

Functional tree - Wireless sensor



product tree - Wireless sensor



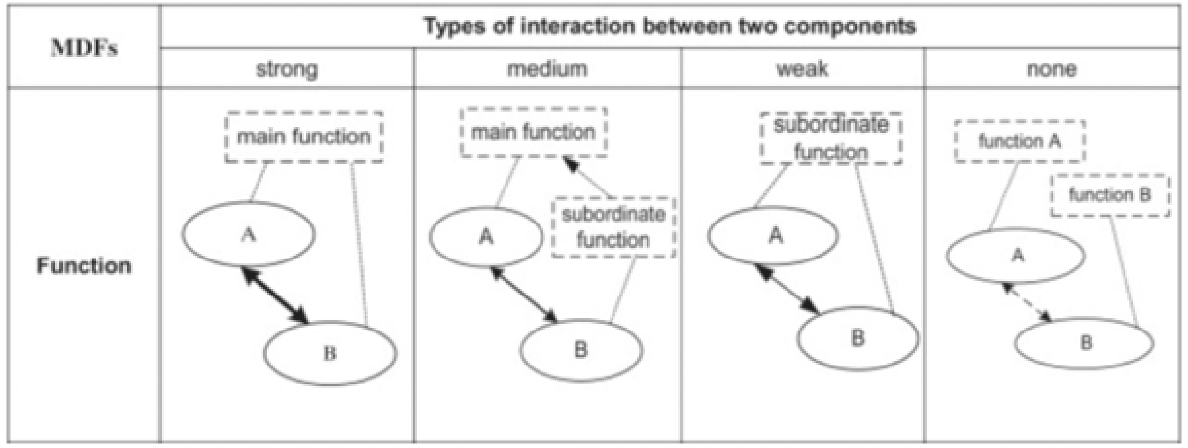
Top; functional tree of current sensor node, bottom; product tree of current sensor node

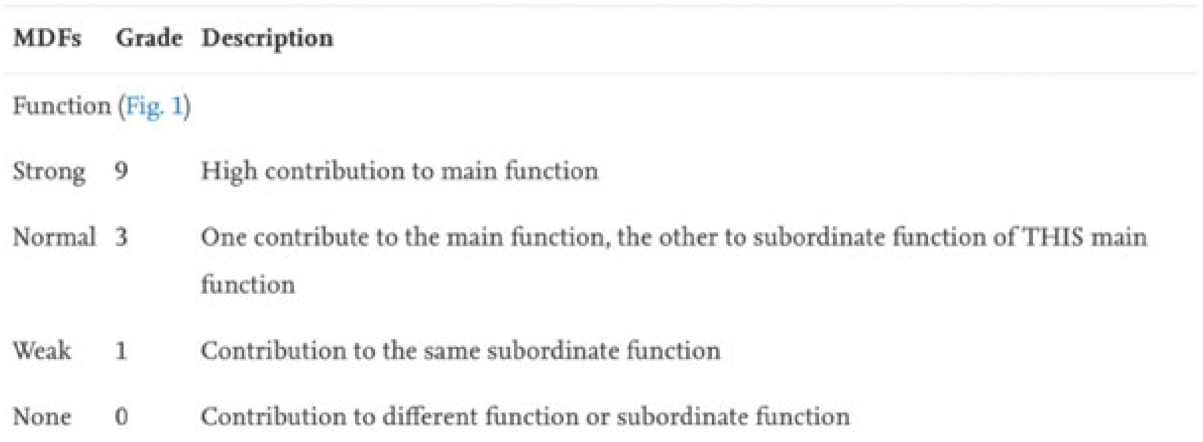
MODULARITY METRIC: DECREASE FUNCTIONAL COUPLING

The first modularity metric used in the product assessment is the functional coupling. Decreasing the interface couplings, the type of interaction between two components, between functional carriers of different modules will reduce the interdependencies of modules. These modules are numbered from 1 to 3 (product tree).

Analysing the interactions between components (next spread), 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, however these have functionally no resemblance.
- The (power) button is physically dependent on the casing, 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.
- The battery is physically connected to the communication PCB, while these components contribute to different functions. Obviously, the battery needs to be physically connected if it wants to perform its function, providing power.

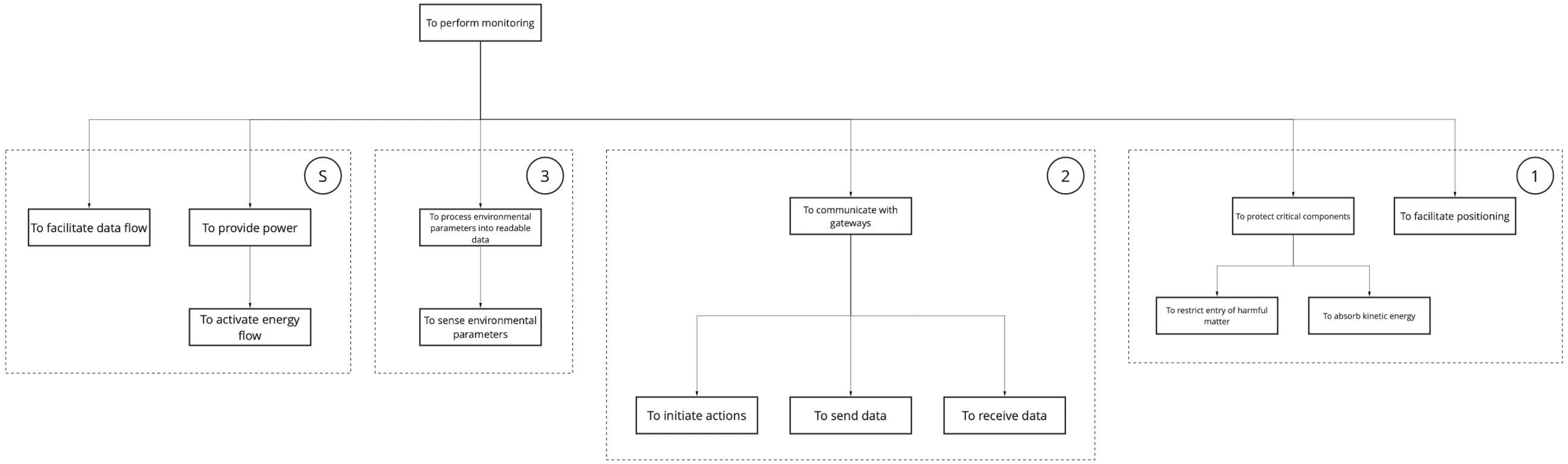




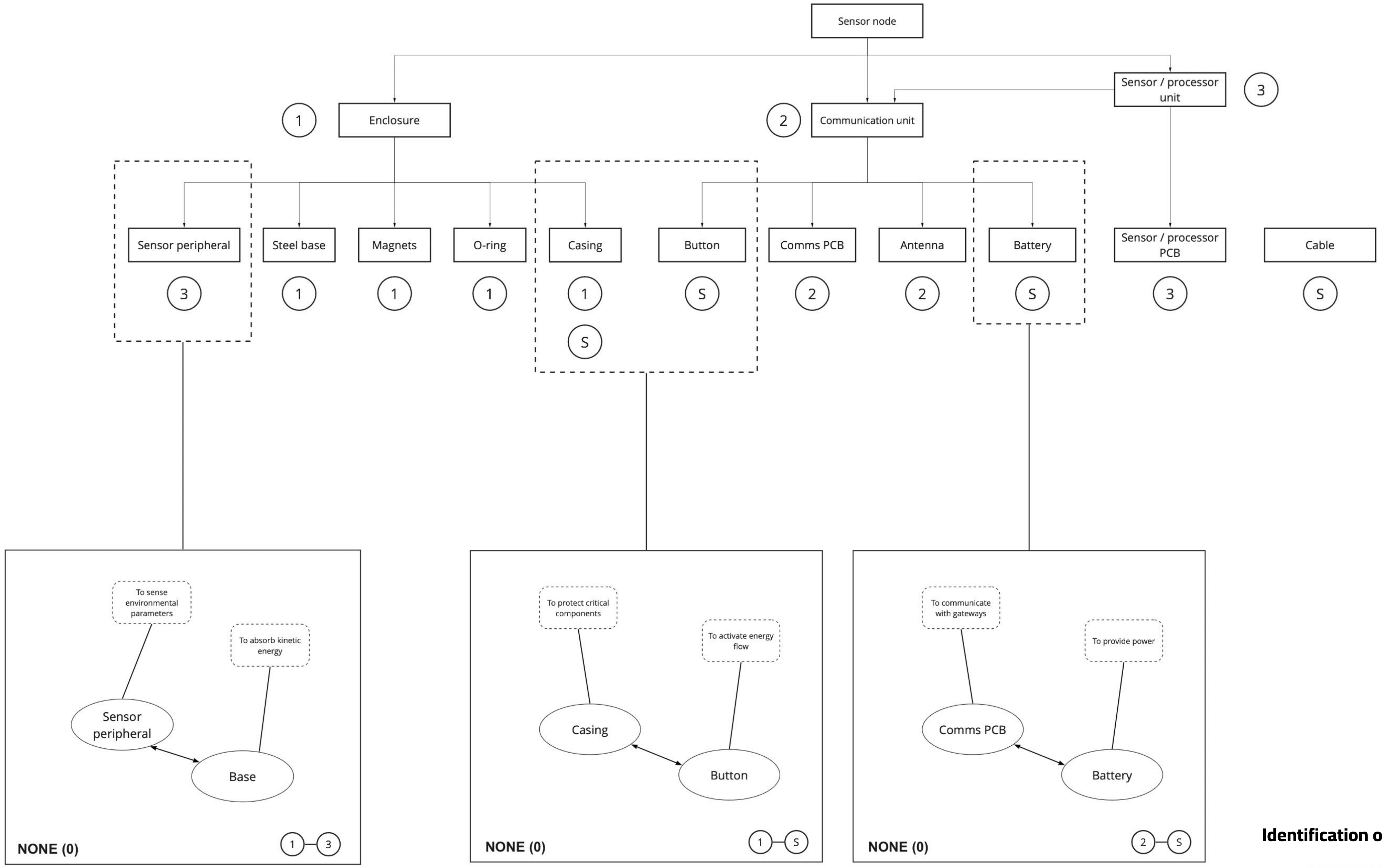
MDFs	Grade	Description
Function (Fig. 1)		
Strong	9	High contribution to main function
Normal	3	One contribute to the main function, the other to subordinate function of THIS main function
Weak	1	Contribution to the same subordinate function
None	0	Contribution to different function or subordinate function

Grading of the functional coupling between two components

Functional tree



Product tree



Identification of components that contribute to different (sub)functions

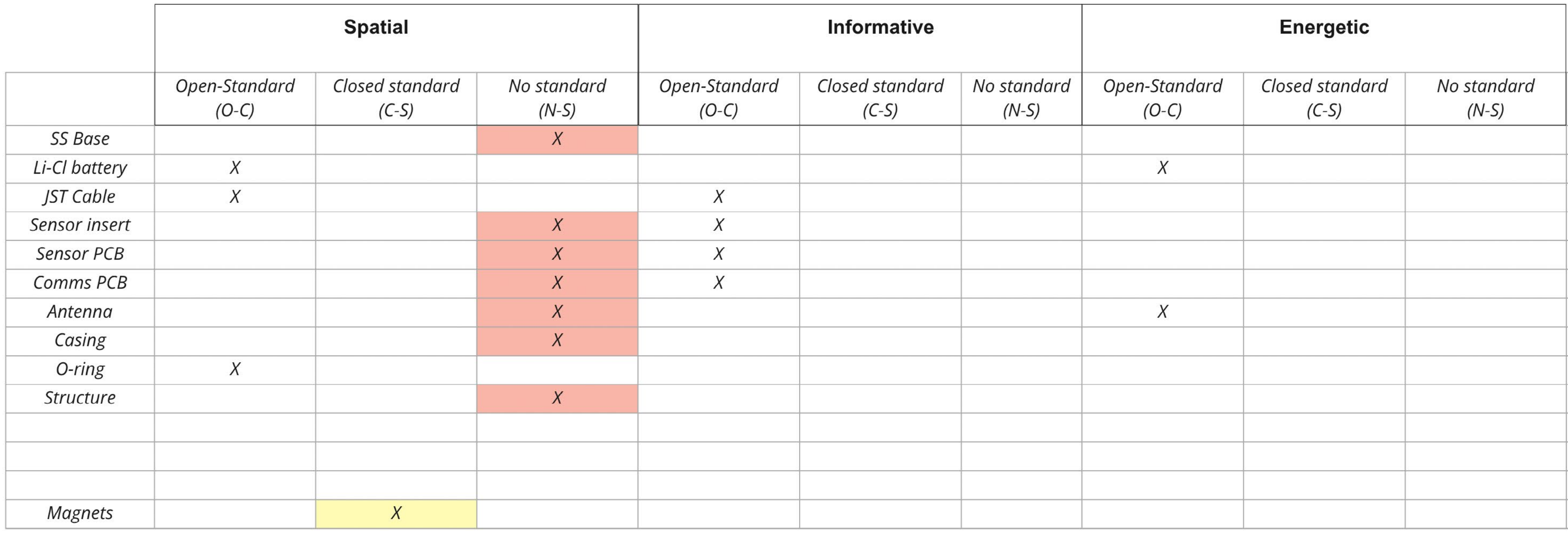
Standardisation

MODULARITY METRIC: INCREASE INTERFACE STANDARDISATION
By having interfaces between different modules standardised and the variety in different interfaces used reduced, the product can be simplified and its interchangeability improved.

The table below shows the components and the degree of standardisation of their interfaces. The interfaces are categorised on spatial, informative and energetic standards. An open standard 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 means anyone within a particular industry can interact with a component. No standard indicates that the component is custom and likely only appears on that particular product.
In case of modularity, an open standard is aimed for. This could support the supply of (aftermarket) spare parts and modding. A closed standard might mean it will be harder for consumers to repair their products if spare parts are unavailable or sold at a high price. No standard means a component is entirely custom to that particular product and no other product outside of the OEM uses it.

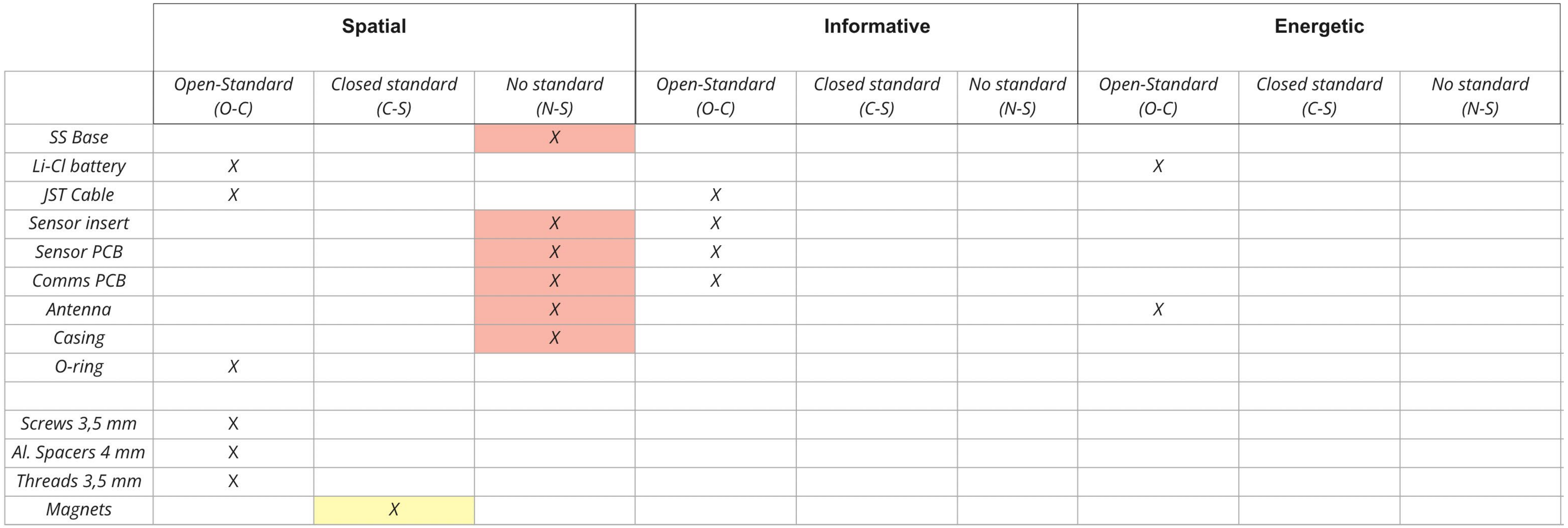
The table below shows that several components have no standard spatial interface. In many cases this simply means these are custom to this product, likely for trade secrets in case of PCB design and its proprietary firmware, but also for aesthetic reasons.

The product interfaces that interact with other equipment are standards 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.



	Spatial			Informative			Energetic		
	Open-Standard (O-C)	Closed standard (C-S)	No standard (N-S)	Open-Standard (O-C)	Closed standard (C-S)	No standard (N-S)	Open-Standard (O-C)	Closed standard (C-S)	No standard (N-S)
SS Base			X						
Li-Cl battery	X						X		
JST Cable	X			X					
Sensor insert			X	X					
Sensor PCB			X	X					
Comms PCB			X	X					
Antenna			X				X		
Casing			X						
O-ring	X								
Structure			X						
Magnets		X							

Overview degree of standardisation current sensor node



	Spatial			Informative			Energetic		
	Open-Standard (O-C)	Closed standard (C-S)	No standard (N-S)	Open-Standard (O-C)	Closed standard (C-S)	No standard (N-S)	Open-Standard (O-C)	Closed standard (C-S)	No standard (N-S)
SS Base			X						
Li-Cl battery	X						X		
JST Cable	X			X					
Sensor insert			X	X					
Sensor PCB			X	X					
Comms PCB			X	X					
Antenna			X				X		
Casing			X						
O-ring	X								
Screws 3,5 mm	X								
Al. Spacers 4 mm	X								
Threads 3,5 mm	X								
Magnets		X							

Functional grouping

MODULARITY METRIC: GROUP COMPONENTS PER FUNCTION
Grouping components that are supporting the same function will create modules with a clear role within in a product.

From the product tree three main modules can be recognised. The communication module includes the battery and button. The sensor unit is powered by the communication PCB, which is connected to the battery. The enclosure incorporates the sensor insert, which is connected to the sensor unit.

Based on the grade criteria described in table to the right, the attribution to each (main) function can be measured. The figure below shows that the sensor insert is grouped with components it has no relevance to in order to fulfil its functioning. In addition, the button is integrated on the communication PCB, while it does not need to be in order to fulfil its functionalities.

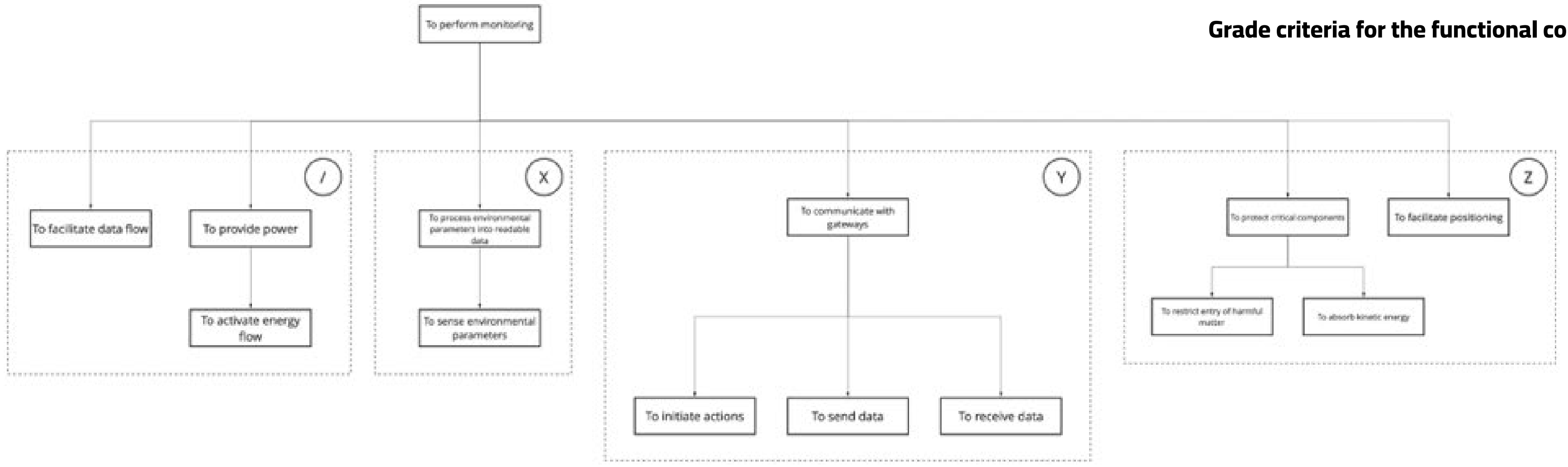
The outcome of the modularity metrics show the current product is to a high degree already modular. Component coupling only occurs in two situations, where coupling is not absolutely necessary.

Identification of non-functional compatibility

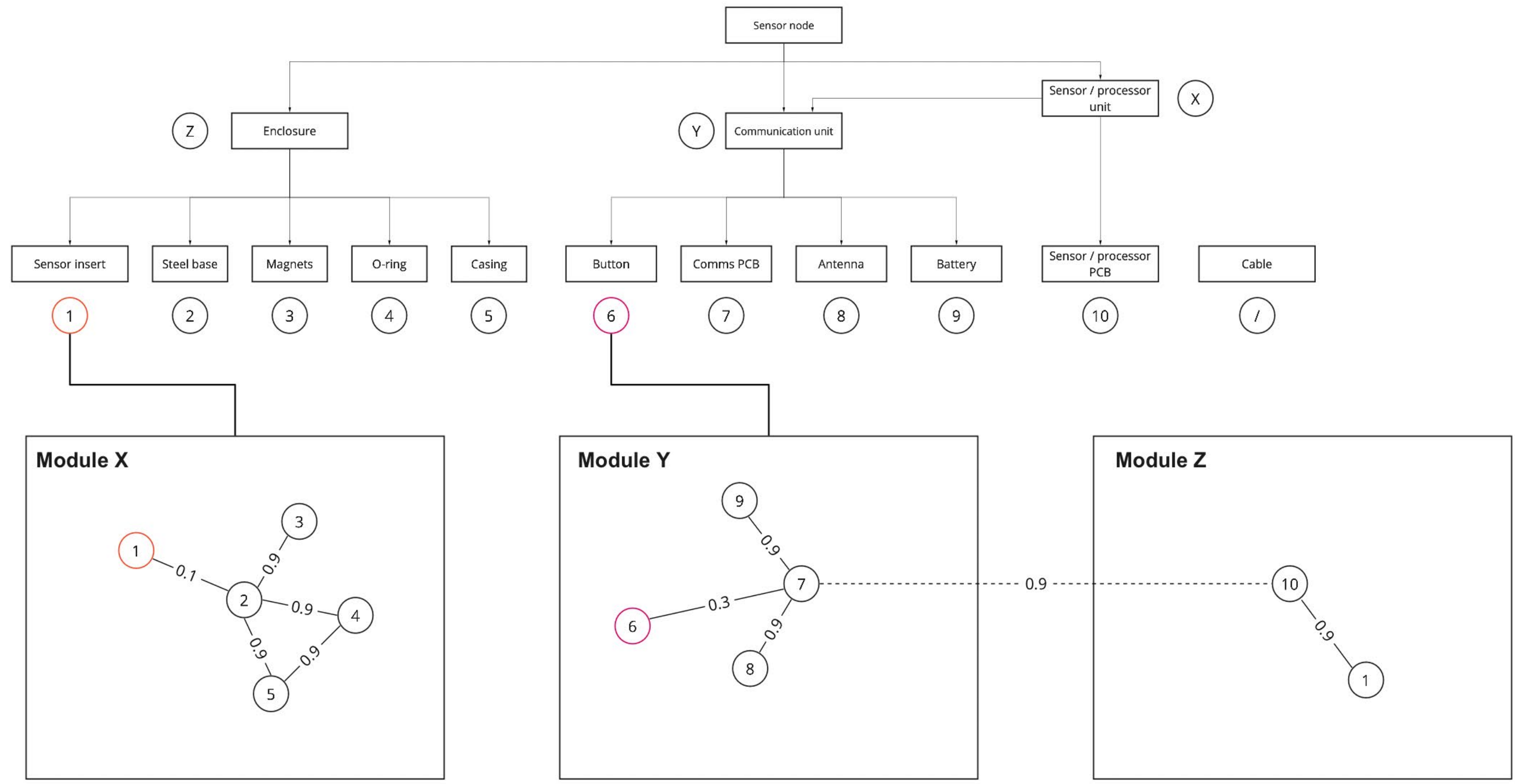
Can exist in a product concurrently, and function fulfilment of a component is necessary to the other	0.9
Can exist in a product concurrently, and function fulfilment of a component is accessorial to the other	0.3
Can exist in a product concurrently, but they are irrelevant to each others function fulfilment	0.1
Cannot exist in a product concurrently	0

Grade criteria for the functional compatibility

Functional tree



Product tree



Appendix G: Design for Recycling Guidelines

Level	Topic	Guideline
Materials	Diversity	Minimise the number of different (types of) materials
		Avoid mixing materials in assemblies
		Use a single material per sub-assembly (monomaterial strategy)
		Avoid creating permanent connections between materials (e.g. through 2K moulding)
	Compatibility	Choose compatible materials (i.e. that can be recycled together)
		Use fasteners made of a material that is compatible with the part(s) they're attached to.
		Avoid fixing ferrous metals to non-ferrous metals (as parts or as fasteners). Either stream will likely be polluted after the product is shredded.
	Recyclability	Use materials that are recyclable
		Use materials that retain their original quality/ properties as much as possible when recycled
		Avoid using magnets (because they will pollute the ferrous metal stream)
	Use of recycled materials	Use recycled materials, whenever possible
	Hazardous substances	Avoid harmful materials, substances and additives
		Avoid substances on the SIN list
		Avoid SVHC (Substances of Very High Concern)
		Avoid the use of BFR's (Brominated Flame Retardants)
		Do not use halogenated polymers (e.g. PVC, which degrades at processing temperatures of common plastics. The hydrochloride acid that is generated can damage moulds and extruders)
Fasteners	Complexity	Minimise the total number of fasteners
	Diversity	Minimise the number of different types of fasteners
		Minimise the number of different disassembly tools required
	Identifiability	Make sure fasteners are easy to identify
	Accessibility	Make sure fasteners are easily accessible (with a disassembly tool)
	Disassemblability	Make sure fasteners are easy to remove
	Standardisation	Whenever possible use fasteners that can be removed with standard disassembly tools
	Durability	Protect fasteners from wear and corrosion
	Cables and connectors	Minimise the number of wires/ cables and their length
Components	Identifiability	Valuable/ hazardous/ non-recyclable or non-compatible components must be easy to identify
	Accessibility	Valuable/ hazardous/ non-recyclable or non-compatible components must be easy to access
	Disassemblability	Valuable/ hazardous/ non-recyclable or non-compatible components must be easy to remove
		If parts or sub-assemblies contain incompatible materials make sure they are easy to separate.
	Recyclability	Avoid permanently enclosing materials (e.g. through insert moulding)
		Avoid magnetic components on PCBs (valuable non-ferro PCBs may get lost in and pollute the ferrous metals stream)
Product	Complexity	Minimise the total number of components
	Modularity	Consider modular design (e.g. to facilitate dismantling of hazardous and/ or valuable components)
	Disassemblability	Reduce disassembly time and total number of steps
		Increase the linearity of the disassembly sequence
		Minimise divergence in the dismantling sequence order
		Homogenise the principles of assembly and disassembly
		Design the product so it can be easily transported after use (i.e., allow for pre-disassembly)
Marking and labelling	Identification	Use standardised coding and marking of materials to facilitate their identification (plastic parts in particular)
		Use standardised labelling of products and components on recyclability, incompatibility, and/ or toxicity so that they can be easily identified
		Eliminate labels that are incompatible with end-of-life treatment
		Place identification elements on visible locations
Information	Communication	Provide useful processing-related information
		Provide information to the consumer on how the product should be disposed

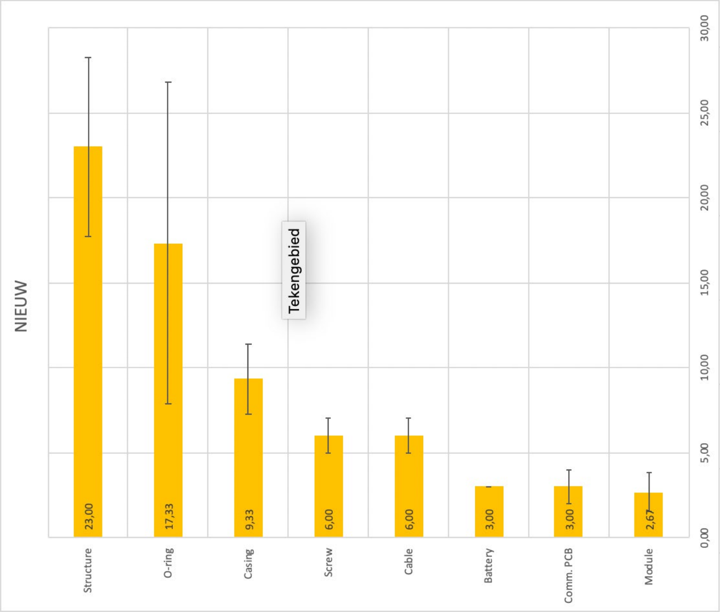
Design for Recycling guidelines (Martínez et. al., 2020)

Appendix H: Assessment of concept node

Time recording based on video footage of three disassemblies using a mock-up / prototype

Component	Dis1 (in seconds)	Dis2 (in seconds)	Dis3 (in seconds)	gemiddelde	std
Module	4	2	2	2,67	1,15
Comm. PCB	3	4	2	3,00	1,00
Battery	3	3	3	3,00	0,00
Cable	6	7	5	6,00	1,00
Screw	7	6	5	6,00	1,00
Casing	7	10	11	9,33	2,08
O-ring	10	28	14	17,33	9,45
Structure	29	19	21	23,00	5,29

Step	Rec1	Rec2	Rec3	Gemiddelde	std
T. to battery	16	18	17	**17,00**	**1,00**
T. to comm.	40	35	32	**35,67**	**4,04**
T. sensor	40	35	32	**35,67**	**4,04**
Totaal dis	87	83	69	**79,67**	**9,45**



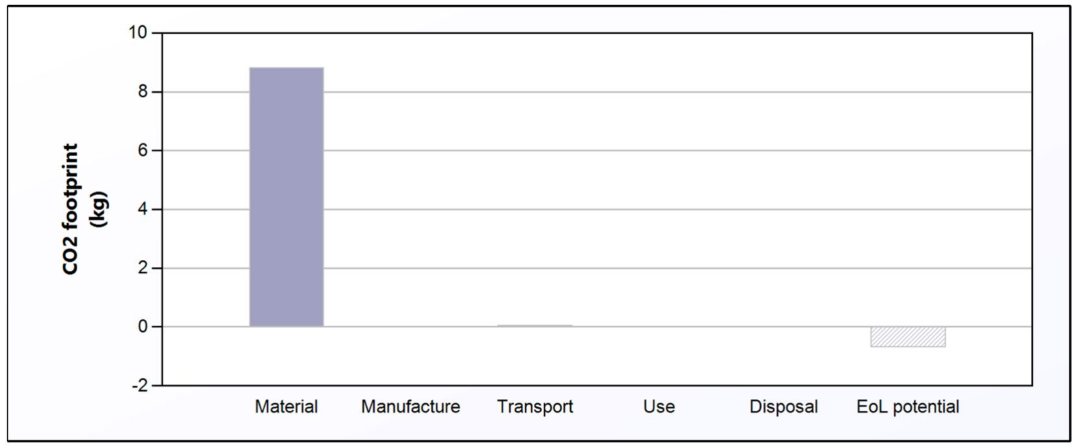
Appendix I: EcoAudit results sensor nodes

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)	CO2 footprint (kg)	%
Base	Stainless steel, austenitic, AISI 316, annealed	Virgin (0%)	0,095	1	0,095	0,67	7,6
O-ring	Ethylene propylene (diene) (EPDM/EPM, unreinforced)	Virgin (0%)	0,00041	1	0,00041	0,0014	0,0
Sensor PCB	Integrated circuit (IC), logic or memory type	Virgin (0%)	0,005	1	0,005	3,6	40,5
Thread/screw	Carbon steel, AISI 1010, annealed	Virgin (0%)	0,0015	6	0,009	0,02	0,2
Spacer	Aluminum, 3004, H11	Virgin (0%)	0,0013	3	0,004	0,055	0,6
Battery	Li-Ion AA cell battery	Virgin (0%)	0,055	1	0,055	0,82	9,3
Comm. PCB	Integrated circuit (IC), logic or memory type	Virgin (0%)	0,005	1	0,005	3,6	40,5
Cables	Cable	Virgin (0%)	0,0005	1	0,0005	0,0034	0,0
Casing	PBT (general purpose)	Virgin (0%)	0,02	1	0,02	0,1	1,2
Total				**16**	**0,19**	**8,8**	**100**

CO2 footprint per component, current node

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)	CO2 footprint (kg)	%
Sensor PCB	Integrated circuit (IC), logic or memory type	Virgin (0%)	0,005	1	0,005	3,6	40,4
Comm PCB	Integrated circuit (IC), logic or memory type	Virgin (0%)	0,005	1	0,005	3,6	40,4
Base	Stainless steel, austenitic, AISI 316, annealed	Virgin (0%)	0,095	1	0,095	0,67	7,6
Battery	Li-Ion AA cell battery	Virgin (0%)	0,055	1	0,055	0,82	9,3
Cables	Cable	Virgin (0%)	0,00025	1	0,00025	0,0017	0,0
O-ring	Ethylene propylene (diene) (EPDM/EPM, 30-50% carbon black, plasticized)	Virgin (0%)	0,00041	1	0,00041	0,0012	0,0
Structure	ABS (heat resistant, injection molding)	Virgin (0%)	0,014	1	0,014	0,05	0,6
Screw	Carbon steel, AISI 1010, annealed	Virgin (0%)	0,0015	1	0,0015	0,0034	0,0
Casing	PBT (general purpose)	Virgin (0%)	0,029	1	0,029	0,15	1,7
Total				**9**	**0,2**	**8,8**	**100**

CO2 footprint per component, concept node



	CO2 (kg/year)
Equivalent annual environmental burden (averaged over 8 year product life):	1,12

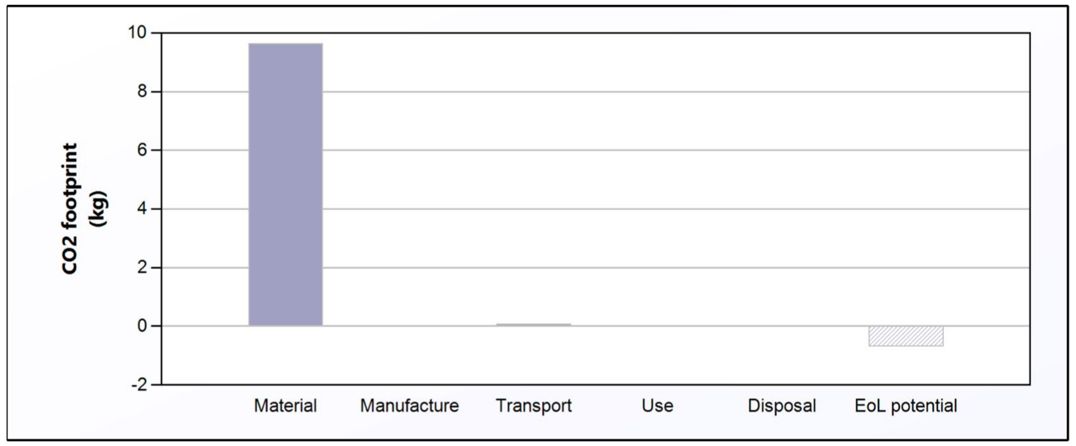
CO2 footprint fraction per lifecycle aspect

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)	CO2 footprint (kg)	%
Base	Stainless steel, austenitic, AISI 316, annealed	Virgin (0%)	0,095	1	0,095	0,67	7,0
O-ring	Ethylene propylene (diene) (EPDM/EPM, unreinforced)	Virgin (0%)	0,00041	1	0,00041	0,0014	0,0
Sensor PCB	Integrated circuit (IC), logic or memory type	Virgin (0%)	0,005	1	0,005	3,6	37,0
Thread/screw	Carbon steel, AISI 1010, annealed	Virgin (0%)	0,0015	6	0,009	0,02	0,2
Spacer	Aluminum, 3004, H11	Virgin (0%)	0,0013	3	0,004	0,055	0,6
Battery	Li-Ion AA cell battery	Virgin (0%)	0,055	2	0,11	1,6	17,1
Comm. PCB	Integrated circuit (IC), logic or memory type	Virgin (0%)	0,005	1	0,005	3,6	37,0
Cables	Cable	Virgin (0%)	0,0005	1	0,0005	0,0034	0,0
Casing	PBT (general purpose)	Virgin (0%)	0,02	1	0,02	0,1	1,1
Total				**17**	**0,25**	**9,6**	**100**

CO2 footprint per component, current node - repair scenario

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)	CO2 footprint (kg)	%
Sensor PCB	Integrated circuit (IC), logic or memory type	Virgin (0%)	0,005	1	0,005	3,6	36,9
Comm PCB	Integrated circuit (IC), logic or memory type	Virgin (0%)	0,005	1	0,005	3,6	36,9
Base	Stainless steel, austenitic, AISI 316, annealed	Virgin (0%)	0,095	1	0,095	0,67	7,0
Battery	Li-Ion AA cell battery	Virgin (0%)	0,055	2	0,11	1,6	17,0
Cables	Cable	Virgin (0%)	0,00025	1	0,00025	0,0017	0,0
O-ring	Ethylene propylene (diene) (EPDM/EPM, 30-50% carbon black, plasticized)	Virgin (0%)	0,00041	1	0,00041	0,0012	0,0
Structure	ABS (heat resistant, injection molding)	Virgin (0%)	0,014	1	0,014	0,05	0,5
Screw	Carbon steel, AISI 1010, annealed	Virgin (0%)	0,0015	1	0,0015	0,0034	0,0
Casing	PBT (general purpose)	Virgin (0%)	0,029	1	0,029	0,15	1,6
Total				**10**	**0,26**	**9,7**	**100**

CO2 footprint per component, concept node - repair scenario



	CO2 (kg/year)
Equivalent annual environmental burden (averaged over 16 year product life):	0,611

CO2 footprint fraction per lifecycle aspect - repair scenario

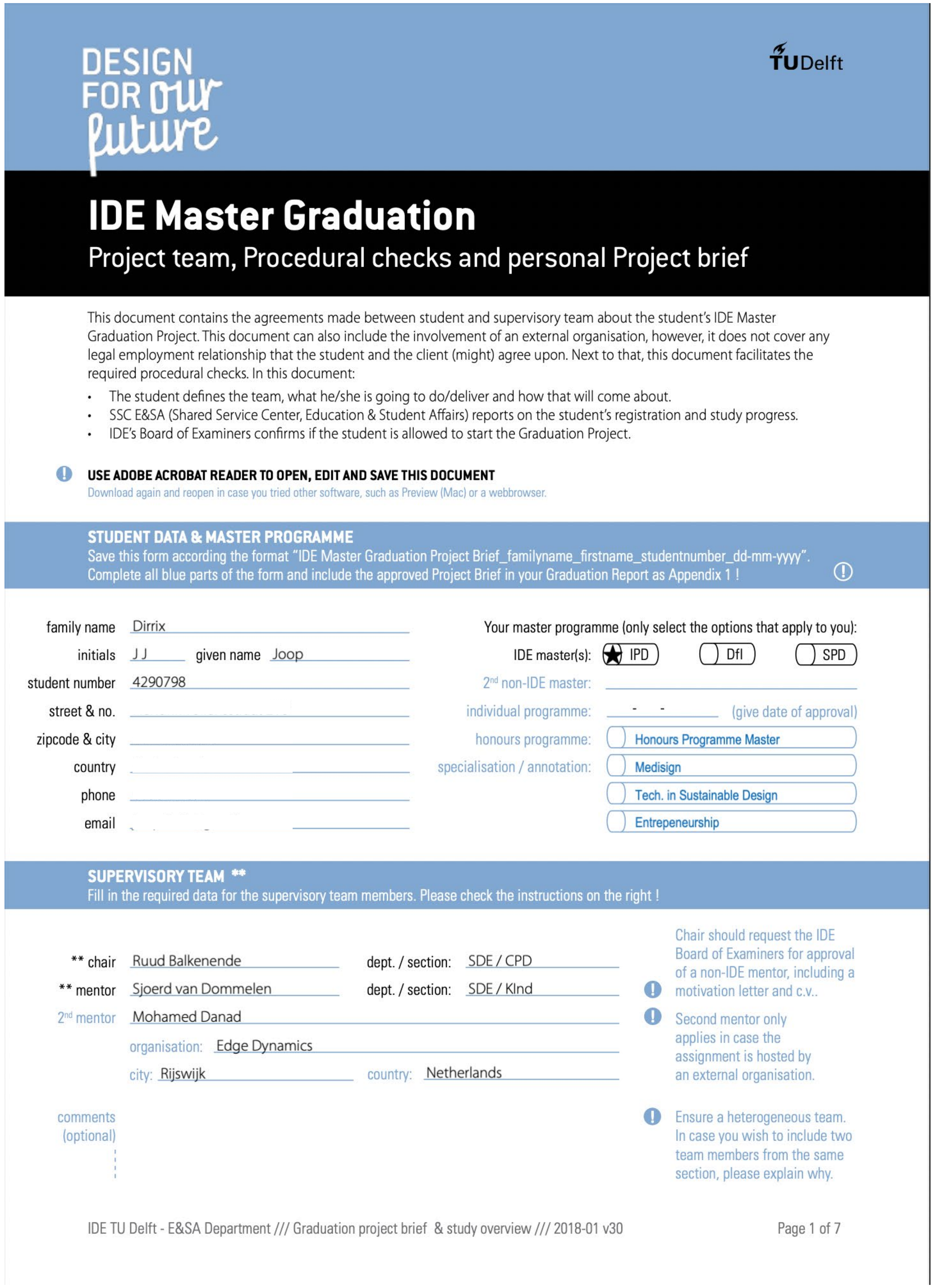
Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)	CO2 footprint (kg)	%
Base	Stainless steel, austenitic, AISI 316, annealed	100,0%	0,095	1	0,095	0,12	1,5
O-ring	Ethylene propylene (diene) (EPDM/EPM, unreinforced)	Virgin (0%)	0,00041	1	0,00041	0,0014	0,0
Sensor PCB	Integrated circuit (IC), logic or memory type	Virgin (0%)	0,005	1	0,005	3,6	43,8
Thread/screw	Carbon steel, AISI 1010, annealed	100,0%	0,0015	6	0,009	0,006	0,1
Spacer	Aluminum, 3004, H11	100,0%	0,0013	3	0,004	0,011	0,1
Battery	Li-Ion AA cell battery	Virgin (0%)	0,055	1	0,055	0,82	10,1
Comm. PCB	Integrated circuit (IC), logic or memory type	Virgin (0%)	0,005	1	0,005	3,6	43,8
Cables	Cable	Virgin (0%)	0,0005	1	0,0005	0,0034	0,0
Casing	PBT (general purpose)	100,0%	0,02	1	0,02	0,035	0,4
Total				**16**	**0,19**	**8,1**	**100**

CO2 footprint of sensor node with ideal recycling rates

Component	Material	Recycled content* (%)	Part mass (kg)	Qty.	Total mass (kg)	CO2 footprint (kg)	%
Base	Stainless steel, austenitic, AISI 316, annealed	Typical %	0,095	1	0,095	0,39	4,6
O-ring	Ethylene propylene (diene) (EPDM/EPM, unreinforced)	Virgin (0%)	0,00041	1	0,00041	0,0014	0,0
Sensor PCB	Integrated circuit (IC), logic or memory type	Virgin (0%)	0,005	1	0,005	3,6	42,0
Thread/screw	Carbon steel, AISI 1010, annealed	Typical %	0,0015	6	0,009	0,013	0,2
Spacer	Aluminum, 3004, H11	Typical %	0,0013	3	0,004	0,035	0,4
Battery	Li-Ion AA cell battery	Virgin (0%)	0,055	1	0,055	0,82	9,7
Comm. PCB	Integrated circuit (IC), logic or memory type	Virgin (0%)	0,005	1	0,005	3,6	42,0
Cables	Cable	Virgin (0%)	0,0005	1	0,0005	0,0034	0,0
Casing	PBT (general purpose)	0,0%	0,02	1	0,02	0,1	1,2
Total				**16**	**0,19**	**8,5**	**100**

CO2 footprint of sensor node with typical recycling rates

Appendix J: Project brief



IDE Master Graduation

Project team, Procedural checks and personal Project brief

This document contains the agreements made between student and supervisory team about the student's IDE Master Graduation Project. This document can also include the involvement of an external organisation, however, it does not cover any legal employment relationship that the student and the client (might) agree upon. Next to that, this document facilitates the required procedural checks. In this document:

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT

Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME

Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy".
Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name Dirrix
initials J J given name Joop
student number 4290798
street & no.
zipcode & city
country
phone
email

Your master programme (only select the options that apply to you):
IDE master(s): ● IPD ○ DfI ○ SPD
2nd non-IDE master:
individual programme: - - (give date of approval)
honours programme: ○ Honours Programme Master
specialisation / annotation: ○ Medisign
○ Tech. in Sustainable Design
○ Entrepeneurship

SUPERVISORY TEAM **

Fill in the required data for the supervisory team members. Please check the instructions on the right !

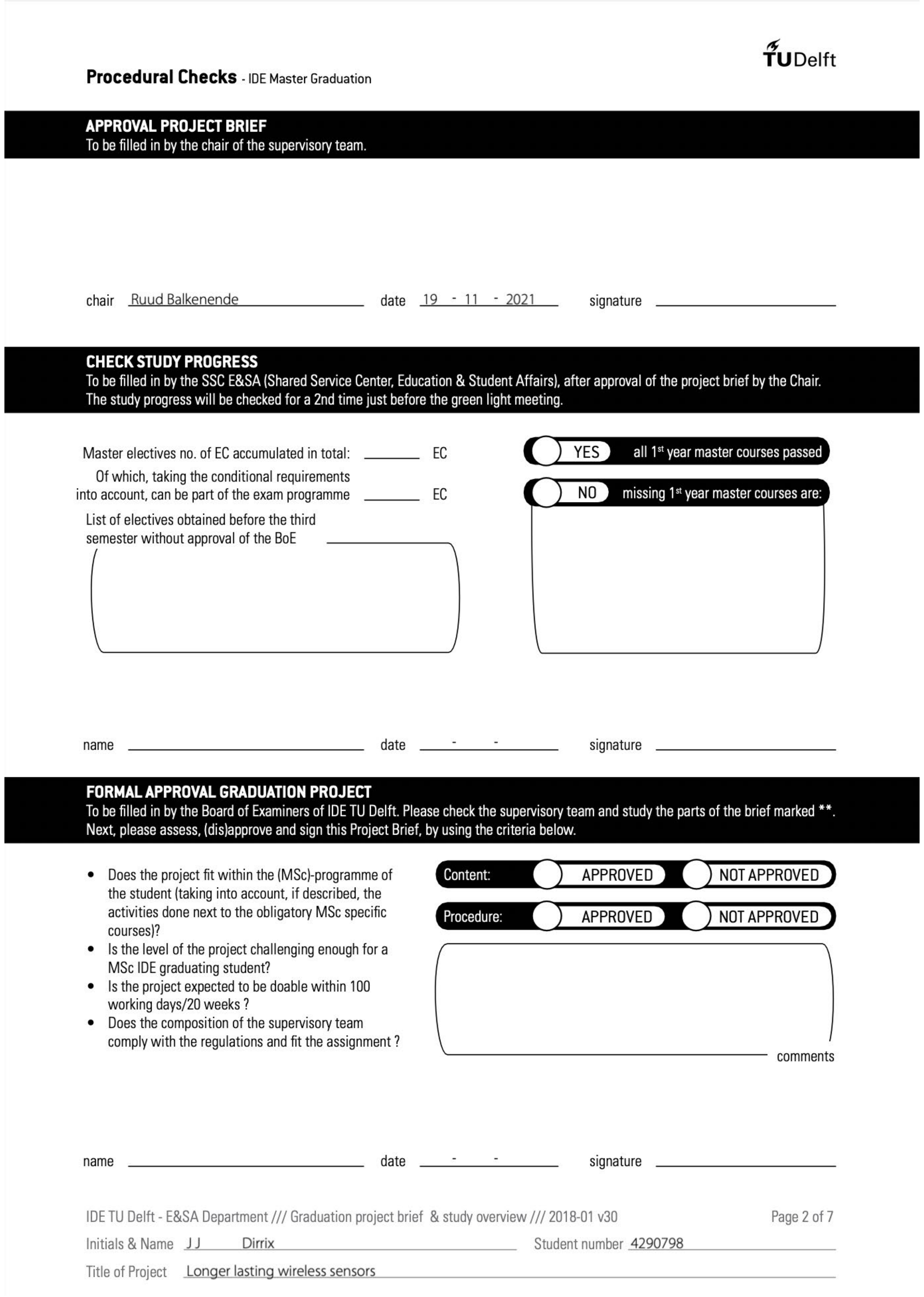
** chair Ruud Balkenende dept. / section: SDE / CPD
** mentor Sjoerd van Dommelen dept. / section: SDE / Klnd
2nd mentor Mohamed Danad
organisation: Edge Dynamics
city: Rijswijk country: Netherlands
comments (optional)

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

Ensure a heterogeneous team. In case you wish to include two team members from the same section, please explain why.

IDE TU Delft - E&SA Department /// Graduation project brief & study overview /// 2018-01 v30 Page 1 of 7



Procedural Checks - IDE Master Graduation

APPROVAL PROJECT BRIEF

To be filled in by the chair of the supervisory team.

chair Ruud Balkenende date 19 - 11 - 2021 signature

CHECK STUDY PROGRESS

To be filled in by the SSC E&SA (Shared Service Center, Education & Student Affairs), after approval of the project brief by the Chair. The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total: ______ EC
Of which, taking the conditional requirements into account, can be part of the exam programme ______ EC
List of electives obtained before the third semester without approval of the BoE

○ YES all 1st year master courses passed
○ NO missing 1st year master courses are:

name date - - signature

FORMAL APPROVAL GRADUATION PROJECT

To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **. Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: ○ APPROVED ○ NOT APPROVED
Procedure: ○ APPROVED ○ NOT APPROVED

comments

name date - - signature

IDE TU Delft - E&SA Department /// Graduation project brief & study overview /// 2018-01 v30 Page 2 of 7
Initials & Name J J Dirrix Student number 4290798
Title of Project Longer lasting wireless sensors

Longer lasting wireless sensors

project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 15 - 11 - 2021

18 - 04 - 2022 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

IIoT (Industrial Internet of Things) is a system consisting of networked smart objects, cyber-physical assets. These enable real-time and autonomous access, collection, analysis, communications, and exchange of process, product and/or service information, within the industrial environment. With this information one can optimise overall production value (e.g. reducing energy consumption, boosting productivity etc.) (Boyes et al, 2018). By equipping legacy assets (e.g. industrial motors) with networked sensors, maintenance can be predicted. This way, down-time due to equipment failure can be reduced, which results in cost reductions.

Edge Dynamics (Rijswijk, The Netherlands) is a start-up operating in the IIoT sensor market. More specifically, they offer 'plug-and-play' wireless IoT sensors for use in industrial environments (see image on next page). Clients can use data points generated by these sensors as input for their monitoring systems and software. With this data, companies can predict imminent maintenance and avoid down-time of their assets. Previously this required costly installation of distributed control systems (DCS), which would be difficult to justify for non-critical applications. Edge Dynamics currently offers sensors for measuring temperature and vibration. In addition to physical products, they offer installation, maintenance, software and data analytics. Their physical products are ATEX certified. This is a requirement to ensure safety in environments with risk at explosions. They achieved the highest level, zone 0, which states that more than 10% of the operational time an explosive atmosphere is present.

The physical products offered by Edge Dynamics have a lifespan of 10-15 years, limited by the battery life. In case of a malfunctioning component or drained battery, the product is replaced entirely.

Replacing the entire product means product parts that still function as intended are discarded and its remaining value is lost. Repairing sensors is technically possible, but this poses several difficulties. The company's clients are located around the globe and a single client could own dozens or even hundreds of sensors, thus sending sensors back to Edge Dynamics would be a cumbersome process. Dealing with returned products in a systematic manner would also require a dedicated division within Edge Dynamics. At the moment, disassembling the current product takes 15 to 20 minutes.

Edge Dynamics wants to offer their clients the option to continue using their products after they break down.

Boyes, H., Hallaq, B., Cunningham, J., & Watson, T. (2018). The industrial internet of things (IIoT): An analysis framework. Computers in Industry, 101, 1–12. https://doi.org/10.1016/j.compind.2018.04.015

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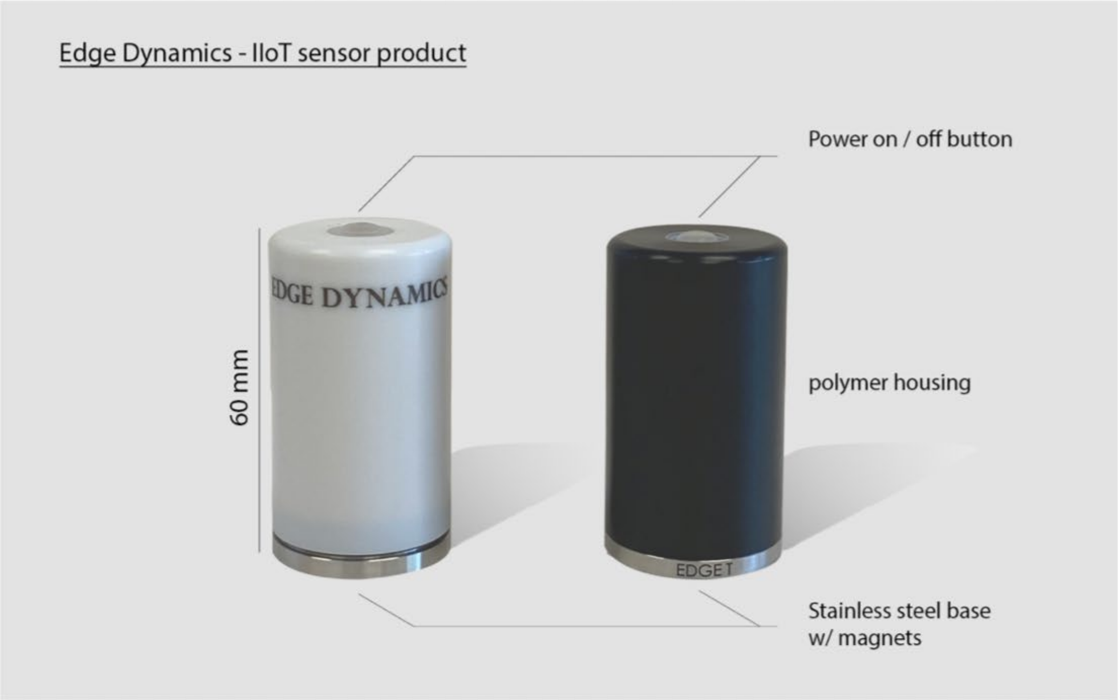


image / figure 1: Edge Dynamics' current product range (white measures vibration, black measures temperature)

TO PLACE YOUR IMAGE IN THIS AREA:
- SAVE THIS DOCUMENT TO YOUR COMPUTER AND OPEN IT IN ADOBE READER
- CLICK AREA TO PLACE IMAGE / FIGURE

PLEASE NOTE:
- IMAGE WILL SCALE TO FIT AUTOMATICALLY
- NATIVE IMAGE RATIO IS 16:10
- IF YOU EXPERIENCE PROBLEMS IN UPLOADING, COVERT IMAGE TO PDF AND TRY AGAIN

image / figure 2:

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

What is the problem?
The sensors have a finite life. Returning a malfunctioning product back to a working state is currently not feasible. Having to deal with a broken product is a hindrance.

Who has the problem?
Operational personnel managing the sensors, for instance field technicians.

What are relevant context factors?
The product will likely operate remotely in an industrial setting (dynamic, possibly outdoors environment). This environment can range up to several hundreds of square meters.

What are the goals?
The goal of the project is to develop an IIoT senor that can be repaired by the same people who require the product to work.

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

I will explore, generate and validate solutions that facilitate repair of the product in case it ceases to work. These have to make it possible for anyone operating the sensors to bring them back to life.

The expected outcome of this assignment is a redesign of the current product incorporating ways that make it feasible to prolong its lifespan in case of damage, malfunction or loss of power.

Maintaining the ATEX certification of the current product concerning explosion safety is important as achieving this certificate is a lengthy and expensive process. This certification is a major selling point for clients.

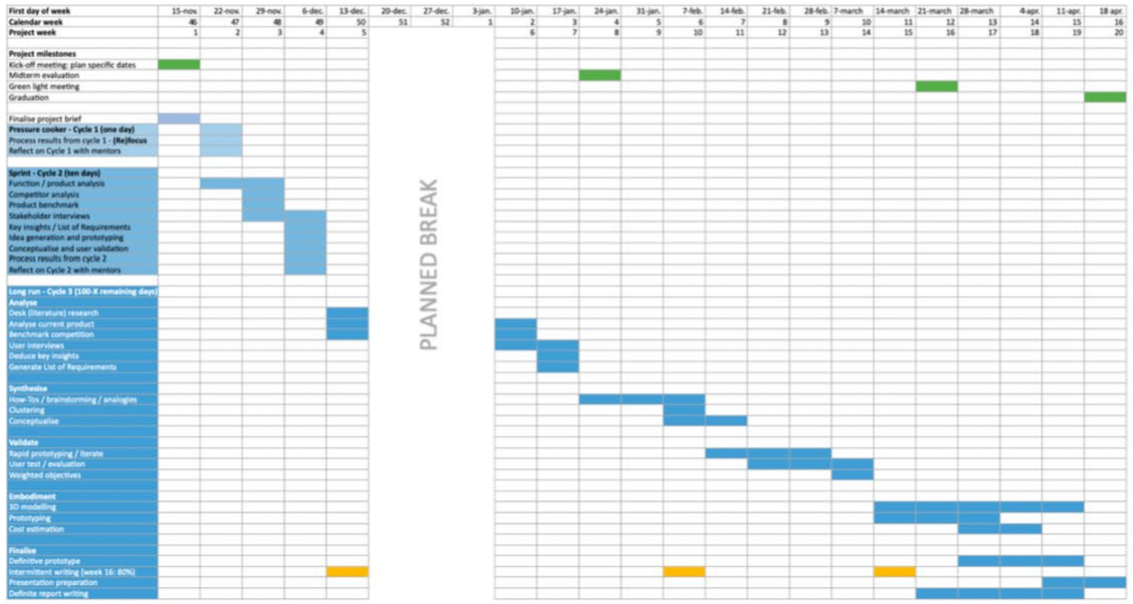
Understanding the context in which the sensor is used will form the base of this project and will provide input for idea generation. Validation of ideas and concepts can be done by rapid prototyping and user tests. A final prototype will facilitate a direct comparison with the current product.

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 15 - 11 - 2021

18 - 4 - 2022 end date



I will kick-start this project with a pressure cooker (executing the entire project in one day) followed by a ten-day cycle. A third and final cylce will cover the remaining days (1/10/100 method). Most of the following phases will be executed within each cycle in varying depth:

- Initial (literature) research; explore existing knowledge on e.g. IIoT, modularity, repairability, industrial certifications. Benchmark existing (competitor) products. Analyse the current product (disassembly, function analysis).
- Context analysis; investigate the setting the product will operate in, from users (interviews) to physical environments (observation). Identify key insights for compiling a list of requirements that will support the next steps.
- Idea generation; produce a variety of ideas that aim to solve the stated problem definition.
- Conceptualisation; validate several of the ideas on the requirements, user tests, their feasibility through rapid prototyping and perform a weighted selection.
- Embodiment; continue the development of the chosen idea by optimisation of the design and cost estimation.

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

As stated in my MyM report, I find it interesting to work on sustainability challenges with proportions large enough to make a difference. I think Edge Dynamics' products perfectly examplifiy that sustainability can go hand in hand with increasing a company's profit (in this case by reducing its cost), which i think is the way to go. Therefore, I am happy I can help them improve their products, which intrinsically works best in large numbers, on its sustainability. To finish my education with such a challenge would be a great fit.

Within the next 20 weeks, I want to put the skills I experienced during my studies and internships to the test. I want to utilise rapid prototyping to validate my ideas and concepts during this project. But I also want to be more conscious about my project planning and management, as I have realised these are skills of mine that could use training. When applicable, I would like to acquire basic knowledge of coding with Python.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.