Using local energy and material flows to redevelop the Applied Physics building

As part of a circular and CO_2 neutral TU Delft campus

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Abstract

The TU Delft aims to have a CO_2 neutral and circular campus that departs from the linear economy to closed material cycles by 2030, meaning that the campus becomes climate neutral. However currently the TU Delft is accountable for 47.957 tCO_2-eq emissions, uses 166.038 MWh of energy for electricity and heat, and is for approximately 5-15% circular. The research is conducted through an analysis of the location following the method of Superuse Studios on the energy (heat and electricity) and material flows.

There are multiple interventions needed at the TU Delft campus and in building 22 to reduce its current impact and redevelop the building into a fully circular, energy neutral and CO_2 neutral building. By adding cyclifiers to the energy and material system a locally closed loop is created. The environmental impact of the building is reduced by improving the thermal qualities of the façade as well as reusing the existing materials.

Keywords: *industrial ecology urban mining, flows, cyclifiers, circular renovation, TU Delft, educational building*

I. Introduction

In the TU Delft strategic framework 2018-2024[1], the aim for the TU Delft is to have a CO_2 neutral and circular campus by 2030. This is more ambitious than the European Green Deal, which states the following: "achieve climate neutrality by 2050 [...] to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use."[2]

Another pressing issue related to the construction sector is its high demand on resources. The Ministries of Environment and Economic Affairs estimated that this sector in the Netherlands is accountable for 40% of the total energy consumption, 50% of raw material usage and 40% of the waste comes from construction and demolition activities. Together, the sector is responsible for approximately 35% of the CO_2 emissions in the Netherlands.[3] To move toward a circular economy, there is a need to reduce the amount of raw materials used as well as produce no

[1] TU Delft, (2018), Impact for a better society, TU Delft strategic framework 2018-2024, TU Delft

[2] European Commission, (2019) The European Green Deal, Communication from the commission to the European Parliament, the European Council, The Council, the European Economic and Social Committee and the Committee of the Regions, Brussels

[3] Ministry of infrastructure and the environment and the ministry of economic affairs (2016). A Circular Economy in the Netherlands by 2050

waste. There lies an opportunity in Urban Mining (UM), where materials and components are harvested from cities and buildings to recover these materials and energy for reuse.[4]

1.1 The current impact of the TU Delft

The TU Delft needs to move from a linear economy to a circular economy and become a circular and CO_2 neutral campus. The circular campus means a campus that departs from the linear economy to closed material cycles. When new materials or products are required, only sustainably produced products are contracted. Also, the lifespan of raw materials is maximized without harmful emissions to the environment. For all construction related projects, it is required that the constructions are adaptable and demountable. A CO_2 neutral campus is a campus that is climate neutral, meaning that no CO_2 and other greenhouse gasses are emitted as a result of activities directly related to the campus. The energy needed for electricity and heat comes from a renewable source.[5]

Currently the TU Delft is accountable for 47.957 tCO_2-eq emissions (Appendix A), uses 166.038 MWh of energy for electricity and heat[6], and is for approximately 5-15% circular.[7] There is a need to improve in order to meet the goals by the TU Delft.

1.2 The case of building 22 Applied Physics

This paper focusses on the TU Delft and specifically on building 22 Applied Physics, further referred to as building 22, which has the biggest energy consumption on campus, equivalent to 12.873,2 MWh or 425 kWh/m^2 in 2018 for electricity and heat combined. [8] This can be explained by the many laboratories present in the building and the poorly insulated shell. The technical state of the building is mediocre, which means that the building and installations regularly show defects in finishing layers, materials, parts and constructions. Nuisance and malfunctioning of construction and installation parts (for example due to leaks) can occur several times a year and malfunctioning of the building services occur more and more often. The building is in need of a thorough renovation to meet the current standard.[9]

The aim of this research is to develop a roadmap for building 22 to reduce its current impact, by closing the energy system locally and investigate the possibilities and potential of reusing the existing materials. This results in the following research question: *"What interventions are needed in building 22 to reduce its current impact by using the available flows (heat, electricity and materials) and their potential to redevelop the building into a fully circular, energy neutral and CO_2 neutral building?"*

1.3 Method

The research is conducted through an analysis of the location following the method of Superuse Studios on the energy (heat and electricity) and material flows.[10] This is split up into two parts. Firstly, the energy flows will be studied based on the principles of industrial ecology. A description of the principles of industrial ecology will be given, followed by a system analysis, potentials and cyclifiers, and possible solutions.[11]

[4] Lukkes, D. (2019) Urban Mining as tool to stimulate component reuse in architecture, TU Delft
[5] Campus and Real Estate, (2019), KPIs duurzaamheid TU Delft: versie maart 2019. TU Delft
[6] Blom, T., Dobbelsteen, A. van den, (2019), CO2-roadmap TU Delft
[7] Ellen, L. van (2019), Roadmap Circulaire Campus 2030, TU Delft
[8] emonitor.tudelft.nl
[9] Blom, T., Dobbelsteen, A. van den, (2019), CO2-roadmap TU Delft p. 33
[10] Jongert, J. (2014), INSIDEflows research group 2013-2014 reader
[11] 2012Architecten, & Goossens, F. (2009). Recyclicity: Industrial Ecology applied in the urban environment.

The second part is the material flow which will be studied via the principles of urban mining and the materials will be valued for their reuse potential using the value assessment of Dronkers. This contains several steps: creating a material inventory, description of factors that influence the process of reuse and constructing a value assessment and proposing design applications.[12] The research is supported by a literature review and case studies on closed loop energy systems that use cyclifiers and buildings constructed from reused building materials.

II. ENERGY: HEAT & ELECTRICITY

2.1 Industrial Ecology

When analysing the energy flows present in building 22, the principles of Industrial Ecology (IE) are followed. A goal of IE is to change the linear industrial system into one that is cyclical where waste is reused as energy or as raw materials in other processes. It is fundamental to identify and trace flows of energy and materials through a system. IE has two fundamental principles; a systems perspective and the analogy with biological systems.[13] The systems approach provides a holistic view on environmental problems, thus making it easier to identify and solve these problems. It requires a multi-disciplinary approach to identify the different layers in a system.[14] By a systems approach, one analyses the functioning of the system as a whole and not just at some of the parts. [15]

The second fundamental principle of IE, the analogy with biological systems, emphasises the interaction between industrial and ecological systems where they have a harmoniously integrated relation. The natural system is seen as the ultimate cyclical (closed) system where waste becomes a recourse for another organism. In an ecosystem, energy cascading occurs very efficiently as well as the nutrient recycling. IE aims to reach the dynamic equilibrium and high degree of integration and interconnectedness that exists in nature. Appling IE principles to the built environment can result in a reduced energy demand and fewer material recourses are needed from outside the system boundaries. It will also lead to less waste and emissions.[16]

Based on the principles of IE, Superuse Studios (former 2012Architecten) developed a design strategy with the goal to find potentials in the urban context to create closed loop systems. The strategy consists of the following steps: (1) define the system boundaries, (2) analysing the system and its streams, (3) find cyclifiers that can help in connecting the streams, (4) do this not only for the physical layer but also on the higher information and strategic layers, (5) integrate the design to come up with a consistent whole.[17]

2.2 System analysis building 22, TU Delft

2.2.1 Background information

The TU Delft started out in 1843 in the city centre of Delft and slowly developed the buildings in the north of the campus. After the Second World War the developments of the Campus further towards the south started and it grew to the campus as we know it now. Many different architects

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[12] Dronkers, M. (2020), The application potential of reclaimed materials in architectural design, TU Delft
[13] 2012Architecten, & Goossens, F. (2009). *Recyclicity: Industrial Ecology applied in the urban environment.*
[14] Garner, A., and G.A. Keoleian (1995). Industrial Ecology: An Introduction.
[15] Boer, N. de, (2018) Connecting walk-up apartments to local closed flows, TU Delft.
[16] Garner, A., and G.A. Keoleian (1995). Industrial Ecology: An Introduction & 2012 Architecten, & Goossens, F. (2009). *Recyclicity: Industrial Ecology applied in the urban environment.*
[17] 2012 Architecten, & Goossens, F. (2009). *Recyclicity: Industrial Ecology applied in the urban environment.*

have designed buildings and urban spaces commissioned by the TU Delft and the central government.[18]

Building 22 is designed by the architecture firm Roosenburg, Verhave and Luyt and built in 1963[19] and has an area of 43.100 m^2 making it one of the largest buildings on campus. The building has a located in the centre of the campus next to the Aula and the Library. It is embedded in the urban fabric of the TU Delft with a 175-meter-long rhythmic façade facing toward the Mekelpark. The concrete façade has a sense of monumentality however, it has quite a closed look and is not overly inviting to visit.

The building was specifically designed for the Applied Sciences faculty for educational and research purposes. Nowadays, the building still has these functions and a commercial function is added as two wings of the building are rented out to QuTech and Microsoft (Appendix B). In 2018 there were 24.232 students and 5.383 employees (in FTE) present at the TU Delft in 2018. At the Faculty of Applied Sciences where building 22 is part of 3144 students and 1010 employees (in FTE) are present. Approximately 1270 of the 3144 students study in building 22. [20] Additionally, 210 (in FTE) employees work at QuTech[21] and an unknown amount of people works for Microsoft in the building.

2.2.2. System analysis

In IE the system approach is used, and a boundary of the system is defined as the TU Delft campus (Figure 1). The TU Delft covers an area of 140 hectares.[22] Within the system boundary building 22 (Applied Physics) is highlighted in yellow as the renovation case.

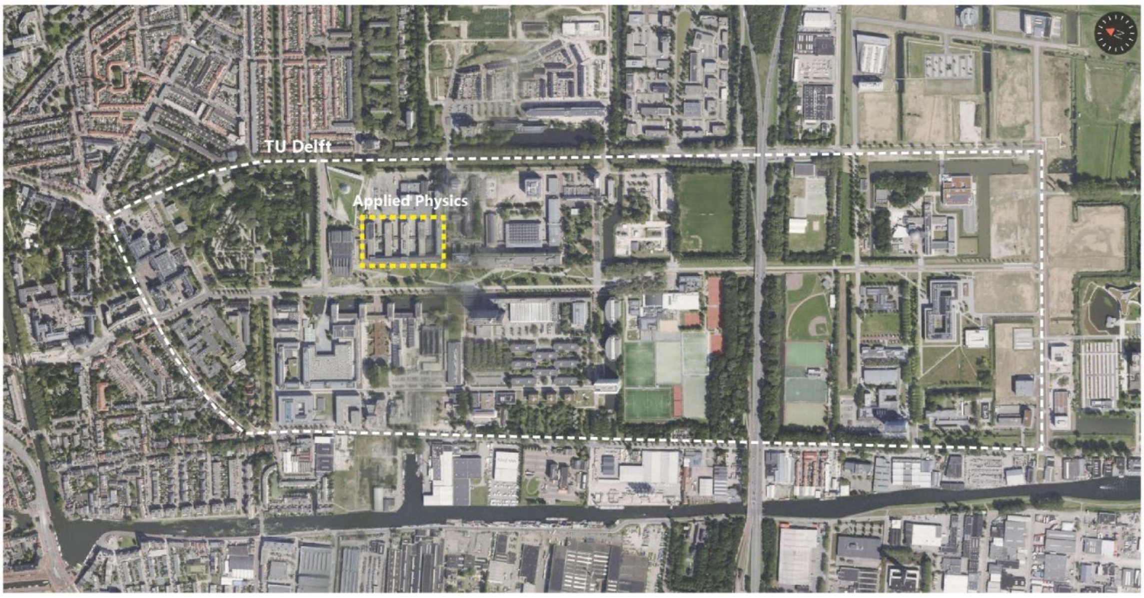


Figure 1 System boundary of the TU Delft (image source: apple maps)

[18] Campus and Real Estate, History, [online] https://campusdevelopment.tudelft.nl/en/history/ accessed on 15-5-2010
[19] TU Delft, Architectenkaart, [online] https://campusdevelopment.tudelft.nl/wp-content/uploads/2018/05/Architectenkaart-campus-18-04.pdf retrieved on 4-05-2020
[20] TU Delft (2020), Facts & Figurs 2019-2020, [online] https://www.tudelft.nl/en/about-tu-delft/facts-and-figures/ retrieved on 12-05-2020
[21] QuTech, (2019) Annual report 2018, TU Delft
[22] Measurement taken form google maps area measuring tool

The system analysis looks at the energy system of the TU Delft and how the electricity and heat flow through it. The electricity used at the TU Delft is partly imported wind energy, partly produced in the Combined Heat and Power plant (CHP) on campus and a very small portion is generated by PV panels. The CHP runs on natural gas and produces the heat for the central heat grid. In the CHP there are three gas boilers with an efficiency of 75% and two CHP's with an efficiency of 40% electricity and 45% heat. Building 22 is connected to the heat grid on campus (Figure 2). Thirteen buildings on campus are connected to their own heat and cold storage system to supply their heat. The buildings also have small individual boilers to generate running hot water.[23] A schematic drawing of the system can be seen in Figure 3 (next page).

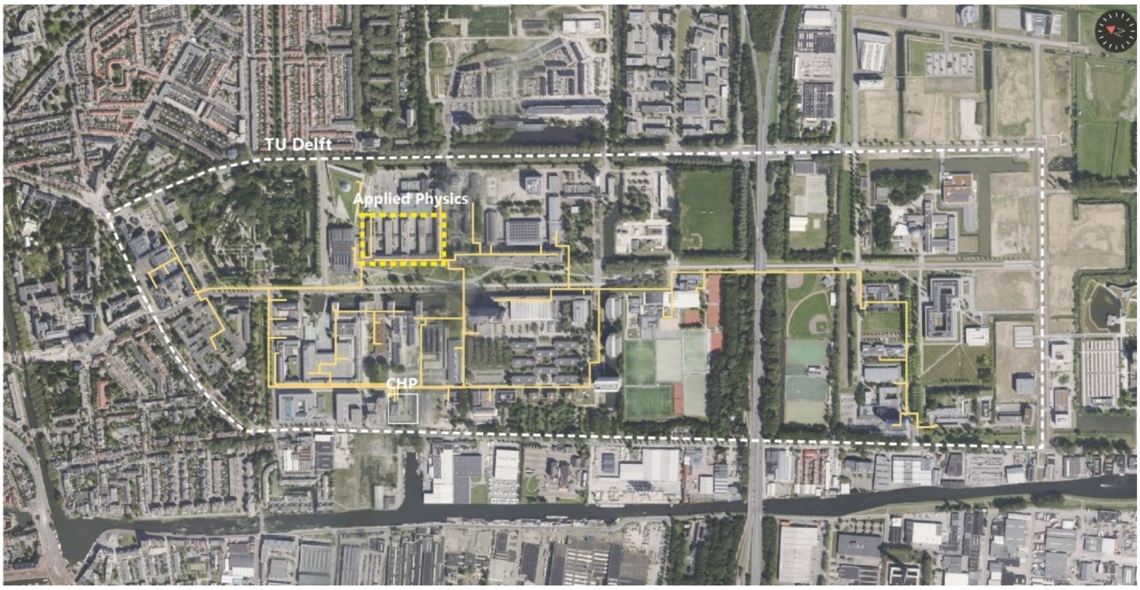


Figure 2 Combined heat and power plant (CHP) with heat grid on campus (image source: Apple maps)

[23] Blom, T., Dobbelsteen, A. van den, (2019), CO2-roadmap TU Delft

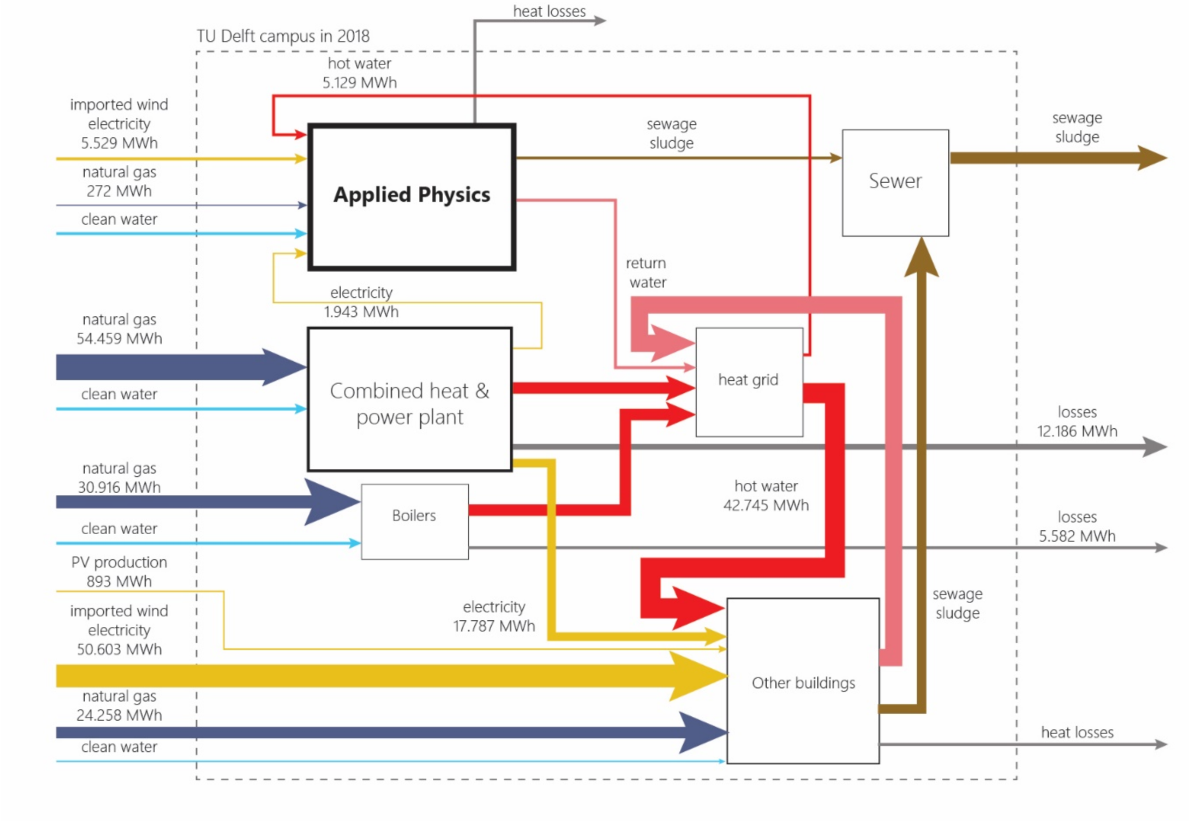


Figure 3 Energy system TU Delft

Building 22 has the highest energy consumption on campus, equivalent to 12.873,2 MWh or 425 kWh/m^2 in 2018 for electricity and heat combined. [24] This results in 916 tons of CO_2 emissions due to electricity usage and 539,8 tons CO_2 emissions due to heat. Nine hectares of forest can absorb 87,3 t CO_2 eq[25] which would mean there is 150 hectares of forest needed to compensate for the CO_2 emissions of building due to heat and electricity. The emissions related to energy of this one building would already need more hectares of forest land to compensate than the TU Delft campus has (140 hectares in total). It is clear that the energy demand of the building needs to be reduced to lower the CO_2 emissions. Campus and Real Estate (CRE) defined the KPI's for heat and electricity for the existing building stock both need to be reduced to 50 kWh/m^2 and needs to come from a sustainable source in 2030.[26] In the case of building 22 this means that the energy demand needs to be reduced with at least 71% for electricity and 60% for heat to meet the KPI's in 2030.

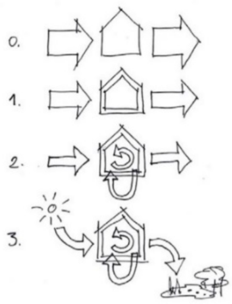
2.2.3. Possible solution energy system

In order to reduce the current impact of the energy system on campus and specifically of building 22, the New Step Strategy is used. Step 0 researches the current situation followed by step 1 where the current demand is reduced as much as possible through smart design solutions. Step 2 residual energy is reused and in step 3 the remaining energy demand is supplied sustainably. [27] According to the CO_2 roadmap study by Blom and Dobbelsteen the following actions need to be taken: 1) Reduce: the energy demand for buildings through renovations and transformations, use

[24] emonitor.tudelft.nl
[25] Blom, T., Dobbelsteen, A. van den, (2019), CO2-roadmap TU Delft
[26] Campus and Real Estate, (2019), KPIs duurzaamheid TU Delft: versie maart 2019. TU Delft
[27] Dobbelsteen, A. van den, (2008), 'Towards closed cycles - New strategy steps inspired by the Cradle to Cradle approach', in: Proceedings TU 2008 - 25th Conference on Passive and Low Energy Architecture. Dublin (UDC)

smart bioclimatic design solutions and start with passive solutions. Use energy efficient equipment where it is needed anyway. 2) Reuse: make more use of residual heat and recovery of heat from air and water. Exchange energy on campus (surpluses versus shortages) and use advanced energy storage systems. 3) Produce: place more solar panels, preferably architecturally integrated in roofs and facades. Install a geothermal grid.[28]

This strategy is closely related to the R-ladder (Figure 5) and they can support each other to evaluate the circular campus. The top is the most circular principle and the further you go down the less circular the principle becomes.[29]



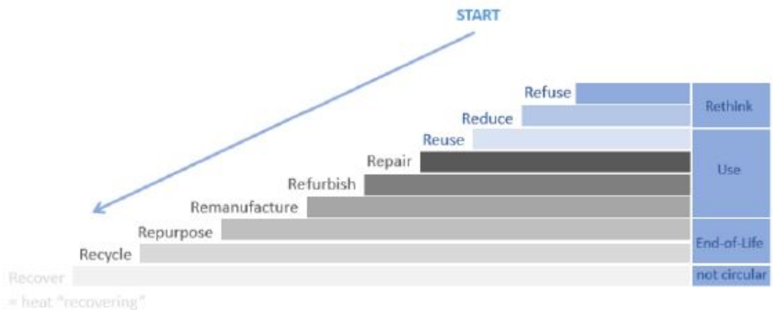


Figure 4 The New Step Strategy (image source: Dobbelsteen 2008)
Figure 5 R-ladder to evaluate the circular campus (image source: Ellen, 2019)

Currently building 22 has a poorly insulated façade with an Rc-value of 1,5 m²K/W resulting in large transmission losses. The performance of the façade needs to be increased to a well-insulated façade with an average Rc-value of between 4,5 and 7 m²K/W, which will reduce the demand for heat drastically. Further calculations and research are needed to determine the exact savings in relation to improving the Rc-value of the façade.

To reduce the energy demand for both heating and electricity the use of domotics is promising with an estimated reduction of 10%. This system only activates lighting, heating and ventilation when the sensors detect a need in a specific space using movement, lighting, CO_2 and temperature sensors as well as a link with the room booking system. A test conducted by Marko Djuričić to reduce the energy consumption of the air treatment system in a lecture hall at 3ME by using CO_2 sensors to detect the need for ventilation, reduced the energy usage with 50%. The heat demand can also be reduced by introducing atria in building 22, which simultaneously results in more roof area for PV panels.[30]

Currently lighting is responsible for 30% of the total electricity consumption. This can easily be reduced by swapping the lighting to LED and reduce the operation hours of lighting with 20%. This results in a reduction of 49% for the demand for lighting. Also increasing the use of natural daylight is favourable.[31]

[28] Blom, T., Dobbelsteen, A. van den, (2019), CO2-roadmap TU Delft P. 63-64
[29] Ellen, L. van (2019), Roadmap Circulaire Campus 2030, TU Delft
[30] Blom, T., Dobbelsteen, A. van den, (2019), CO2-roadmap TU Delft P. 65-66
[31] Blom, T., Dobbelsteen, A. van den, (2019), CO2-roadmap TU Delft P. 65

2.2.4. Potentials and cyclifiers

In two case studies[32] presented in the Recyclicity report, some common cyclifiers were used in both. The local closed energy system consisted of an energy source, energy production and energy storage. As an energy source, the production of biogas out of sewage sludge[33] and solar energy can be used on campus. Biogas can replace the natural gas that is currently used in the CHP that is already present on campus. Another possibility is using geothermal energy to supply the campus of heat, as a by-product CO_2 is emitted. However, this could be used to produce algae which then can be used to produce biogas for the CHP.[34] The TU Delft already has a plan to install a geothermal installation (Appendix J). The CHP produces electricity and heat which can be distributed on campus. To provide extra heating it is possible the use solar collectors as done in the project Slim MSP in Heerlen.[35]

The potential to use on roofs and facades of buildings is applicable to the buildings on campus. On the roofs of the buildings on campus approximately 6500 m^2 is available for PV panels, this would mean a production of approximately 1.094.000 kWh/year.[36] In Appendix C a map is found of the available roof surfaces on campus that have potential for PV. To produce more energy on the buildings, it is useful to integrate PV panels on east, south and west facing facades, as this allows for a more even production of electricity throughout the day and the year. The maximum potential electricity production of PV panels on facades needs a more in-depth research into the potential on the specific buildings on campus. [37] The façade PV panels will produce 80-150 Wp/m^2 depending on the colour, orientation and available cell space.[38]

The third component needed for a closed energy system is energy storage, simply because the demand and supply do not always occur at the same time. Heat can be stored in seasonal thermal storage in the underground, where the excess heat in summer can be stored to be used in winter and visa versa.[39]

2.2.5. TU Delfts closed loop energy system

To create a closed loop energy system at the TU Delft multiple cyclifiers are implemented, shown in grey (see Figure 6). It is only possible to create this closed system if the current demand is reduced. The PV panels will produce up to 6.000 MWh and on building 22 this will be 1.094 MWh. To reduce the energy demand multiple buildings will be disposed, other buildings need a thorough or light renovation (Appendix D). This will lead to a saving of 4.722 MWh of gas, 19.077 MWh of heat and 14.756 MWh for electricity on campus. The proposed savings result in a 52% reduction in CO_2 emissions for heat and electricity.[40] The aim is to reduce the energy demand for building 22 as much as possible with a minimum reduction of 71% for electricity and 60% for heat both to 2.155 MWh to meet the KPI's in 2030. It is necessary to maximising the reduction on energy consumption to reduce the environmental impact and thus the CO_2 emissions as much as possible. The biogas plant turns waste into three valuable products, namely biogas, fertiliser and

[32] The case studies were "De Goudse Poort" in Gouda and project Slim MSP in Heerlen
[33] 2012 Architecten, & Goossens, F. (2009). Recyclicity: Industrial Ecology applied in the urban environment. [online] Available at: https://issuu.com/2012architecten/docs/recyclicity_research
[34] Blom, T., Dobbelsteen, A. van den, (2019), CO2-roadmap TU Delft
[35] Boer, N. de, (2018) Connecting walk-up apartments to local closed flows, TU Delft.
[36] Vattenfal, Premium Power PV panel with 198 Wp/m^2, https://www.vattenfall.nl/kennis/jaaropbrengst-zonnepanelen/
[37] Blom, T., Dobbelsteen, A. van den, (2019), CO2-roadmap TU Delft
[38] Kameleon Solar, (2020), Producetne ColorBlast, [online] https://kameleonsolar.com/nl/colorblast/
[39] 2012 Architecten, & Goossens, F. (2009). Recyclicity: Industrial Ecology applied in the urban environment. [online] Available at: https://issuu.com/2012architecten/docs/recyclicity_research & Blom, T., Dobbelsteen, A. van den, (2019), CO2-roadmap TU Delft
[40] Blom, T., Dobbelsteen, A. van den, (2019), CO2-roadmap TU Delft P. 70-77

clean water.[41] The fertiliser can be used on campus for the greenery as well as to grow food in the greenhouse at Westland for example. The proposed cyclifiers have a spatial influence on the built environment and need to be integrated into the design to create additional value.

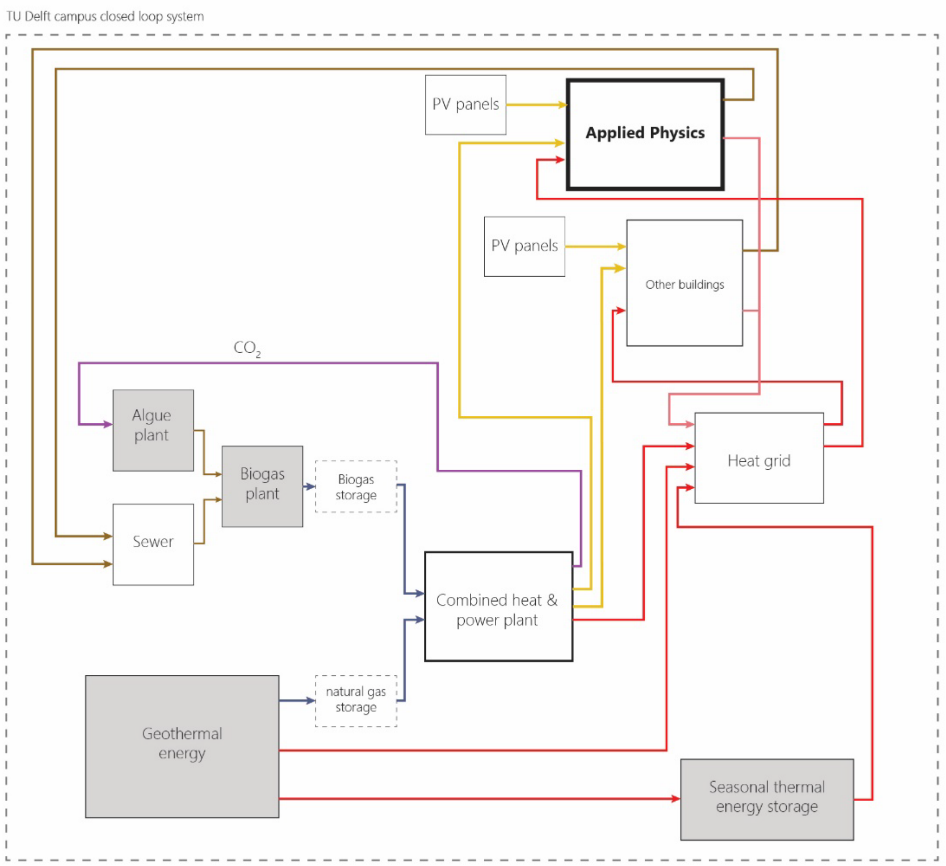


Figure 6 Future closed loop energy system at TU Delft

III. Materials

The impact and reuse potential of the materials present in building 22 have their place within the system of industrial ecology. A closer look into the building materials will be studied through the lens of Urban Mining (UM). This tool can help to move from a linear economy to a circular economy where 'waste' becomes a resource. In UM, cities and buildings become potential material mines where materials and energy are recovered for reuse. Thereby reducing the need for newly mined raw materials to create new buildings.[42] Rather than demolishing buildings, where the materials and components are being destroyed, they can be harvested for reuse.[43]

3.1 Inventory building materials

By conducting a Material Flow Analysis (MFA), an inventory of the materials found in the structure and façade of building 22 has been made. Based on data on embodied energy and CO_2 emissions of the Pulse building at the TU Delft, the structure is accountable for 64% and the façade for 28% of the environmental impact. The remaining 8% is due to building installations and

[41] 2012 Architecten, & Goossens, F. (2009). Recyclicity: Industrial Ecology applied in the urban environment. [online] Available at: https://issuu.com/2012architecten/docs/recyclicity_research
[42] Baccini, P. & Brunner, P.H. (2012). Metabolism of the Anthroposphere – Analysis, Evaluation, Design. Cambridge: The MIT Press, Massachusetts Institute of Technology.
[43] Lukkes, D. (2019), Urban Mining as tool to stimulate component reuse in architecture, TU Delft

interior walls.[44] Therefore this research will make an inventory of these two layers of the building. The analysis is done through studying the building drawings and details[45] and a physical observation of the building to calculate the amounts of materials that is present in the building (see Figure 7).

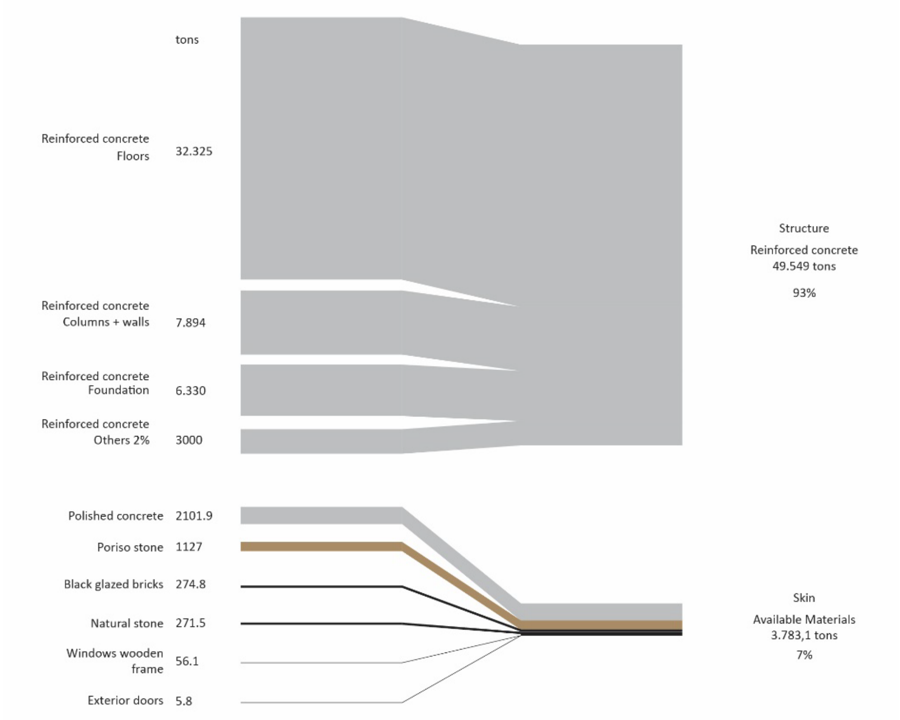


Figure 7 Inventory materials present in building 22

There structure of the building is made from reinforced concrete that is poured in situ and will be reused in its current state. The building has 14.500 m^2 façade, which is made from mainly stony materials, with doors and windows. The façade consists for 57% closed parts and 43% are openings. The windows are available in a large quantity and in a range of different sizes. Most window frames are either wood or steel with single glazing. There are not any insulation materials present in the building, resulting in a poor thermal performance (Rc-value of 1,5 m^2K/W).

3.2 Factors influencing reuse potentials of reclaimed materials

There are multiple factors that influence the potential for reuse as defined by Dronkers[46] based on multiple literary studies[47] that describe the opportunities and threats for the reuse of components. Viability, environmental impact and costs are the most important factors determining the success of reusing materials. A description of the factors will be given, and it is important to keep in mind that some of the factors below can be measured in clear numbers, while others are based on vague terms which could lead to more subjective choices.

[44] Blom, T., Dobbelsteen, A. van den, (2019), CO2-roadmap TU Delft
[45] Found in the City archive of Delft and the personal archive of the TU Delft
[46] Dronkers, M. (2020), The application potential of reclaimed materials in architectural design, TU Delft
[47] Addis, 2006; Guy & Esherick, 2006; Gorgolewski & Morettin, 2009, Hobbs & Adams, 2017, Slager & Jansen, 2018, Kernan, 2002; Te Dorsthorst et al., 2002

3.2.1 Viability [48]

In order for materials to be reused it is important to determine the viability, to see whether it is feasible to harvest the existing materials. The following characteristics define the viability for reuse: availability, ease of detachment, ease of refurbishment and reuse potential. Analysing these characteristics will give a first impression whether reuse is viable.

Firstly, availability is related to the quality and quantity of a certain material or component at a building site. It is preferred to harvest a large quantity of the same material or component from one location because of the logistical and financial benefits. Harvesting materials from multiple locations in a similar timeframe, will allow for a large stack of materials for designers to work with and it makes the integration into the design easier.

The second characteristic, ease of detachment, also benefits from the logistic and financial benefits of harvesting from one location. The deconstruction process becomes easier if the surrounding area can cater towards transport and storage of the harvested materials. The ease of detachment is influenced by the way the building was originally constructed and which systems are used, how well this is documented, and the availability of relevant information is present. The way a building is deconstructed determines the quality and reuse potential of the materials. Apart from metals, where approximately 90% can be easily separated in the demolition process, other materials are difficult to retrieve because they need to be harvested by hand.

The third and fourth characteristic, ease of refurbishment and reuse potential, closely relate to each other. The effort it takes to make a material or component ready for reuse is the ease of refurbishment. The more energy and effort are needed to refurbish a material for reuse in a new design the less favourable it is. The reuse potential gives insight into the (multiple) possibilities a material or component can be used in a new design. Often, the easier it is to refurbish a material the higher the reuse potential will become.

3.2.2 Environmental impact [49]

Reusing materials lowers the need for raw materials, prolongs the lifespan, saves energy and less waste ends up in landfills. The characteristics that influence the environmental impact that Dronkers uses are embodied energy and voluminous impact. In this research the CO_2 emissions related to materials is also important to consider, because of the goal to reduce the current impact of the building and to redevelop it into a circular, energy neutral and CO_2 neutral building.

The first characteristic, embodied energy, is the energy invested in creating the materials and components and is relatively easy to calculate based on databases.[50] The manufacturing, transport to the site, assembly and maintenance are measured and included in the calculation.

The second characteristic, CO_2 emissions, closely relate to embodied energy. The same database provided information and key figures to calculate the CO_2 emissions that were emitted during the production, transport and assembly of the materials. It is common that materials that needed more energy to be produced often also emitted more CO_2. The materials and components with the highest embodied energy and CO_2 emissions will result in the biggest saving and will have the biggest environmental gain. In the case of building 22 this would mean that reusing the concrete structure and polished concrete found on the façade have the highest priority, followed by the windows.

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[48] Dronkers, M. (2020); based on Addis, 2006; Slager & Jansen, 2018; Gorgolewski & Morettin, 2009; Guy & Esherick, 2006

[49] Dronkers, M. (2020); based on Addis, 2006; Te Dorsthorst et al., 2002; Gorgolewski & Morettin, 2009;

[50] Federal Ministry of the Interior, Building and Community, Ökobaudat platform, [online] https://oekobaudat.de/OEKOBAU.DAT/datasetdetail/process.xhtml?uuid=a758fb6a-7fb1-4cdc-b652-c42cf2f7632c&stock=OBD_2020_II&lang=en retrieved on 18-05-2020

Lastly, the voluminous impact is considered, where one looks at the materials and components on a larger scale and the environmental impact they will have when they are not reused, but instead end up in landfills. Here it is important to consider the volume and weight of the available materials to evaluate the impact on the environment. The more there is of a material the bigger the voluminous impact is.

3.2.3 Costs [51]

The value of materials and components can create either a barrier or an opportunity for reuse. A barrier of using reused materials is the relatively higher cost to source and make the materials ready for reuse in comparison to new factory-based products. The higher manufacturing cost may lead to a lower demand for reused materials and components, even though the environmental impact is lower.[52] However, there is an opportunity to reduce construction costs by reusing reclaimed materials. During the deconstruction process approximately 30-50% could be saved due to lower disposal and machinery costs compared to traditional demolition. To evaluate the reuse potential on costs, market value and production costs are considered.

Firstly, the market value of material or components needs to be evaluated before storage when it is not reused right away and whether these materials have a potential to be sold after they have been harvested. The attractiveness, price and competing solutions are factors that determine the market value. When a material or component has a low market value, the cost of harvesting does not way up to a financially feasible case for reuse.

When evaluating the production cost, it is important to consider the costs that are initially made to produce the materials and components as well as the extra costs that are needed to remanufacture the materials to make them ready for reuse. Factors that determine the production costs are resources, time, labour hours and process complexity. Comparing these costs to the production of new materials is evaluated.

Vandkunsten evaluated the production costs and sales potentials for the following reused materials; wood, steel, bricks, concrete, glass and soft flooring. Wood, steel and glass have a high sales potential, but the production cost for wood and glass are costly while the costs for steel are competitive with the production of new components. The production costs of reused brick are also comparable with the costs of new materials, but their sales potential is below average. Reused concrete is both very costly to produce and has a low potential to be sold on.[53]

Lastly, it is important to consider whether there is transport and storage needed for the harvested materials, because this could rise the costs. It is most favourable for a costs and environmental standpoint, that the materials and components are directly reused on the same location or close to the original location.

3.3 Value assessment

A value assessment is made to determine the reuse potential of the materials found in building 22. This is based upon the above described factors (see Appendix E for the complete assessment) and the simplified conclusions are presented in Table 1.

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[51] Dronkers, M. (2020); based on Kerman 2002; Gorgolewski, 2008; Addis, 2006; Hobbs & Adams, 2017; Gorgolewski & Morettin, 2009

[52] Vandkunsten Architects & Manelius, A., (2017). Rebeauty: Nordic Component Reuse. Vallensbæk: Knudtzon Graphic

[53] Vandkunsten Architects & Manelius, A., (2017). Rebeauty: Nordic Component Reuse. Vallensbæk: Knudtzon Graphic P. 53

	Viability				Environmental impact			Costs	
	availability	ease of detachment	ease of refurbishment	re-use potential	Embodied energy	CO2 emmisions	Volominous impact	Market value	Production costs
Polished concrete	green	orange	orange	orange	red	red	red	red	red
Poriso stone	green	orange	orange	red			red	orange	orange
Black glazed bricks	green	orange	orange	orange	red	red	red	orange	red
Natural stone	green	orange	orange	orange	red	red	red	orange	red
Windows + frames	green	green	orange	green	red	red	red	green	red
Exterior doors	orange	green	orange	green			red		green

Table 1 value assessment materials in building 22, TU Delft
(green – positive; orange – intermediate; red – negative)

The cladding on the façade is difficult to disassemble due to the way the building was originally assembled. The polished concrete, poriso stone and natural stone are attached to each other with either mortar or glue and possibly with anchors. The black glazed bricks are connected with cement mortar as is the case in most modern buildings, it is not possible to separate the bricks from the mortar without breaking the bricks. [54] However, there is a potential to reuse the bricks by cutting out panels is the most promising option.

It is noticeable that all materials present in the façade have a big environmental impact, thus ensuring the reuse of the materials can result in a great saving in embodied energy and CO_2 emissions. Overall, the façade is composed of interesting materials that are readily available and their characteristics allow for multiple reuse implementations.

When integrating the reused materials and components into the new circular design, it is important to design fastening systems that are easy to detach and reassemble. This will ensure easier reuse in the future, because the ease of detachment and refurbishment will increase as well as the reuse potential. First the production costs of façade cladding with a detachable fastening system will increase, but ones these panels have been made they do not require extra production costs for the next reuse cycle and therefore making it more financially feasible to keep reusing these materials over and over again in the future.

3.4 The application of reused materials in architecture

There are multiple tools that are being used more and more to stimulate the reuse of materials and components. The Material Flow Analysis (MFA), is becoming a tool that is integrated in the practice of architects and engineers and has been adopted by several architectural firms like EXCEPT, Doepel Strijkers Architects, De Urbanisten, van Bergen Kolpa Architecten and Superuse Studios. (Jongert et al., 2015) The MFA can help to conserve resources and protect the environment. (Brunner & Rechberger, 2016) This is increasingly relevant now as Europe needs to transition to a circular economy. (European Commission, 2019)

A tool that has been developed by Superuse Studios, is the www.oogstkaart.nl where the Dutch real estate and construction industry gets the opportunity to offer their waste flows to the market. The goal of the website is to offer a platform that stimulates the circular economy and reduces the CO_2 footprint. This tool helps designers find materials and components that are available for reuse in the Netherlands. Buildings that are ready to be demolished are published on the website as an urban mine were material resources can be found.

[54] Durmisevic, E. & Binnemars, S. (2014). *Barriers for Deconstruction and Reuse/Recycling of Construction Materials in Netherlands.* University of Twente.

Designing with reused materials and components is different than designing with new materials. Dronkers has developed a decision chart to determine whether a component can be reused in its original function or one should look for new types of applications. The chart is added in Appendix F.[55] To investigate the possibilities a designer has to implement reuse materials into architecture, four case studies are chosen (Appendix G). Villa Welpeloo by Superuse Studios and Circle House by 3XN are two new buildings primarily made from existing materials, while BlueCity by Superuse Studios and Haka Rotterdam by DoepelStrijkers implemented reuse materials and components to design an interior infill inside an existing building.

3.4.1. Façade materials

The façade materials found at the Applied Physics building are polished concrete, bricks, natural stone and poriso stone. When starting a renovation project, it is important to first consider leaving the materials in place. When this is not possible, reusing materials as describe in this paragraph is the second-best option.

The quality of the harvested materials is determined by the way they can be disassembled. In this case they are all either glued together or connected with concrete mortar. For the materials in the façade, there is a potential to cut out pieces from the façade to create a new façade with.[56]

The most used materials in the Applied Physics building is (polished) concrete is the façade and structure. Where concrete is responsible for most of the construction waste as it is the most widely used material in the construction industry. Because of the structural properties of concrete, it is hard to disassemble the components without damaging it. [57] Due to the big environmental impact of concrete, it is important to find ways to reuse existing concrete. Either by keeping an existing concrete structure and create a new infill of cut it in modular panels or bricks and reuse those in a new design. Currently most of the construction waste in the Netherlands is reused on a low level as rubble to create the foundation for roadworks.[58] In the Circle House by 3XN they used concrete and created demountable connections to ensure easy reuse in the future.

Similarly, bricks and natural stone can be reuse by cutting the existing material into modular panels. These could be hung on a demountable system or lime mortar can be used, which can be removed from the panels. Examples of projects that reused bricks, are the Resource Rows by Lendager Group and Cubo House by Phooey Architects where they cut smaller modular pieces out of brick walls to create a new façade with.[59] The natural stone could also be used for interior or exterior flooring.

Lastly, a more creative approach can be taken when reusing materials for façade cladding as done in Villa Welpeloo and Circle House. In both projects they experimented with waste and turned it into façade cladding. At Villa Welpeloo they used excess wood from cable reels to clad the façade. At Circle House they created façade tiles out of plastic waste and they created a varied colour pallet giving the façade a visually interesting look.

3.4.2. Windows

The windows found at Applied Physics are mainly single glazing with steel or wooden frames, thus having a poor thermal performance. The reuse potential of windows is depended on the thermal performance in order for them to be suitable for reuse in the exterior. The windows in building 22

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55 Dronkers, M. (2020) P. 8
56 Vandkunsten Architects & Manelius, A., (2017). Rebeauty: Nordic Component Reuse. Vallensbæk: Knudtzon Graphic
57 Vandkunsten Architects & Manelius, A., (2017). Rebeauty: Nordic Component Reuse. Vallensbæk: Knudtzon Graphic
58 Ministry of infrastructure and the environment and the ministry of economic affairs (2016). A
Circular Economy in the Netherlands by 2050
59 Dronkers, M. (2020), The application potential of reclaimed materials in architectural design, TU Delft

do not meet the current quality norms for windows in the façade as there U-value is too low. The glass needs to be replaced with double or triple glazing and the frames need to be upgraded as well, which is quite an extensive refurbishment to get a sufficient thermal performance. Villa Welpeloo by Superuse studios is an example of a project that reused existing window frames where the glass has been replaced.

There is also a potential to reuse windows to create interior infill as this does not require a specific thermal performance. Blue City by Superuse Studio reused existing windows to create rooms inside an existing building. This way of using reclaimed windows has potential at the Applied Physics building. Another application for reused windows that does not need mayor refurbishment is to use them as a second skin or where you only need protection from wind and rain. An example of this is the Afvalbrengstation by Wessel van Geffen Architecten.[60]

3.4.3. Doors

Similar to windows, doors need to meet building regulation in terms of measurements and thermal performance which does not always allow for reuse in the same function. Since this is a renovation project it is allowed to use doors lower than 2,3m and/or smaller than 0,85m. When the thermal performance is not sufficient to use the doors on the exterior of the building, the doors can be used to create interior infill just like windows. A project where this has been done is the interior of HAKA Rotterdam by DoepelSpijkers.

IV. CONCLUSION

There are multiple interventions needed at the TU Delft campus and in building 22 to reduce its current impact and redevelop the building into a fully circular, energy neutral and CO_2 neutral building. The roadmap in Figure 8 gives a summary of the required interventions to create a closed loop energy & materials system (enlarged version Appendix H). These interventions have an influence on the built environment of the campus and a preliminary placement of the added cyclifiers has been displayed in Figure 9 (enlarged version in Appendix I).

An inventory of the materials present in the structure and façade of building 22 is made. The reuse potential of these materials is evaluated on three factors; viability, environmental impact and costs. The reuse of the existing materials has a priority in this project to minimise the CO_2 emission of the redevelopment of the building and meet the goals of Campus and Real Estate to become a circular campus.

Building 22 is with is 175-meter-long façade facing toward the Mekelpark and the concrete façade has a sense of monumentality. However, it has quite a closed look and is not overly inviting to visit. Thus, to improve the thermal qualities as well as create a lighter and more inviting building the façade needs to be (partially) redesigned.

[60] Dronkers, M. (2020), The application potential of reclaimed materials in architectural design, TU Delft

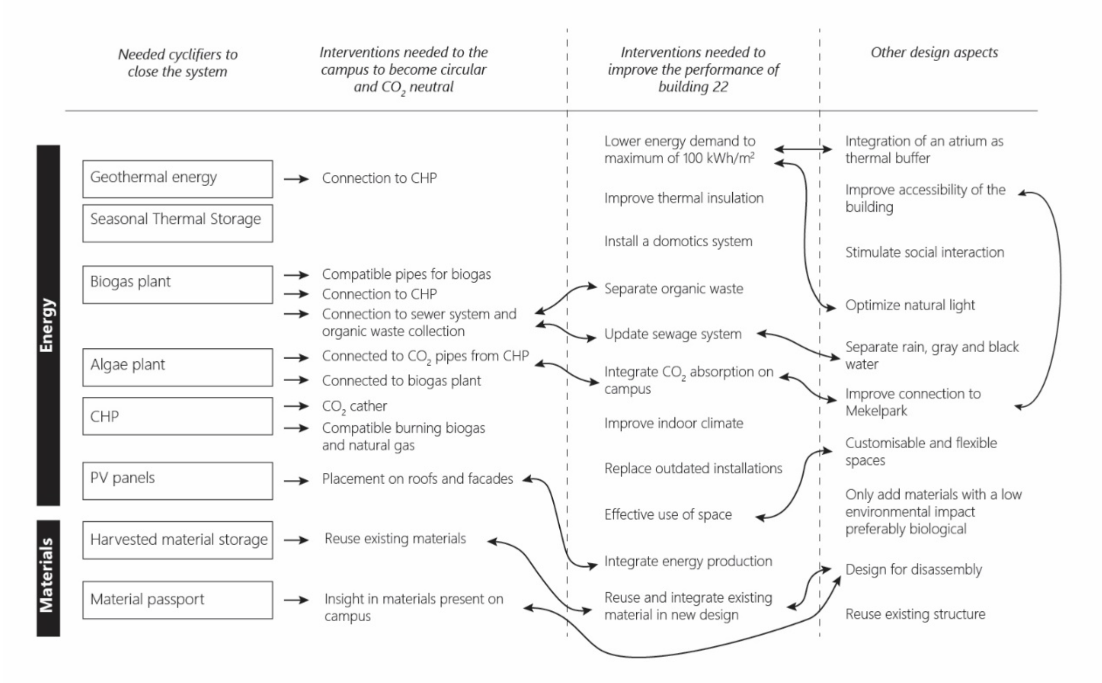
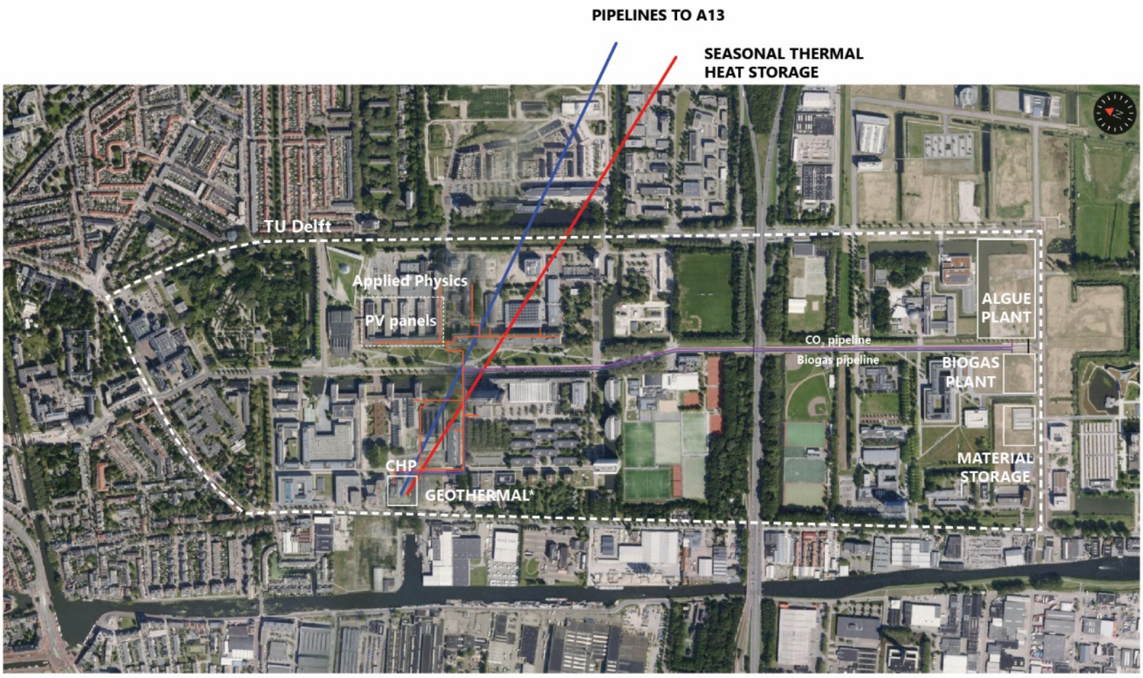


Figure 8 Roadmap on needed interventions at the TU Delft Campus and the building 22



*Geothermal Energy: The installation consists of an (1) intake pipe and a (2) discharge pipe that will drop 800 metres vertically from Leeghwaterstraat. At around 500 metres deep, a (3) pump will pump 300 cubic metres of water per hour – enough to fill twelve lorries. From a bend at 800 metres deep, the pipelines run off to different parts of the same hot water source located at a depth of 2.3 kilometres. At the surface the intake (producer) has a temperature of about 75 degrees. The discharge (injector) has a temperature of 50 degrees. As the groundwater flows from the injector to the producer, it heats up again due to the geothermal heat. (Source: Wassink, J. (2019), Delft Intergraal Campus switching to geothermal energy, [online] https://www.tudelft.nl/en/delft-outlook/articles/campus-switching-to-geothermal-energy/

Figure 9 Prelimary placement of cyclifiers on the TU Delft Campus

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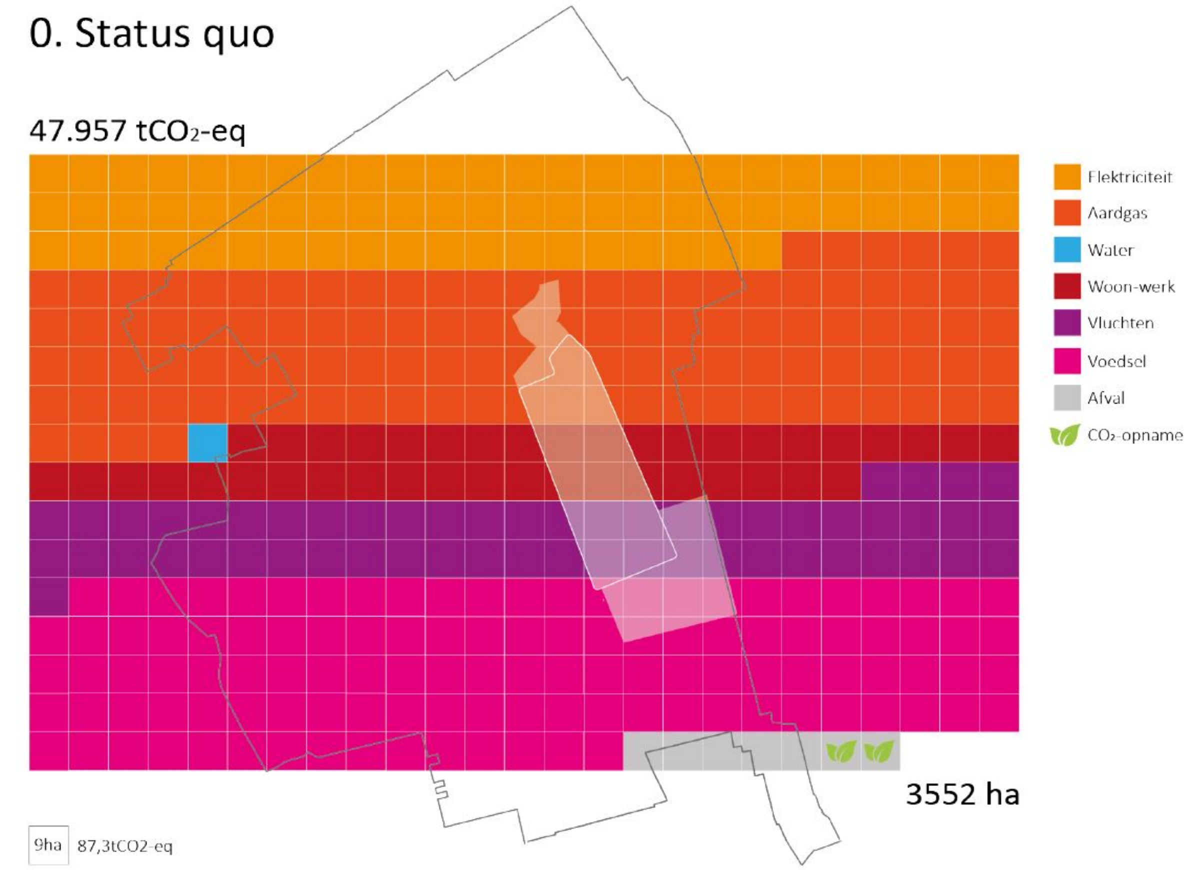
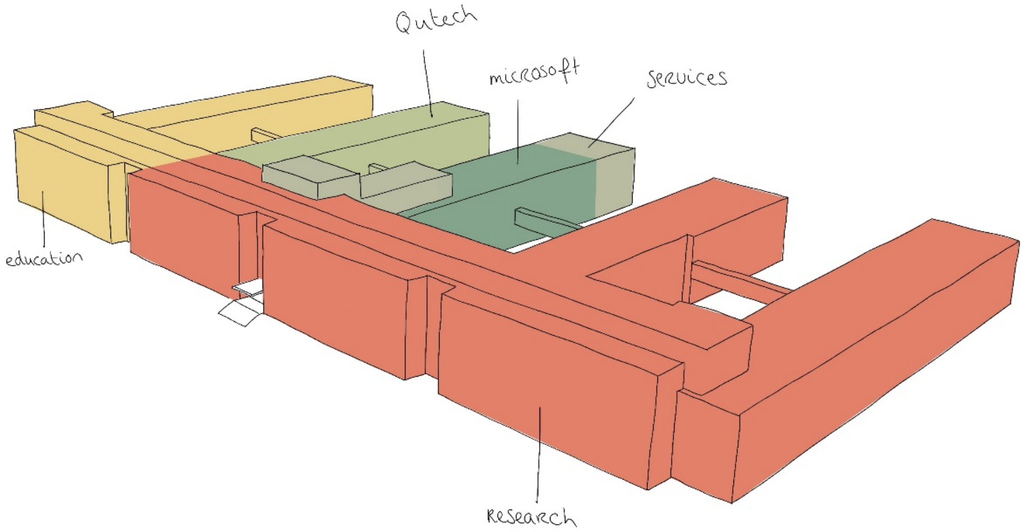
V. Appendices

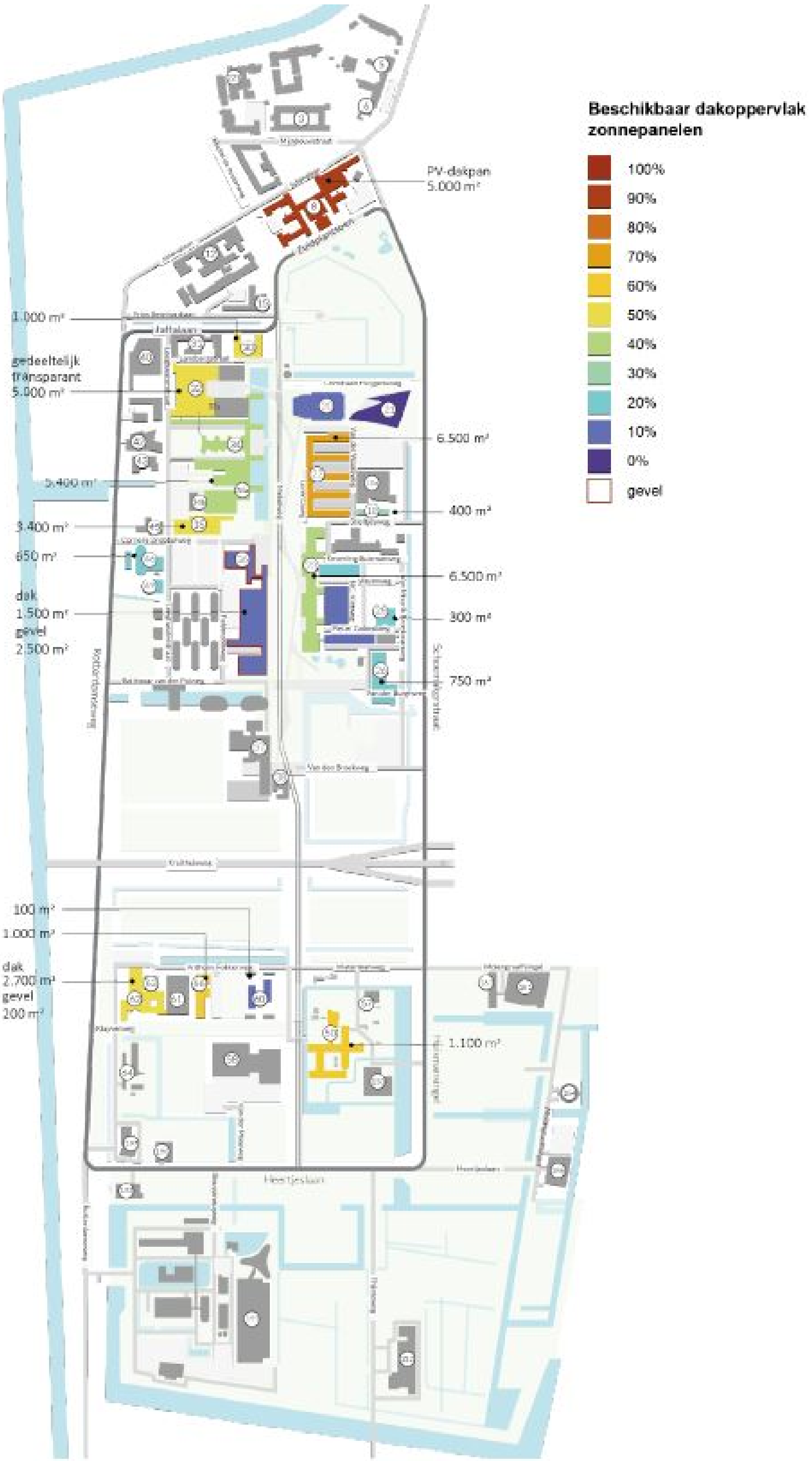
Appendix A CO_2 emission of the TU Delft campus in 2018



Appendix B Current functions in building 22



Appendix C Available roof surface for PV panels on the TU Delft campus



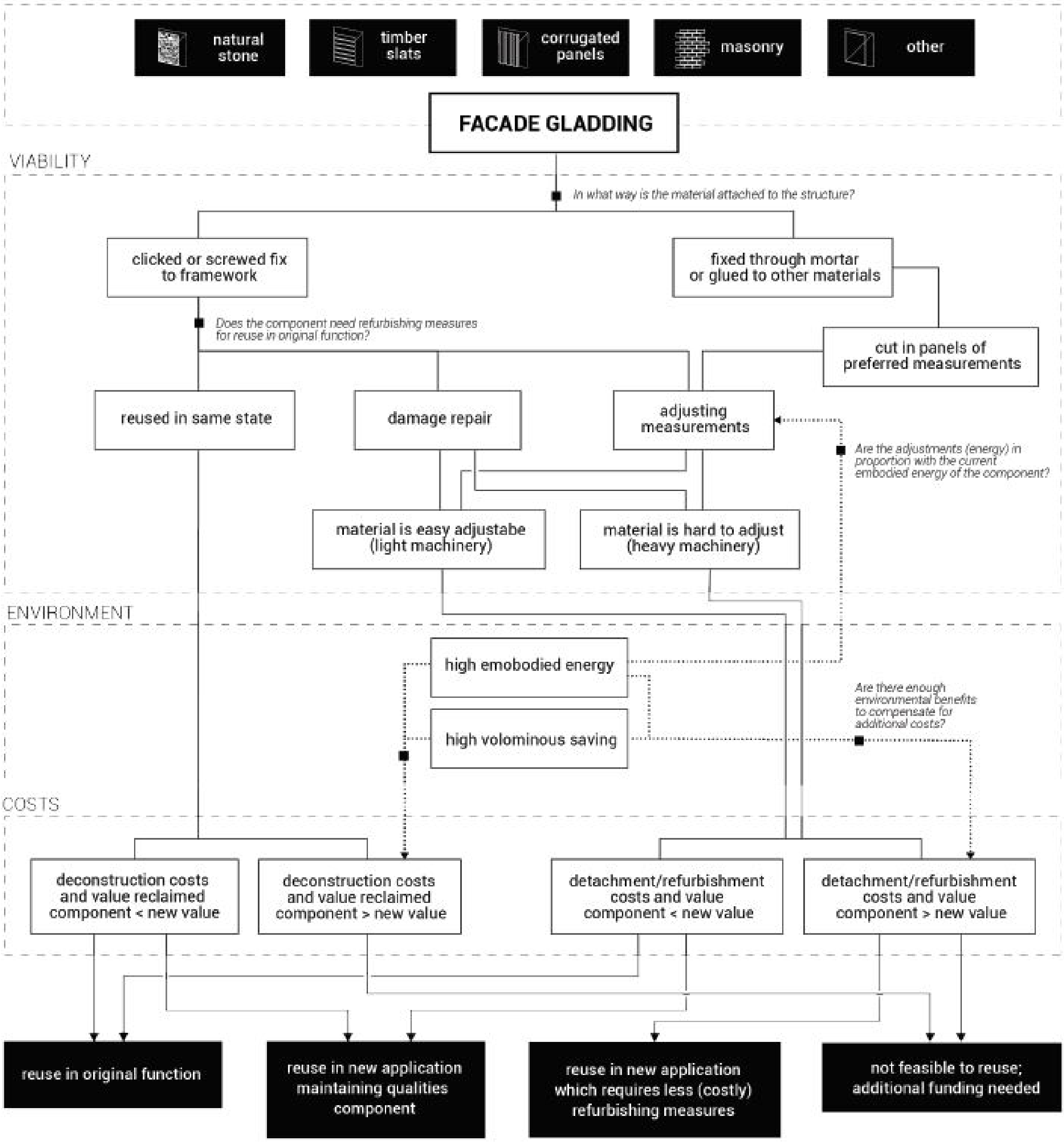
Appendix D Level of renovation needed

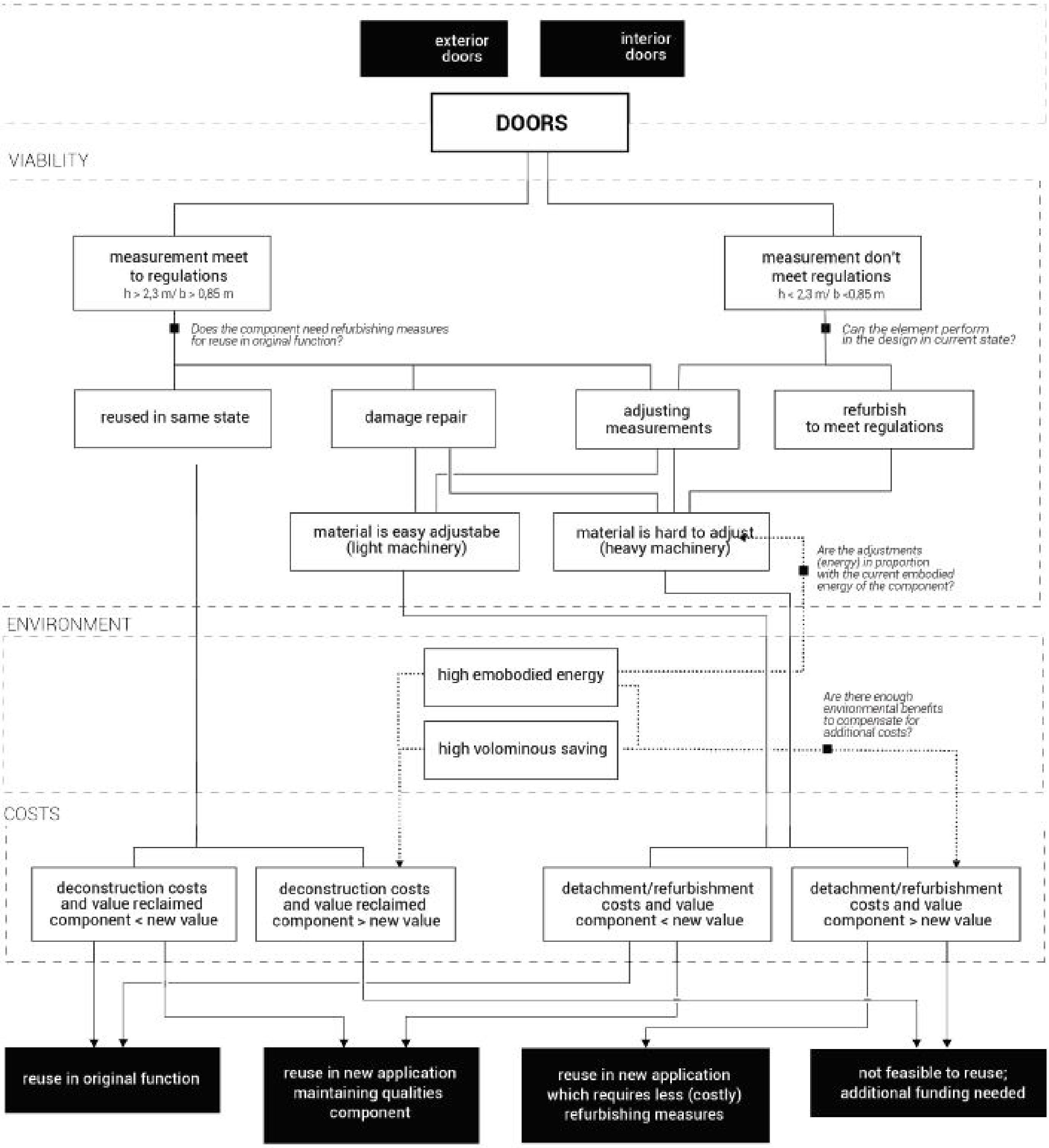
Appendix E Value assessment materials in the façade of building 22

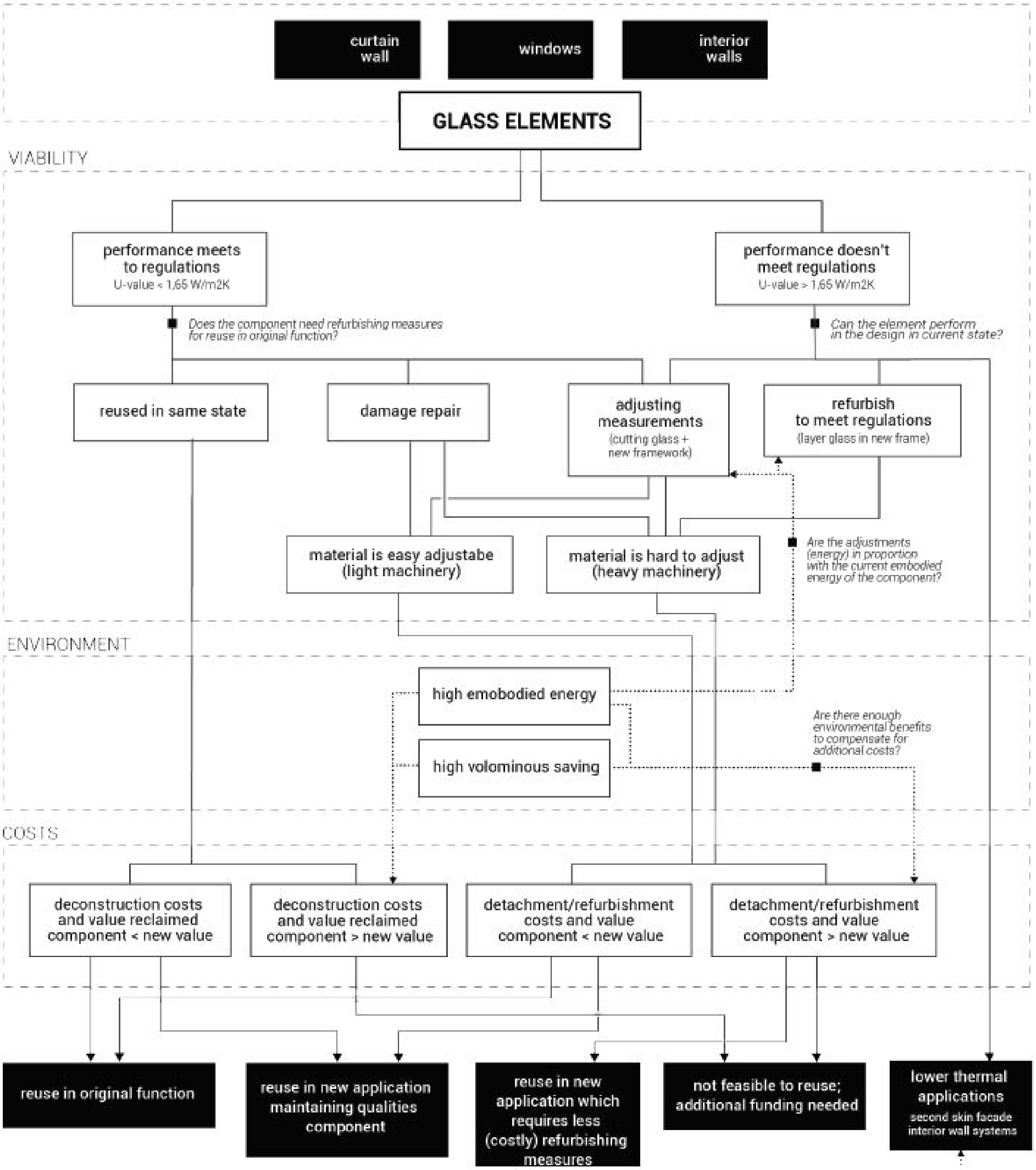
	Viability				Environmental impact			Costs	
	availability	ease of detachment	ease of refurbishment	re-use potential	Embodied energy	CO2 emmisions	Volominous impact	Market value	Production costs
Polished concrete	2969 m2 876 m3 2101.9 tons 54.8% of façade	glued possible with ankors	Panels can be cut to size. Might break New attachment system needed	Same function Interior panels Paving Water tight qualities	1,079 GJ/t 2.268 GJ	0.284 t CO2 eq/kg 597.000 t CO2eq	High	Low (Vandkunsten & Manelius, 2017)	High (Vandkunsten & Manelius, 2017)
Poriso stone*	8348 m2 835 m3 1127 tons 29.4% of façade	cement based mortar, can't be unbind	Difficult to clean from mortar. Larger panels (including mortar) can be cut	Same function Interior panels Paving Rubble reuse			High	Medium	Medium
Black glazed bricks	1886 m2 189,4 m3 274.8 tons 7.2% of façade	cement based mortar, can't be unbind	Difficult to clean from mortar. Larger panels (including mortar) can be cut	Same function Interior panels	2,5-3,0 GJ/t 687 - 824 GJ	529,8 kg CO2 eq / m3 100 t CO2 eq	Intermediate	Medium (Vandkunsten & Manelius, 2017)	High (Vandkunsten & Manelius, 2017)
Natural stone	2514 m2 106 m3 271.5 tons 7.1% of façade	glued possible with ankors	Can be cut in smaller sizes. Attachment system adjusted to new design. Panels might	Same function Interior panels Paving Water tight qualities	440.8 MJ/m2 113 GJ source	27.74 kg CO2 eq 70 t CO2 eq	Intermediate	Medium	High
Windows + frames	6126.5 m2 56.1 tons 1856 pieces 11 types	glass might break	Glass may break due to storage. New size needs new frame. Regulations needs to be	Same function (depending on glass quality). Lower glass quality: double façade.	glass 20-30 GJ/t metal frames 150 GJ/t 1683 - 2158 GJ	4.9 t CO2 eq/t 275 t CO2 eq source source	Intermediate	High (Vandkunsten & Manelius, 2017)	High (Vandkunsten & Manelius, 2017)
Exterior doors	135 m2 5.8 tons 28 pieces, various types 2% of façade	doors easy to detach, frame depends on the way of fixation	Depending on material size can be adjusted; enlarging tends to be difficult. Regulations need to be	Same function (depending on passing Interior panels Material reuse			Low		Low

* combination of clay, sawdust, pulverized coal ash, slate mud

Appendix F Decision chart Dronkers, 2020




exterior doors
interior doors
DOORS
VIABILITY
measurement meet to regulations
h > 2,3 m/ b > 0,85 m
measurement don't meet regulations
h < 2,3 m/ b <0,85 m
Does the component need refurbishing measures for reuse in original function?
Can the element perform in the design in current state?
reused in same state
damage repair
adjusting measurements
refurbish to meet regulations
material is easy adjustabe (light machinery)
material is hard to adjust (heavy machinery)
Are the adjustments (energy) in proportion with the current embodied energy of the component?
ENVIRONMENT
high emobodied energy
high volominous saving
Are there enough environmental benefits to compensate for additional costs?
COSTS
deconstruction costs and value reclaimed component < new value
deconstruction costs and value reclaimed component > new value
detachment/refurbishment costs and value component < new value
detachment/refurbishment costs and value component > new value
reuse in original function
reuse in new application maintaining qualities component
reuse in new application which requires less (costly) refurbishing measures
not feasible to reuse; additional funding needed



curtain wall
windows
interior walls
GLASS ELEMENTS
VIABILITY
performance meets to regulations
U-value < 1,65 W/m2K
performance doesn't meet regulations
U-value > 1,65 W/m2K
Does the component need refurbishing measures for reuse in original function?
Can the element perform in the design in current state?
reused in same state
damage repair
adjusting measurements
(cutting glass + new framework)
refurbish to meet regulations
(layer glass in new frame)
material is easy adjustabe (light machinery)
material is hard to adjust (heavy machinery)
Are the adjustments (energy) in proportion with the current embodied energy of the component?
ENVIRONMENT
high emobodied energy
high volominous saving
Are there enough environmental benefits to compensate for additional costs?
COSTS
deconstruction costs and value reclaimed component < new value
deconstruction costs and value reclaimed component > new value
detachment/refurbishment costs and value component < new value
detachment/refurbishment costs and value component > new value
reuse in original function
reuse in new application maintaining qualities component
reuse in new application which requires less (costly) refurbishing measures
not feasible to reuse; additional funding needed
lower thermal applications
second skin facade
interior wall systems

Circle House

3XN/GXN, Lendager Group, Vandkunsten
Copenhagen, Denmark
2019
Demonstration pavilion
40m2
Re-use & design for disassembly

60 general housing units

Circle House is a scalable demonstration project to give the building industry new knowledge about circular construction.

Assembled, disassembled and reassembled.

90% of the materials being used for the buildings, can be reused without losing significant value.

Exhibition of circular materials, products and solutions.

Shingles made from upcycled plastic waste.

Villa Welpeloo

Superuse Studios
Housing
250m2
2008
Enschede, The Netherlands

maximize the use of recycled materials

60% of the buildings is constructed out of second hand materials.

Re-used materials:
Structure is made from steel beams from a used machine. Facades are made from of excess wood from cable reels from the Twentse cable factory. Interior: building boards have become drawers and cabinets.

Environmental gain:
cladding: 85% reduction compared to new simple wooden cladding
steel construction: 95% reduction compared to same construction with new steel

BlueCity
Superuse Studios
2017
Offices
1300 m2 (total building 10.500 m2)
Rotterdam, The Netherlands

transformation project of the Club Tropicana

100 circular workplaces in BlueCity, varying from shared to own offices and permanent or flexible workplaces.

built inside the existing structure

90% of the materials are locally harvested materials, the remaining 10% are materials that are easy to recycle.

HAKA Rotterdam
1932 – 2008
Monument - Offices
DoepelStrijkers
Architecten
13.000 m2
Interior renvotion
ground floor
Rotterdam

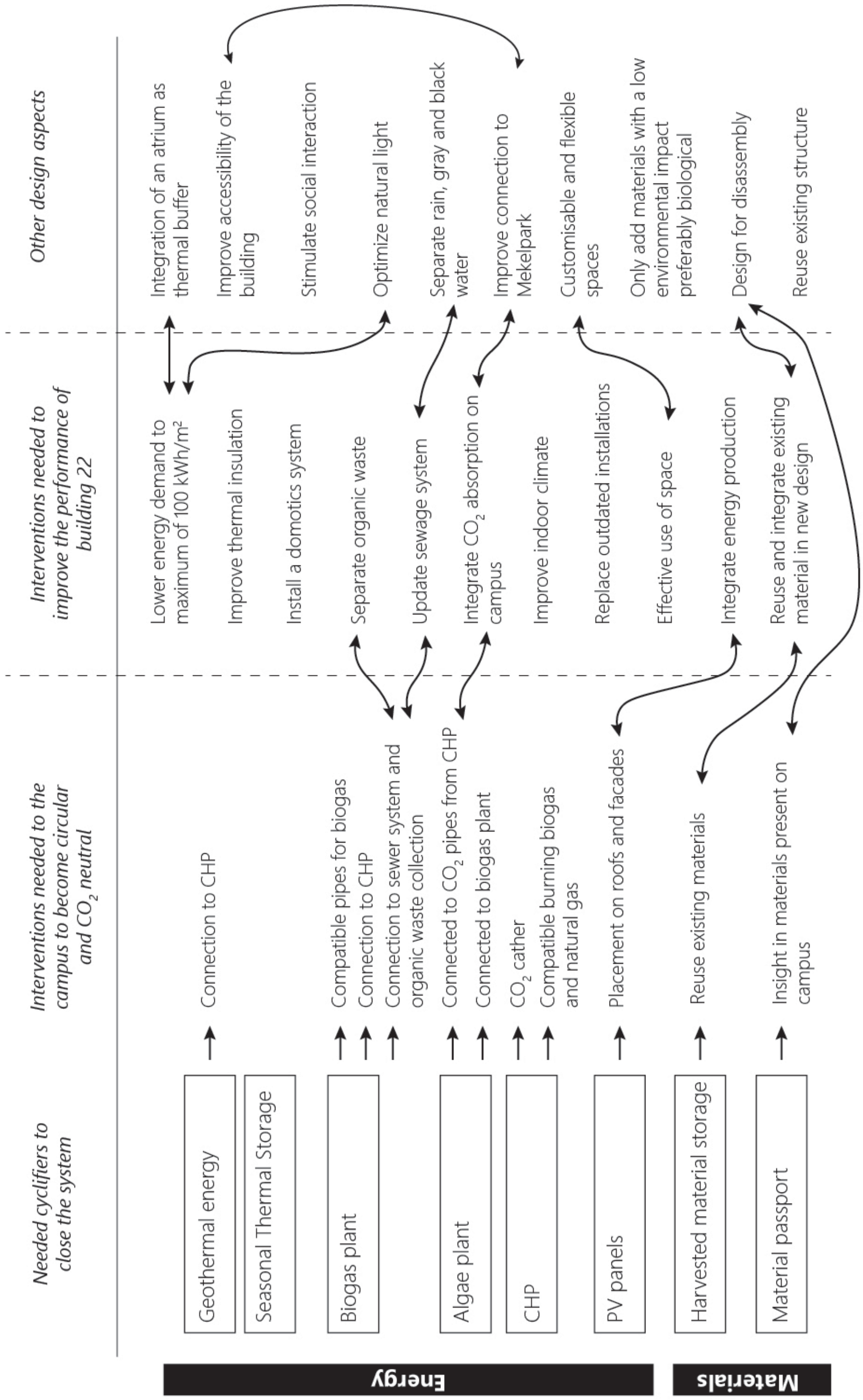
Temporary interior on the ground floor

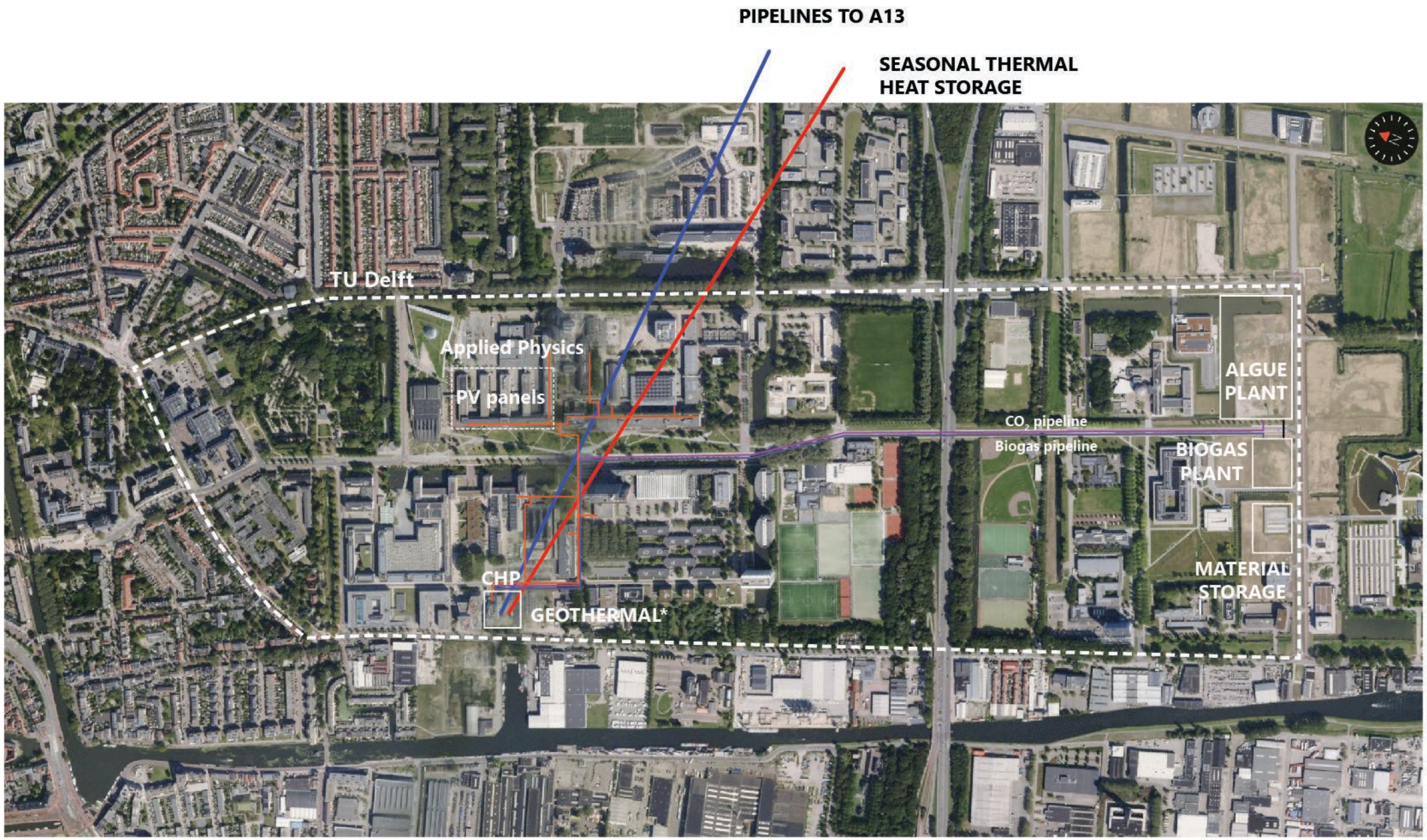
Recycled materials from the surrounding area

70% saving on material, energy and CO2 emissions

Re-used materials:
- 25920 kg hour
- 970 kg glas
- 100 kg aluminium
- 8000 kg textiel

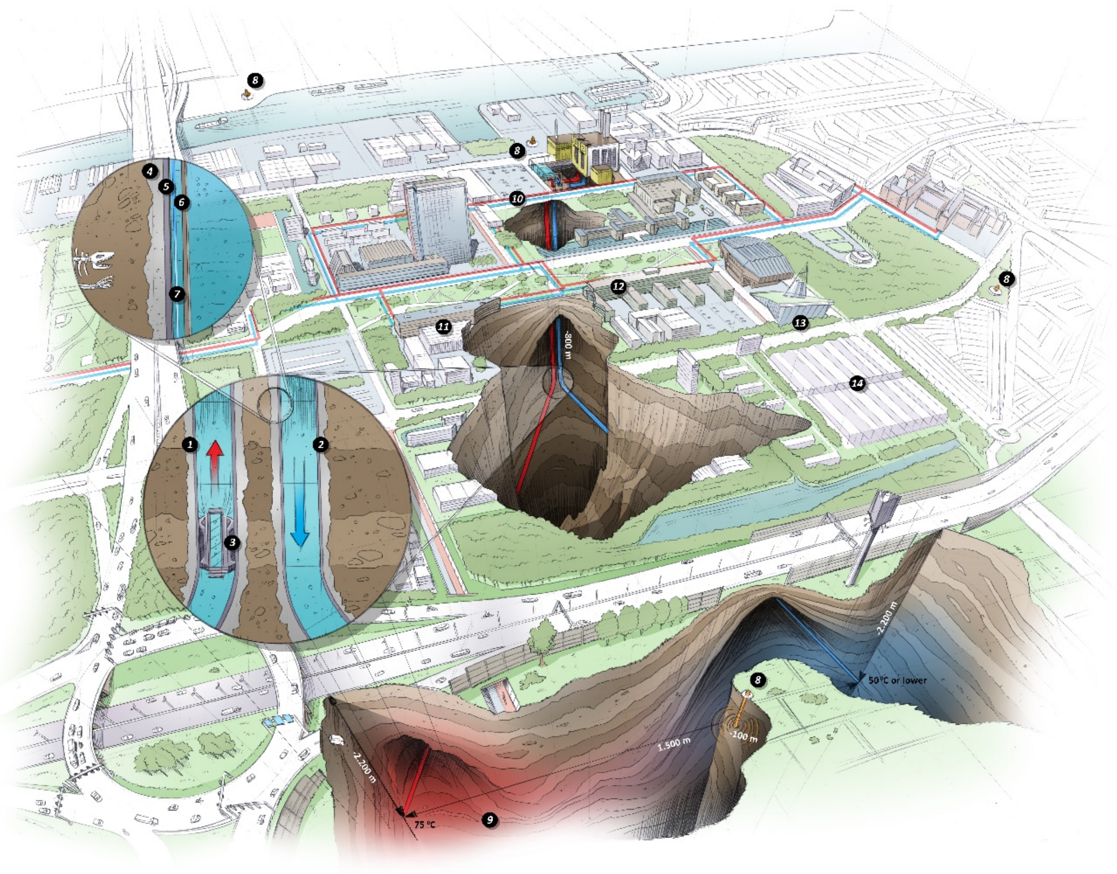
Dry connections so that the materials can be reused even after this building


Energy
Materials
Needed cyclifiers to close the system
Geothermal energy
Seasonal Thermal Storage
Biogas plant
Algae plant
CHP
PV panels
Harvested material storage
Material passport
Interventions needed to the campus to become circular and CO_2 neutral
Connection to CHP
Compatible pipes for biogas
Connection to CHP
Connection to sewer system and organic waste collection
Connected to CO_2 pipes from CHP
Connected to biogas plant
CO_2 cather
Compatible burning biogas and natural gas
Placement on roofs and facades
Reuse existing materials
Insight in materials present on campus
Interventions needed to improve the performance of building 22
Lower energy demand to maximum of 100 kWh/m²
Improve thermal insulation
Install a domotics system
Separate organic waste
Update sewage system
Integrate CO_2 absorption on campus
Improve indoor climate
Replace outdated installations
Effective use of space
Integrate energy production
Reuse and integrate existing material in new design
Other design aspects
Integration of an atrium as thermal buffer
Improve accessibility of the building
Stimulate social interaction
Optimize natural light
Separate rain, gray and black water
Improve connection to Mekelpark
Customisable and flexible spaces
Only add materials with a low environmental impact preferably biological
Design for disassembly
Reuse existing structure



*Geothermal Energy: The installation consists of an (1) intake pipe and a (2) discharge pipe that will drop 800 metres vertically from Leeghwaterstraat. At around 500 metres deep, a (3) pump will pump 300 cubic metres of water per hour – enough to fill twelve lorries. From a bend at 800 metres deep, the pipelines run off to different parts of the same hot water source located at a depth of 2.3 kilometres. At the surface the intake (producer) has a temperature of about 75 degrees. The discharge (injector) has a temperature of 50 degrees. As the groundwater flows from the injector to the producer, it heats up again due to the geothermal heat. (Source: Wassink, J. (2019), Delft Intergraal Campus switching to geothermal energy, [online] https://www.tudelft.nl/en/delft-outlook/articles/campus-switching-to-geothermal-energy/

Appendix J Geothermal installation on the TU Delft campus



Source image: Stephan Timmers (2019) via https://www.tudelft.nl/en/delft-outlook/articles/campus-switching-to-geothermal-energy/