Facade Leasing Demonstrator Project
2.7.3.FLD D2. Final Technical Delivery Report

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Facade Leasing Demonstrator Project Technical Delivery Report

Annex 4.2.6. FLD D2

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Accelerating deep building energy retrofits within the Circular Economy transition.

This technical report is an annex to the Facade Leasing Demonstrator Project 2019 performance report (2.7.3.FLD.D1). For general information on the Facade Leasing research project, its process, and objectives please refer to the aforementioned document.

This technical delivery report focuses on the design, engineering, construction, and monitoring process towards the energy retrofit of the East facade of the building of the Civil Engineering and Geo-sciences faculty at TU Delft (CiTG in Dutch). Having built an initial prototype in November 2018, on one of the building's typical office spaces, the project continued with the execution of a full large-scale retrofit of the East facade of the building throughout 2019.

The CiTG case is representative of a massive volume of buildings across Europe - over 50% according to some estimates - which have been built during the post-second world war period, and which are currently reaching the end of their original service life. Such buildings need urgent technical intervention in order to improve their energy, safety, and indoor comfort performance. Such interventions, however, must be realized in line with Circular Economy principles, as they demand the strategic investment of immense amount of resources: material, financial, and human. Resources which we cannot afford to keep using under a linear mentality of take - make - dispose.

2018

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Civil Engineering and
Building
23
Civil Engineering and Geosciences

The building of the faculty of Civil Engineering and Geo-sciences (CiTG on Dutch) at the campus of the Delft University of Technology was selected in late 2017 as the possible target of the Facade Leasing Demonstrator Project (FLDP). Built in the late 1960's by the famous Dutch architecture firm Broek Bakema, the building is representative of the brutalist period, with large portions of the building's envelope and exposed structure consisting of massive concrete elements.

In accordance with the technical practices of its time (before the 1970's energy crisis) the building's facade consists of uninsulated steel frames with single glazing and manually operable windows. Solar shading is only present internally, and only in certain areas. This combination results in a poor thermal performance of the building - which becomes too hot in the summer (over 30 overheating days per year) and requires considerable energy investment to keep heated during the winter - and a corresponding negative effect on the indoor comfort and user satisfaction of the faculty's employees.

In 2017 the decision was made by TU Delft's Campus Real Estate (TUD CRE) and the University's board of director's (CvB in Dutch) to continue the operation of the CiTG building for another 10 years. This mid-term strategic horizon meant that some technical intervention would have to be done on the facade to avoid it's further deterioration, such as repainting of the steel framing and minor repair of window sealing. However, no major technical retrofit could be planned, as such an investment would require an exploitation period beyond 10 years in order to be justifiable.

These circumstances represented an ideal scenario for the development of a "Facade Leasing" retrofitting alternative. The research team and project consortium proposed to analyze the case before starting work on the East facade (as the West facade maintenance work was already in process). The project team would compare the expected cost and value offered by a full state-of-the-art technical retrofit, contracted through a long-term service-inclusive agreement, against that of the planned minimum maintenance scenario.

Beyond the simple initial investment cost of a new facade versus a minimum maintenance, the analysis had to include long-term operating costs for each alternative, including (missed) energy savings and deferred maintenance costs which would have to be born at some point in the future. It also had to the take into account the value of an improved indoor comfort for over 300 employees working behind the approximately 2.600m^2 of facade targeted by the intervention decision.

The following pages show the engineering and planning process for a cost-effective facade renovation package. One that would improve the technical quality of the building and lead to considerable energy savings without requiring the use of highly specialized (and high-cost) systems. The engineering process took into account an energy performance and indoor comfort analysis, a technical retrofitting process study leading to an initial prototype, and a financial and business case study (further described in annex *4.2.6 FLD D3. Business delivery report*).

The building of the faculty of Civil Engineering and Geo-sciences (CiTG in Dutch) at the TU Delft campus. Delft, The Netherlands.

Photo: Juan Azcarate-Aguerre, 2018

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2. Energy and indoor climate engineering

The first step towards proposing a deep energy renovation solution for the CiTG building was to understand its current performance through the use of climatic simulation software. The chair of Building Technology and Climate Responsive Design at TU Munich's Faculty of Architecture was responsible for creating this simulation model and experimenting with a number of technical variables such as energy performance of base facade elements (framing and glazing), presence and operation of solar shading, and presence and operation of night-cooling ventilation.

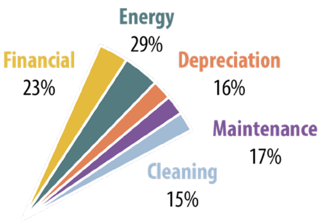
Corresponding to data gathered from user interviews, the model showed over 300 over Kelvin hours per year in the existing situation. Since most of these occur during office hours this translates into more than 30 days per year during which the building's temperature is above that which would be allowed by current indoor comfort regulations.

Improvement of the thermal performance of the base facade elements and use of internal solar shading would normally be a standard response to a building's thermal performance problems. Insulation of the building envelope does indeed reduce energy consumption by vastly reducing the demand for active heating during the winter. However, as shown by variants 1 through 3, over Kelvin hours in scenarios where only glazing and framing are improved actually worsen compared to the benchmark, with indoor shading doing little to solve the problem. The reason for this is that the current facade, after 50 years of operation, has considerable air leakage due to natural deterioration of the facade elements. While this would normally be undesirable, in this case it contributes to lowering the temperature of the building during the summer by providing an uncontrolled form of night-cooling.

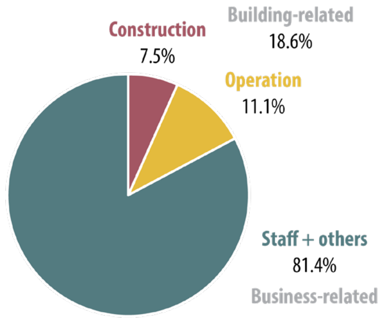
Variables 4 and 5 show the impact of applying either external solar shading or centrally controlled night ventilation, with neither one of these solutions fully solving the over-heating problem. Variant 6 applies both solutions in combination, and achieves the elimination of over-heating hours.

This study shows the importance of taking into account not only energy savings (as variants 1 through 3 provided a reduction of almost 80% in primary energy use) but also indoor comfort and occupant satisfaction. While it is hard to scientifically measure the drop in staff productivity resultant from an inadequate indoor comfort, the high relative cost of staff to a business or organization points towards a much higher monetary value for improving staff comfort and productivity than from simple and direct energy savings (figures on the right).

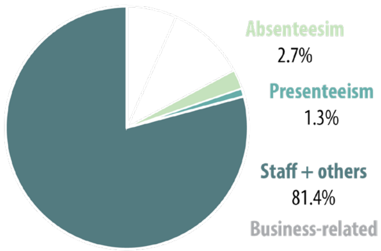
The building envelope's performance is therefore expected to decrease from a current benchmark of 214,3 kWh/m^2 to a post-renovation consumption of 45,6 kWh/m^2. The effects of this from a greenhouse gas emissions and global warming potential mitigation perspective is broken down in section 4 of this report.



Typical building operating cost breakdown over 30 years (as below).



Typical building-related costs in relation to overall business expenses over 30-years (de Jong, P. and M. Arkesteijn (2014). "Life cycle costs of Dutch school buildings." Journal of Corporate Real Estate 16(3): 220-234).

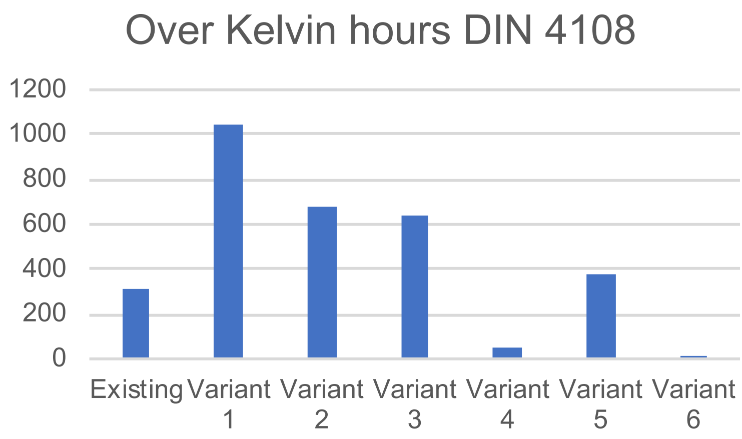


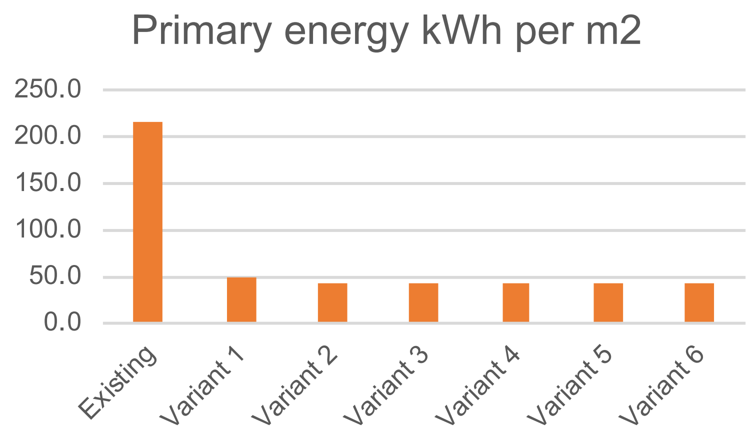
Suggested impact of poor indoor comfort on staff health and productivity (Terrapin Bright Green (2012). "The economics of Biophilia." Why designing with nature in mind makes financial sense. New York (NY): Terrapin Bright Green).

Comparative breakdown of current situation and six technical variables. While all retrofitting variables offer a significant and similar improvement in terms of primary energy consumption (with almost 80% energy savings against the benchmark) only variant 6 virtually eliminates over-heating hours during the summer.

Base case model:
East orientation
3.6 m x 5 m x 4.2 m (L x W x H)
0.75 m overhang
Window: 3.4 m x 2.46 m
2 users – DIN EN 13779
2 laptop
2 x Lighting
Ideal heating
Set point 23 °C
Max power 500 W
Natural ventilation
Top > 23 °C air change rate 1,5
Top > 25 °C air change rate 3
Top > 27 °C air change rate 6
No air conditioning

Scenarios:
Existing. Single glazing, steel frames
Variant 1. Double glass
Variant 2. Triple glass
Variant 3. Triple glass, internal blinds
Variant 4. Triple glass, external sun-shades
Variant 5. Triple glass, night ventilation
Variant 6. Triple glass, external sun-shades, night ventilation





	Infiltration 1/h	Window	Sun protection	Night cooling	Over Kelvin hours DIN 4108	Over Kelvin hours DIN 15251	Primary energy kWh per m²
Base case model	0.35	Single-U ID 122 U=5.4 g-value = 0.81	None	Deactivated	313	10	**214.3**
Variant 1	0.15	**Double-U** ID 3212 U=1.23 g-value = 0.74	None	Deactivated	1039	98	**48.7**
Variant 2	0.15	**Triple-U** ID 11304 U=0.76 g-value = 0.62	None	Deactivated	673	46	**42.6**
Variant 3	0.15	**Triple-U** ID 11304 U=0.76 g-value = 0.62	**Internal fc = 0.7**	Deactivated	634	43	**42.2**
Variant 4	0.15	**Triple-U** ID 11304 U=0.76 g-value = 0.62	**External fc = 0.13**	Deactivated	9	0	**45.8**
Variant 5	0.15	**Triple-U** ID 11304 U=0.76 g-value = 0.62	None	**Activated**	373	19	**42.5**
Variant 6	0.15	**Triple-U** ID 11304 U=0.76 g-value = 0.62	**External fc = 0.13**	**Activated**	0	**0**	**45.6**

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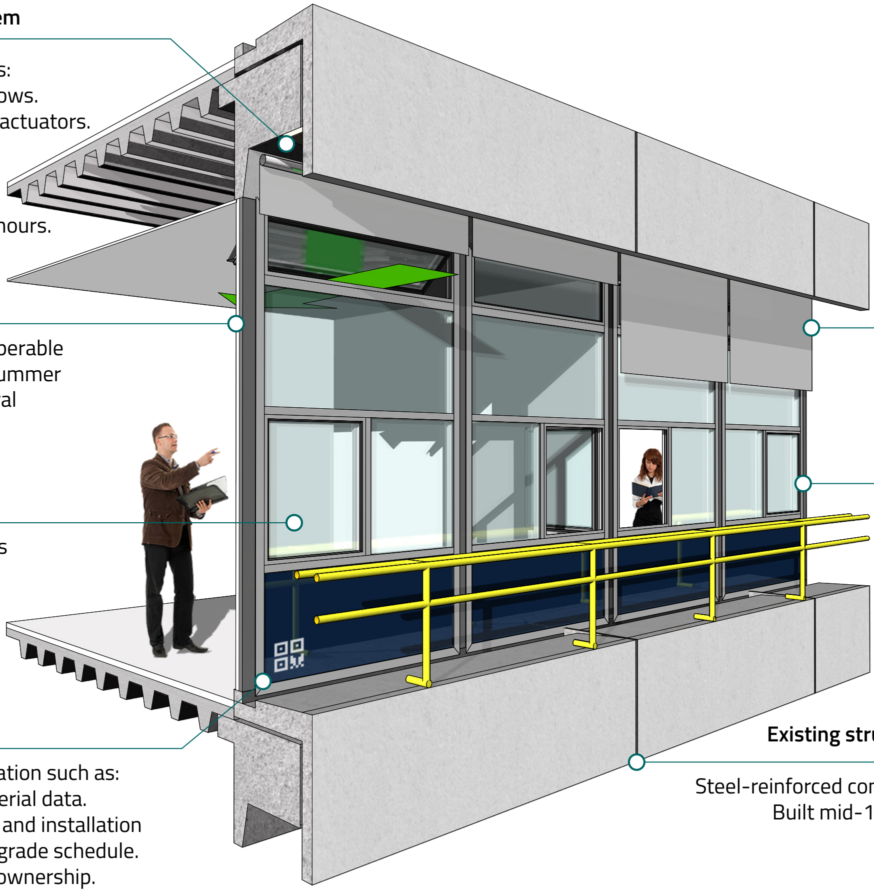


Rendering of new CiTG Facade Leasing renovation solution, which includes high performance framing and glazing, centrally operable windows including an upper window for night-cooling airflow, and external solar shading with high-wind velocity resistance. The panels have also been designed in consultation with the original building architect to ensure its close resemblance to the original architectural appearance of the building.

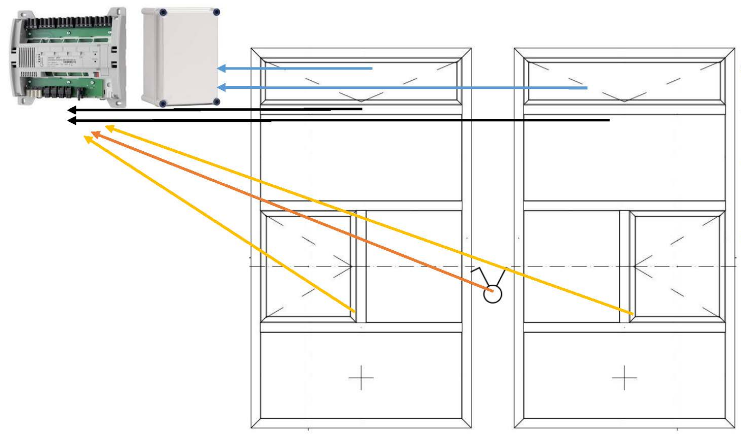
Facade components are operated and monitored by a centralized KNX-based facility management system. This allows for both centralized (facility manager) and decentralized (building user) control of components. It also allows the facade service provider Alkondor to keep track of the correct operation of engines and actuators, so they may be timely replaced before their expected end-of-service, contributing to the reliability of the system and the fulfillment of Key Performance Indicators. Some functions facilitated by this KNX system are:

- *Sun-shades and night cooling.*
- *Sun and wind detection.*
- *Individual control per room.*
- *Overrule function by TU Delft CRE.*
- *Measuring activity and performance (number of cycles and indoor climate).*
- *Service and maintenance by one informed and coordinated party.*

Based on the outcome of the climate and energy design study previously presented TU Delft AE+T and Alkondor Hengelo collaborated on the design and engineering of the facade solution. The proposed facade is based on a high-performance Schüco AWS 75 BS HI aluminium block-frame system, with insulated triple-glazing. The system achieves a U-value (or thermal transmittance coefficient) of approximately 0,8 W/m²K, an 85% improvement from the current facade which has been calculated to have a U-value of 5,4 W/m²K. A block-frame alternative has been selected as it results in more slender framing elements, closer in appearance to the current and original facade system used in the building.

External solar shading is installed within the overhang of the upper floor, reducing the visual presence of the system while not in operation. An automated window at the top of each facade panel is connected to a centralized control system, allowing for simultaneous opening of all windows in order to passively ventilate the office spaces during cool summer nights. Also automated operable windows at user-height can be both decentrally and centrally operated to permit user flexibility while also providing central management capacity to control all windows for indoor climate or building security reasons.

Also connected to a central building management system are the engines powering solar shading systems and actuators powering operable windows. As part of the performance service delivered by the service provider is the maintenance and replacement of such systems. In the current way of working preventive maintenance is rarely enforced, automated systems are operated until an engine or actuator failure, at which point the building manager will request a facade fabricator or system supplier to replace the failing component. The cost of this is needlessly high, as individual service request are issued for each system failure and a service team must visit the building and setup maintenance infrastructure such as elevators or cranes to access the failing system. Under a performance service contract the service provider has the incentive to monitor the operation of these systems, controlling the number of operation cycles through which engines and actuators have gone. As these components reach the end of their expected statistical service life the service provider will plan and execute a single replacement project, removing and replacing hundreds of components in one go with considerable economy of scale savings. The same economy of scale also allows for a circular reprocessing of bulk quantities of components, which can be remanufactured for further use in the same building or another similar service contract.



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4. Global warming mitigation potential

Global warming mitigation potential calculations have been done for the specific CiTG case study, as well as for a standard renovation scenario representative of future upscaling activities. These calculations are described below. Mitigation related to the building facade can be divided into two main groups: 1. Mitigation linked to circular reprocessing of embodied materials, and 2. Mitigation linked to the improved energy performance of the facade and target buildings. Both types of mitigation are addressed by the Facade Leasing systemic innovation proposal, and contribute to a lower total carbon footprint of deep energy renovation projects and new constructions.

The standard Facade Leasing case

The standard case is based on the extrapolation of data from cross-European references. First, embodied energy of materials related to the production and sourcing costs associated to the construction of the façade is estimated at an average of 211 $kgCO_2eq/m^2$ of façade (Hildebrand, 2014). The success of a circular procurement model, in which the fabricator is contractually required, and economically incentivised, to remanufacture components could in principle lead to a no-waste end-of-service scenario. Based on a mean operational period of 50 years ongoing distributed embodied energy savings would amount to 5 $kgCO_2eq/m^2$ of façade per year.

Second, operational energy savings are calculated based on an average energy consumption in the European non-residential building sector of 280kWh/m^2 of ground floor area (BPIE, 2011) , this can be translated to approximately 155 kWh/m^2 of façade, based on an average 55% façade-to-floor ratio for this building typology (Ebbert, 2010) . Buildings from the target time period (1960's to 1970's) majorly contribute to the lower performance end of this average. Operational energy savings of 60% can be expected as a conservative figure for deep energy renovations like the ones facilitated by the Façade Leasing contracting model. This would mean on average 92,4kWh/m2 of façade per year, translated into 51,3 kgCO2eq/m2 of façade per year.

The CiTG case

While an embodied energy analysis of the specific CiTG case has not yet been elaborated, and will be the target of further work in 2019, global warming potential mitigation tied to primary energy savings is expected to be beyond the average scenario previously described. As described in section 2 of this report, operational energy savings on the CiTG east facade are expected to amount to a 78,5% yearly reduction, or 168,7 kWh/m^2 from a baseline of 214,3 kWh/m^2. These savings translate into 93,6 $kgCO_2eq/m^2$ of facade, and 243.370 $kgCO_2eq$ for the entire 2.600m^2 surface area. Over the projected fifteen years of operation this would amount to 3.650.560 $kgCO_2eq$, with further savings to be gained if the CiTG building is maintained as part of the TU Delft building portfolio and the facade remains in place and adequately maintained for its 50- to 70-year service life.

Hildebrand, L. (2014). Strategic investment of embodied energy during the architectural planning process. (Doctoral dissertation, Delft University of Technology), TU Delft.

BPIE (2011). Europe's buildings under the microscope. Brussels, Belgium, Building Performance Institute Europe.

Ebbert, T. (2010). Re-face; refurbishment strategies for the technical improvement of office façades. (Doctoral dissertation, Delft University of Technology), TU Delft.

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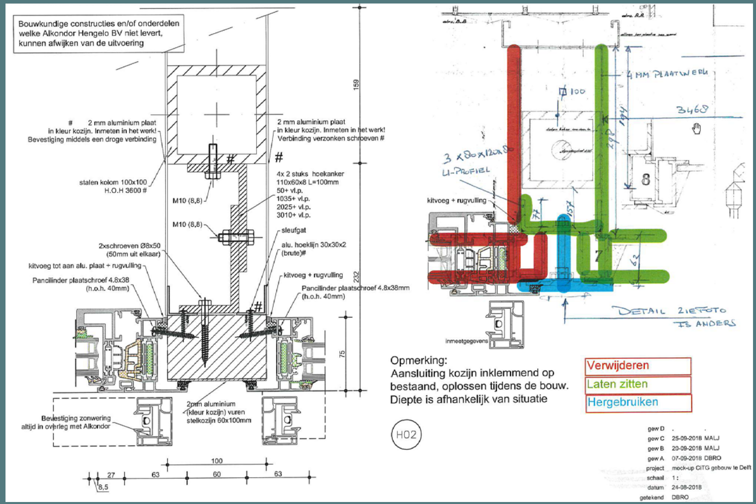
Machining process of a building envelope component. The facade fabricator is traditionally an assembler of components delivered at their factory floor by sub-suppliers such as aluminium systems, insulated glazing units (IGU's), solar shading systems, et. While the process is highly automated and supported by Computer Aided Machining (CAM) techniques, final assembly is still done on a project-by-project basis and relies on specialized manual labour.

Dimensioning (left) and finished facade mock-up (right) for the CiTG east facade. Beyond the regular technical complexities presented by a building renovation, such as dimensioning and interfacing of remaining and new components, the CiTG building facade also presents the challenge of asbestos presence on a number of sealing and closing elements. The removal and recycling of materials therefore requires a particularly careful planning process.

5. Mock-up prototype preparation and execution (2018)

In August 2018 the TU Delft board of directors approved an additional investment to build a mock-up / prototype of the proposed facade. A standard industry procedure, technical mock-ups provide first hand expertise on the engineering and construction challenges that will be faced once the large-scale renovation process begins. Through a mocku-up, the facade fabricator can verify the dimensioning of elements, and secure an effective interface between existing and new components to guarantee technical and indoor climate goals are achieved which resemble as closely as possible the results of the initial climatic and energy efficiency simulations.

In the case of the CiTG facade this process also allowed the TU Delft asbestos management team to analyse the presence of toxic substances in the existing facade and elaborate a protocol to safely remove them. An innovative contribution at this stage has been the involvement of a new company, "Purifed Metal Company" (PMC), which has developed the technological process to remove asbestos from existing steel elements in order to extract clean and reusable recycled steel. Purified Metal, which is in the process of building their new facilities in The Netherlands expected to start operations in 2020, will take over responsibility for the proper reprocessing of the asbestos, a task which is normally the responsibility of TU Delft CRE. By stockpiling industrial input such as the old CiTG facade in the months prior to the opening of their facilities PMC aims to secure the necessary volume of materials to feed their industrial process. This new supply-chain actor is instrumental for the implementation of retroactive circularity on legacy systems which - due to changing regulations regarding performance and health safety - have limited reuse or remanufacturing prospects.



Technical drawing of the new CiTG facade, with diagram showing interface between new (red), existing (green), and reused (blue) components.

Image by: Alkondor Hengelo BV

The new facade system is designed for easy disassembly and removal. Aluminium framing and automated components such as solar shading and window actuators can be recover and remanufactured, adapting them to new buildings with different facade dimensions, or ideally being used in the design process of new buildings which can then take into account the grid of hundreds of panels which would become available (at second-hand prices but with high performance specifications) if they are removed from the CiTG. Economic and governance interests are expected to shift the way in which buildings are designed and commissioned, demanding an increasing rate of reused or reclaimed components as policy instrument to enforce Circular Economy principles in practice.

2019

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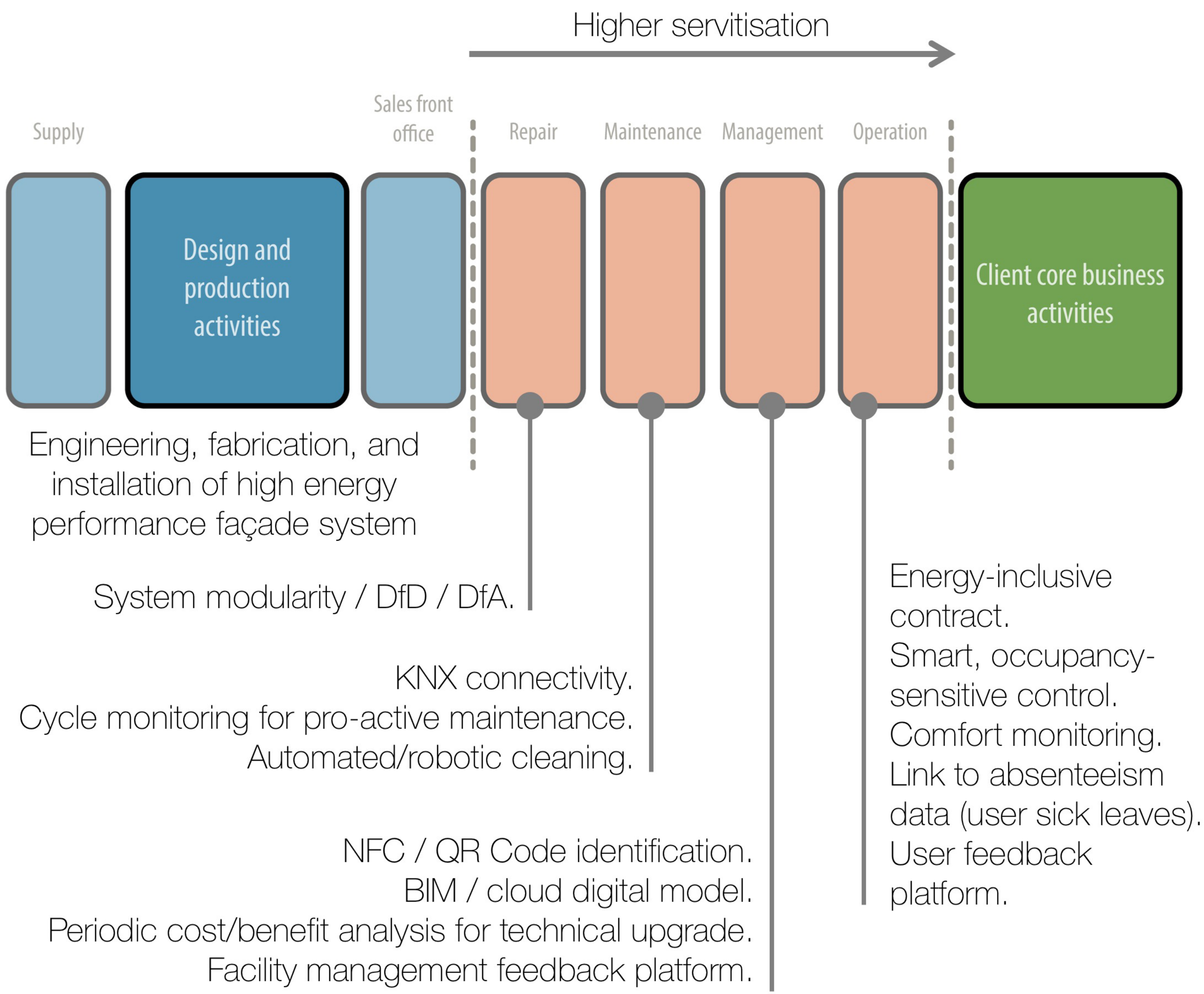

Diagram illustrating the role of various emerging facade and building technologies on the servitisation of the sector and an eventual Circular Economy transition. Activities in blue are those traditionally carried out by product manufacturers. Activities in orange have been traditionally left in the hands of the client (or its maintenance and facility management crews). This results in several problems related to the linear economy, such as: Loss or poor transfer of technical knowledge; Misalignment of economic incentives and technical responsibilities; Focus on tangible material value of components rather than the intangible performance these components deliver.

Adapted from: Baines, T. and H. Lightfoot (2013). Made to Serve: How manufacturers can compete through servitisation and product service systems, John Wiley & Sons.

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The transition towards a Circular Economy in facade construction relies on the understanding and development of new products and processes. While the CiTG demonstrator project 2018-2019 provided a sufficiently large scale platform to demonstrate some innovative technologies, the creation of brand new products and remanufacturing processes is expected to take years of innovation and testing. The ultimate goal of the Facade Leasing project series has therefore been to establish the business and financial incentives for companies in the sector to engage is innovation that will gradually lead to many of these new developments. The diagram on the left identifies key emerging technologies in the construction and facade industries, which will play a role in the energy and circular economy transitions. A number of these have been tested in the CiTG prototype (2018) and large-scale demonstrator (2019), and will be described in more detail in following sections of this report. A brief description of such technological innovations and their relevance is provided, according to each stage in the "servitisation roadmap" (Baines and Lightfoot (2013):

Repair: Ease of repair is largely determined by the compartmentalisation of components and functions within a system, and the use non-destructive connection between such components. Design for Disassembly (DfD) and Design for Adaptability (DfA) are emerging design methods to ensure that components with different expected service-lives can be separated from each other in a non-destructive manner, therefore preserving as much of the products' value as possible. As components are replaced (due to end-of-service or failure) new opportunities emerge to replace such components with newer and more efficient generations, this without each change requiring a complete overhaul and disposal of the previous system.

Maintenance: Maintenance technologies can be divided into two main fields. On the one hand, monitoring technologies such as sensors and Internet-connected actuators allow service providers and facility managers to track component failures or the number of operation cycles a window or solar shading unit has been subject to. In both cases allowing for the scheduling of necessary maintenance works. On the other hand, automated maintenance technologies such as robotic facade cleaning systems (e.g. KITE robotics) allow certain facade cleaning or maintenance operations to be fully automated.

Management: Physical component tracking technologies such as NFC chips or QR codes can be linked to a Building Information Model (also known as a "digital twin") to track data related to the product such as its material content, maintenance history, legal ownership, et. Such information can reduce the chances of disputes between provider and client, and increase the residual value of components by being able to show future purchasers that the "pre-owned" components have been properly maintained throughout their service-lives.

Operation: Smart, climate-responsive technologies connected to optimization logics can make real-time decisions to improve the energy and comfort performance of the facade. An easy example would be an office room's facade in which all components are set to a "minimum energy consumption" setting when the room's occupancy sensor reports the room to be empty of occupants.

7. CiTG Faculty Building large-scale demonstrator project (2019)

Having established the technical feasibility of the intervention through the construction of a mock-up (page 15), the next step in the process was to evaluate the strategic and financial feasibility of the project. Arguments for the execution of the full-scale CiTG demonstrator project were collected in a decision-making template, and presented to TU Delft's Board of Directors (Attached as CKIC02: Innovation opportunities identified).

The decision was finally made to move forward with the renovation of the building's East facade, with the decision to procure the facade through a traditional purchase or leasing model pending due to necessary legal and financial barriers yet to be overcome. More information on this can be found in the attached 2.7.3. Final Business Delivery Report.

To avoid clashing with other ongoing construction projects in the TU Delft campus, the CiTG East facade renovation project needed to meet a very tight deadline: The decision to carry out the project was taken in March 2019, the system had to be engineered and parts ordered to start assembly by Summer 2019, and the four stories of the building which would be renovated would have to be executed in sequence over a period of 6 months and completed by the end of the year. Adding complexity to this process, the faculty building would need to continue in operation throughout the construction works, meaning staff and educational activities would have to be relocated by building section, as work moved on. Also, silent times had to be observed throughout most of the working day (between 9:00 and 12:00, and between 13:00 and 17:00), during which no machinery (including hand drills and saws) could be operated within the building.

In terms of planning, each floor was divided into four segments, and work was planned into weekly goals: In the first week, the first segment would be isolated (via temporary screens), the existing facade removed and all present asbestos cleared (following page, stage 1). As this removal and cleaning work moved down the hallway to segment two, in the second week, segment one would be prepared for the installation of the new facade. This included preparation of all necessary cabling and other infrastructure for electric power and digital communication technologies, the installation of a wooden support structure on which the framing would be installed,among other tasks (stage 2). In the third week the new facade would be installed, connected to digital control and monitoring systems and tested, and finally all interfaces to the existing building would be completed (ceiling and wall panels to close gaps, re-installation of the existing radiators, sound-insulation, et.), (stage 3).

This process would be repeated down the length of each floor, before moving on to the next floor below. As working crews became more familiar with the process work became more efficient and the one-week time-frames could be better achieved. As a result of this, the whole project was completed on time, by December 2019, with both Campus Managers (clients) and Faculty employees (end-users) reporting great satisfaction with the speed and convenience of the project, as well as with the improved user comfort and energy performance delivered by the new system (more on this below).

Scaffolding and preparation work outside the CiTG faculty building's East Facade in early summer 2019. Thanks to the temporary external vertical and horizontal circulation provided by the scaffolding, material could be transported and the works carried with much less disturbance to users.

Image by: Juan F Azcarate, 2019

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Step 1. A section of one-quarter of the area in the targeted building floor was temporarily relocated and closed off to employee and student access. A temporary screen was installed behind the facade to act as closure against wind and rain, and to prevent the spreading of asbestos during cleaning operations.

During the removal process of the existing facade asbestos were cleaned from facade gaskets, ceiling and wall panels. The contaminated material had to be transported by specialized personnel and equipment to a safe disposal location.

Step 2. Once the working area was cleared of the existing facade and any asbestos present, a new wooden substructure was installed in preparation for the new aluminium facade system. Electrical and mechanical installations such as cabling and heating lines had to be temporarily or permanently relocated, and new cabling was installed for the innovative remote and monitoring technologies necessary for the service component of the Facades-as-a-Service model (Chapter 10).

Step 3. The new aluminium framing system was mounted on the wooden substructure. Infill panels such as double-glazing and opaque insulated panels where mounted into the framing, together with operable windows and automated sun-shading systems.

The automated and remotely operable actuators and engines that control windows and sun-shading were connected to the cabling and infrastructure installed during step 2, and tested to guarantee proper working conditions. Lastly, the existing heating system consisting of high-temperature radiators were installed back in their original position.

Step 4. Remote monitoring and control of facade systems is tested using internet-connected software. The information reported by the system includes opening or closure of windows, activation or deactivation of solar shading, operational status of actuators and engines, number of cycles to which these engine have been subjected (to schedule their pro-active replacement at their end-of-service life), and reports from users or facility managers regarding technical failure. Such information allows Alkondor Hengelo, as Facades-as-a-Service provider, to constantly monitor the state of physical and digital components, and guarantee the quality of the performed service.

9. Objective and subjective user comfort monitoring

Indoor climate and user comfort monitoring has been initiated in August 2018 for 50 office rooms randomly selected between floors 2 and 5, on both east and west sides of the building. This monitoring will continue for 24 months until August 2020. It will provide a reliable scientific comparison of the improvement in building performance one year before and one year after renovation.

OfficeVitae, a startup supported by EIT Climate-KIC, monitors indoor performance based on four key parameters:

CO_2 content - A metric of ventilation rate within an enclosed space. At high levels CO_2 concentration can pose a health risk, from causing headaches and drowsiness to oxygen deprivation in extreme cases. At moderate levels it is a good indication of user comfort, as low ventilation rates are often associated with perception of poor air quality, concentration of body odors or other bad smells, among other discomforts. 350-1.000 particles per million (ppm) is a generally good indication of a properly ventilated space. However, a good air exchange rate could be caused (as is the case in the CiTG building) by a poorly performing facade with high infiltration rates, as opposed to a well-performing system in which air-exchange rates are purposefully managed. Air leakage is directly related to poor energy performance, as it leads to unwanted thermal losses or gains. It also means rainwater or air drafts could infiltrate the facade, adding to user discomfort.

Humidity - Humidity levels should be kept between 30% and 70%, with optimum values between 40% and 60%. Extremely low or high humidity rates can cause discomfort, increase chances of illness, and lead to the creation of condensation or mold, which further affect user comfort and health, as well as technical integrity of building components.

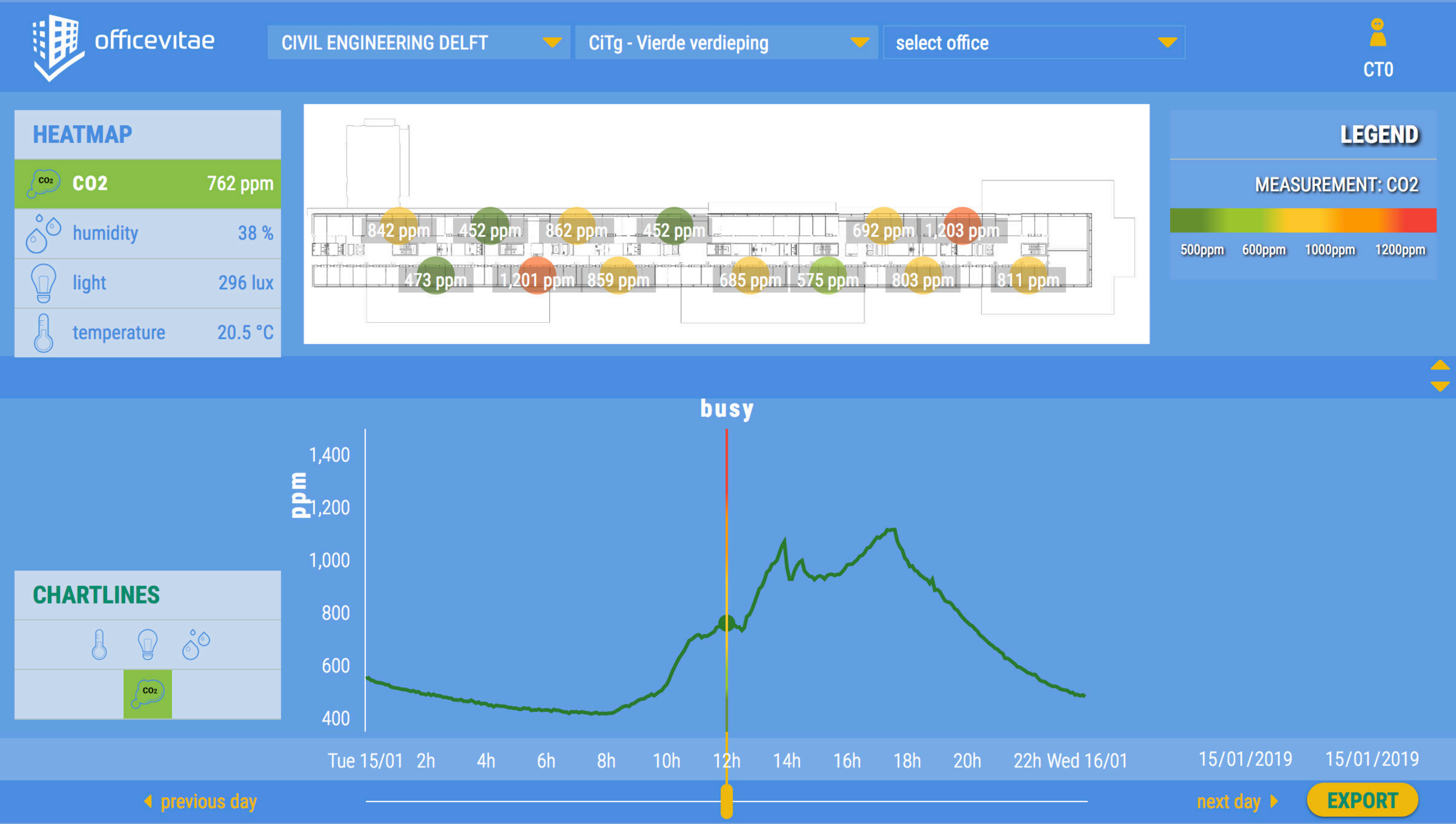
Light - Sufficient lighting in office spaces is crucial to the comfort and productivity of users. Poor lighting conditions can lead to headache or eye-strain. Recommended lighting levels should be between 300 and 500 lux. Quality of lighting is also important, with glare, high or low contrast, unwanted shadows, or other poor light distribution effects affecting the health and productivity of users.

Temperature - Probably the predominant user comfort parameter in office spaces, temperature needs to be kept within a small margin for users to feel comfortable. High or low temperatures are associated with diverse health problems, drop ion productivity and absenteeism. Ideal temperature is generally considered between 21°C and 23°C, but this can vary based on external conditions (eg. summer or winter), and even more between different user preferences.

At the moment of writing, preliminary winter-time monitoring reports a significant improvement in indoor comfort, a reduction of uncomfortable cold drafts through the windows, and a reduction in space dryness thanks to a reduction in need for active heating. All of these factor will also contribute to achieve considerable energy savings. Some spaces show above-optimal concentrations of CO_2 due in part to the improved air-tightness of the new facade. Users must therefore be better instructed on how to use the new facade to allow for better ventilation.

Top: OfficeVitae integrated room sensor.

Right: Online dashboard for the OfficeVitae monitoring application showing user presence and indoor comfort values for selected rooms throughout the day.



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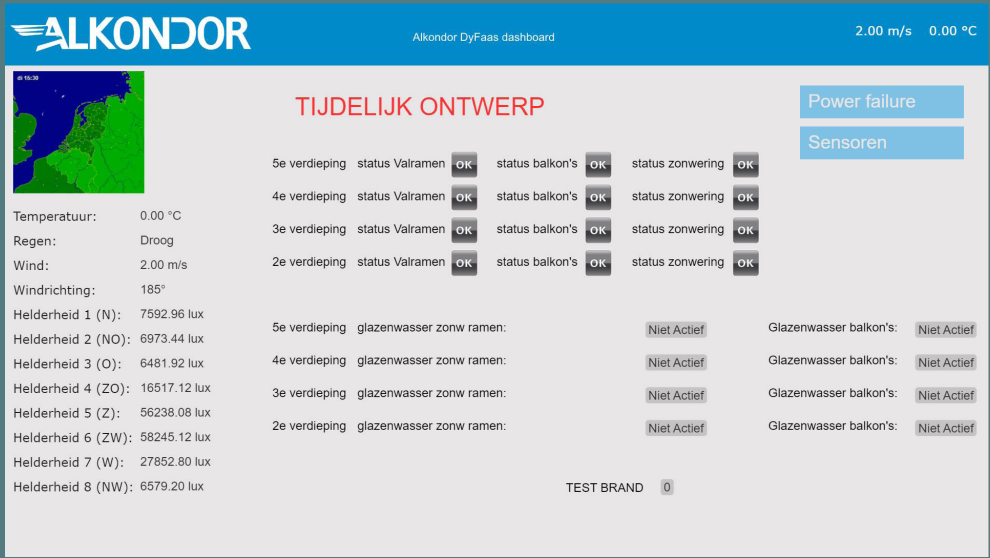


Fig 1. Outdoor climate data reported by a roof-installed weather station. The technical overall status of the system is also reported in this main dashboard.

Fig 2. The status of the facade in each office room is reported. For example whether the windows are open or closed, or the sunshading active or inactive. This information can be compared against OfficeVitae's user comfort data to find patterns between negative user behaviour and negative indoor comfort or energy performance results.

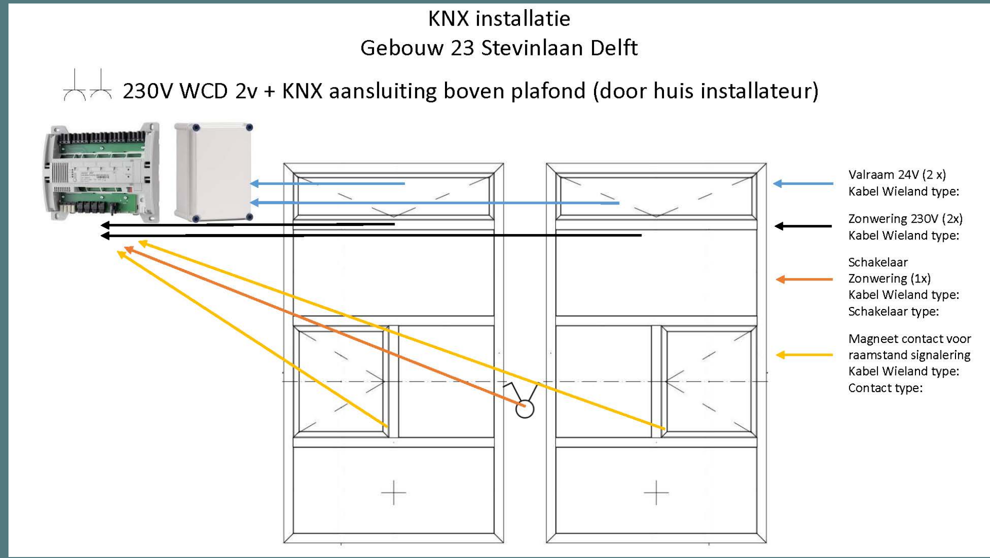
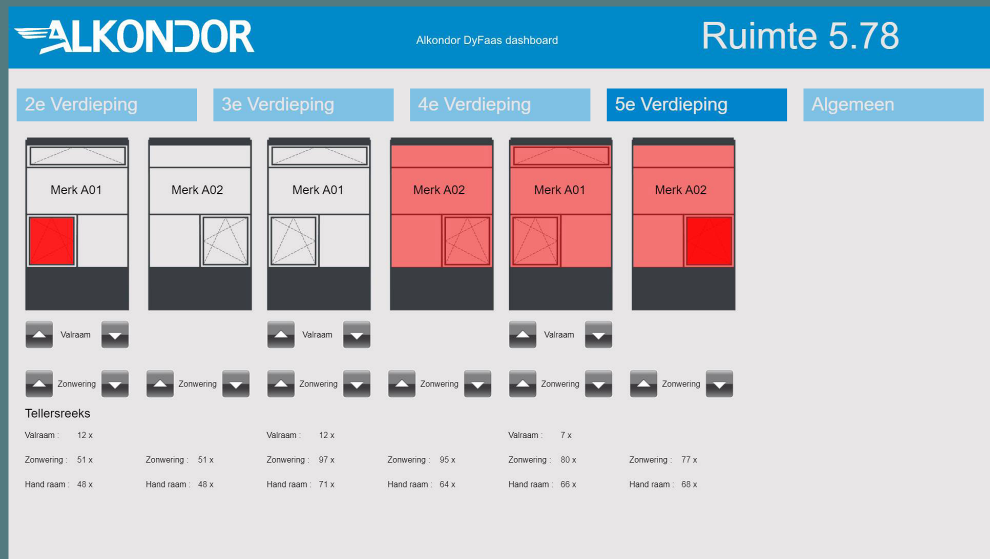


Fig 3. Logic of the KNX remote monitoring and control system installed at the CiTG large-scale renovation prototype to facilitate Facades-as-a-Service performance delivery.

Fig 4. Live status-report for the facade of a typical meeting room in the CiTG building. It shows whether windows and sunshading are active or not, and the number of operational cycles each engine or actuator in the facade has been subjected to.



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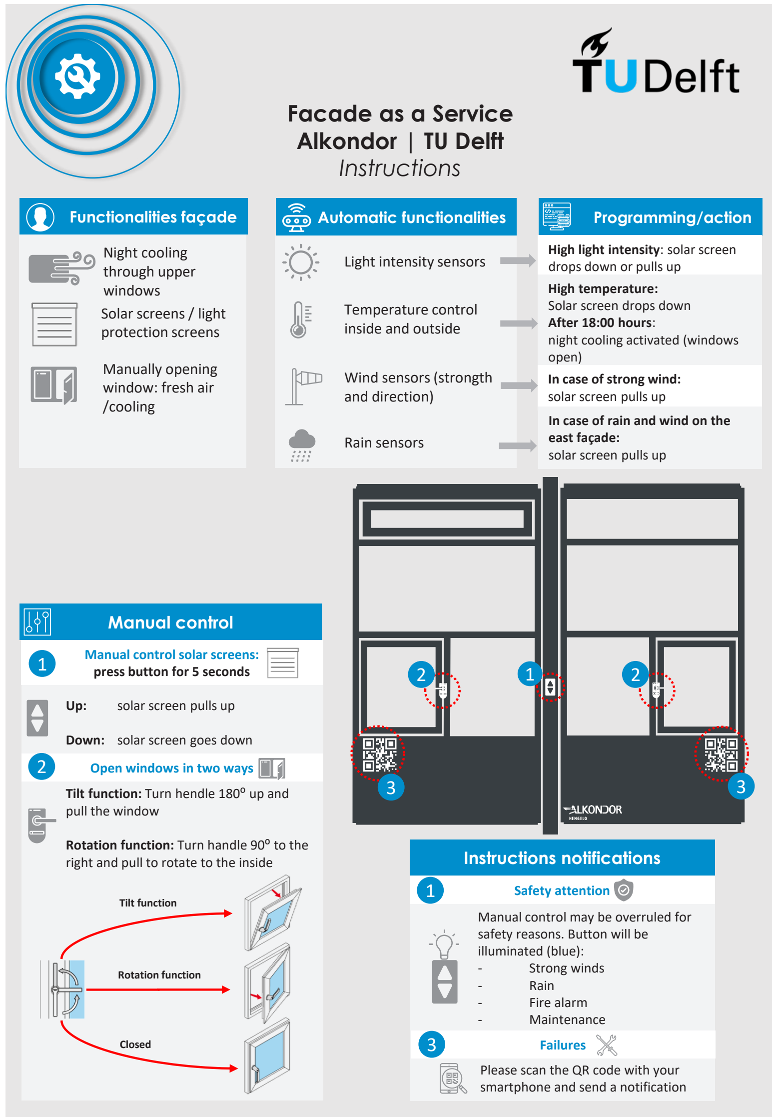
In a Facades-as-a-Service contracting model, the building's owner and facility management team outsource technical responsibility of the facade's performance to the service provider. This new market player is therefore responsible for the ongoing monitoring of the facade and facade-integrated systems, to secure they are operating in accordance with the service contract, and so that any failure or under-performance can be corrected within the limited time-window permitted by this contract.

A number of new building technologies and online monitoring software allow Alkondor's service division to constantly check the condition of the facade. It also allows ongoing data collection regarding user behaviour which could lead to sub-optimal energy performance of the building, such as for example leaving the windows open for extended periods of time during winter months. This data can be used to limit legal disputes arising from under-performance of the renovated facade in terms of energy savings or user satisfaction.

To support end-users in their decisions, and teach them how to operate the new and more technically advanced facade system, an instruction manual (right) has been prepared and distributed throughout the building. It also specifies automatic indoor comfort or energy-saving actions taken by the facade in response to changing internal or external conditions. Such actions can be overruled by the end-user if they affect his or her comfort.



11. Global warming mitigation potential

The following Climate Impact Assessment has been updated from the one submitted by our project in 2018, and which was prepared in collaboration with consultancy company Quantis.

Energy savings for the CiTG large-scale demonstrator prototype (based on energy simulation software)

Considering the improvement of the façade after renovation in terms of insulation and air-tightness, and assuming energy losses due to the (non-renovated) heating system, the study results in 66,4 kWh/m2/year final energy savings per façade area (172.700 kWh/year for the whole façade). Assuming a Combined Heat & Power unit for the campus district heating network, total reduction in CO2-emissions is expected to be 22,4 t CO2-eq per year for the whole facade.

Operational impact versus embodied impact

For the assessment of the upscaling potential, the heterogenic nature of the non-residential building sector results in only a very rough estimation being possible. The study therefore applies the number of the potential savings calculated for the CiTG retrofit, simulated to be approximately 76%, to a generic building with average energy consumption of 155 kWh/m2 of façade area. This results in theoretical energy savings of 117,8 kWh/m2 of façade area, which results in 40,9 kg CO2-eq/m2 of façade area using the mean International Energy Agency value for the EU top 5 countries. Based on LCA data for average façade typologies, average embodied emissions is 188 kg CO2-eq/m2, resulting in yearly emissions of 3,8 kg CO2-eq/m2 which can be significantly reduced or even avoided by a circular use of materials. In the case of the CiTG project operational emissions avoided are calculated at 67,7 t CO2-eq/year, and from embodied energy at 10 t CO2-eq/year, resulting in 1165 t CO2-eq over the 15 year service life currently planned for the façade.

Closing the resource loop in the built environment

Tracking technologies such as NFC chips and QR codes (near right) enable the tracking of building components through the use of "digital twins" (far right, below). The digital twin is an online record of information which will contribute to extending the service life of the facade while maximising the residual value of components, such as:

- Materials and quantities embodied in the facade. Particularly relevant information when dealing with the high-value aluminium alloys of the facade industry.

- Production and installation date of all components, as well as number of operational cycles they have been subjected to. This helps the service provider schedule pro-active maintenance works, taking advantage of economies of scale and increasing the likelihood that replaced components will be remanufactured after being recollected in high volumes.

- Maintenance and cleaning schedules to which the facade has been subjected since its installation. Frequent and thorough maintenance will result in a better technical condition at the end of its current service-life, or when being transferred to a new building, increasing the residual value of components.

Fig 1 and 2. NFC chips and QR codes are used to track the materials and history of each facade panel. This allows long-term asset management of the system and facilitates the eventual remanufacturing of components,

Fig 3. Breakdown of expected energy savings and climate impact mitigation resultant from the CiTG large-scale demonstrator prototype.

Climate Impact Assessment CiTG

		V1.0	V2.0	Savings retrofit	
Simulations					(%)
primary energy total (ideal)	**kWh/m2**	189.2	48	**141.2**	**75%**
primary energy el (ideal)	kWh/m2	4.7	4.7		
primary energy heat (ideal)	kWh/m2	184.5	43.3		
use energy el (ideal)	kWh/m2	2.6	2.6		
use energy heat (ideal)	kWh/m2	167.7	39.4		
use energy total (ideal)	**kWh/m2**	170.3	42.0	**128.4**	**75%**
Assumed losses					
final energy el	kWh/m2	2.6	2.6		
final energy heat	kWh/m2	192.9	45.3		
final energy total	**kWh/m2**	195.5	47.9	**147.6**	**76%**
final energy total (per facade area)	**kWh/m2**	88.0	21.5	**66.4**	**76%**
CO2 emissions					
CO2 emissions per floor area (STEG)	**kg CO2-eq/m2**	25.3	6.2	**19.1**	**76%**
CO2 emissions per floor area (IEA)	kg CO2-eq/m2	76.7	18.8	57.9	76%
CO2 emissions per facade area (STEG)	**kg CO2-eq/m2**	11.4	2.8	**8.6**	**76%**
CO2 emissions per facade area (IEA)	kg CO2-eq/m2	34.5	8.4	26.0	76%
CO2 emssions total (STEG)	**t CO2-eq**	29.6	7.3	**22.4**	**76%**
CO2 emssions total (IEA)	t CO2-eq	89.7	22.0	67.7	76%

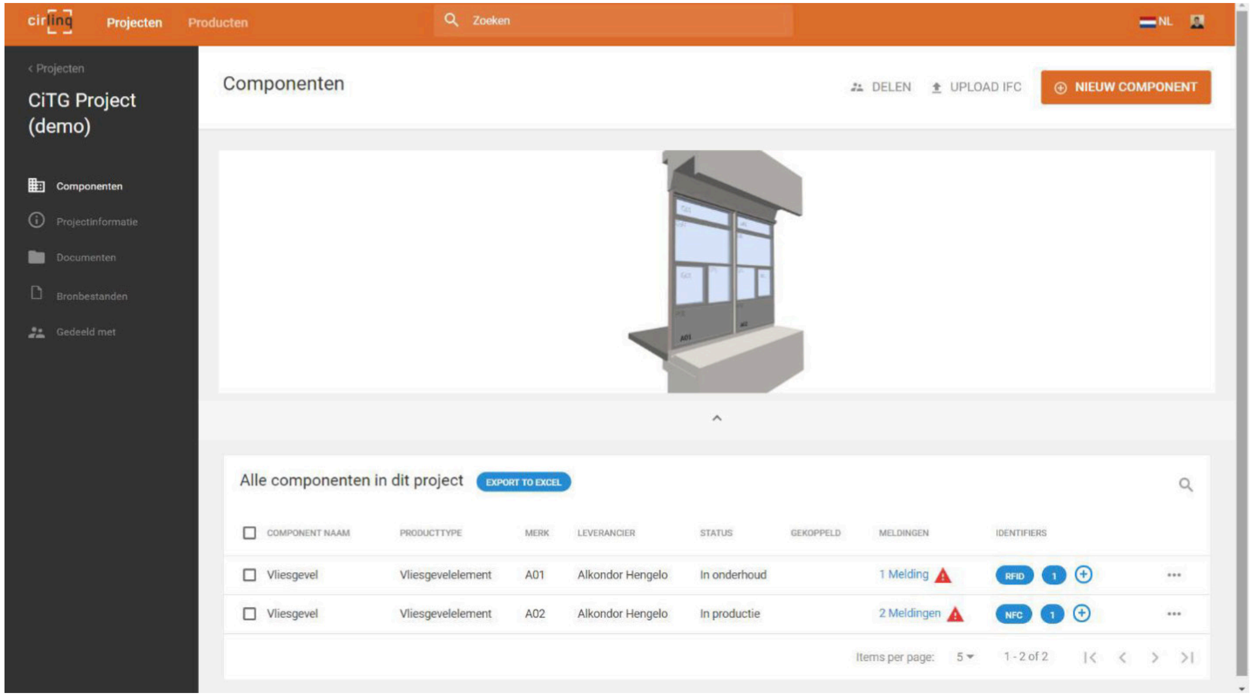


Fig 4. Digital twin of the facade in a typical office room of the CiTG building. Showing data such as time of production, manufacturing details, and maintenance schedule.

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12. Service delivery technical scopes and Key Performance Indicators (KPI's)

The shift from product to service delivery proposed by this innovation project for the facade industry requires the creation of contracts and other collaboration models establishing performance indicators as the key value proposition in the commercial transaction. While these key performance indicators are still been developed and agreed upon for the case of the CiTG facade, such KPI's are not new to the sector. VMRG, the branch organization for the Dutch metal facade industry, establishes quality criteria which must be followed by all member companies when delivering a project. Manufacturing standards, industry standards, local and European building regulations are other types of norms which must be followed by all parties engaged in a building project.

The main difference is the long-term adherence to such norms in a product-based economy versus a service-based one. In the former, the manufacturer is only responsible for delivering such quality, and is committed to the product for a certain number of years due to contractual guarantees. Such guarantees, however, are often too short to properly protect the client, or result in long litigation processes in which sub-contractors debate the sub-optimal performance of each others' work scope. Such a system provides no incentives, other than penalties, for manufacturers to be interested in the long-term performance of their systems.

A transition towards long-term, measurable performance indicators under a service contract makes the service-provider directly responsible for the operation of its systems over the entire period of the contract. Time-frames of 15 to 25 years are much more likely to cover the degradation of products over time than guarantees held over 2 to 5 years after construction. Furthermore, long-term servicing provides incentives for manufacturing and assembling companies to invest resources into engineering of equipment of higher quality, with lower maintenance requirements. Since the client pays a fixed fee for the facade service, and maintenance is responsibility of the service provider, any difference between the calculated service fee and the actual management and maintenance expenses will determine the final profit made by the service provider.

The examples KPI's shown on the opposite table provide an impression of the service provider's responsibility over the facade components over the planned 15 year contract period. Quality and performance metrics are determined by industry standards, and response times are established and agreed upon by both parties. Such agreements form the core of the Facade Leasing contract.

Fig 1. Long-term maintenance schedule and allocation of technical responsibilities between Alkondor and other specialised, sub-contracted parties . As Facades-as-a-Service provider, Alkondor is responsible for over-viewing the integral delivery of performance services, but technically achieving this performance is easier when collaborating with system suppliers through long-term strategic partnerships.

13. Contributors

Facade Leasing meeting at the office of ABN AMRO Lease in summer 2018. Present are representatives from TU Delft (research), TU Delft CRE, Alkondor Hengelo, VMRG, Houthoff and ABN AMRO Lease.

Photo: Juan Azcarate-Aguerre, 2018

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Juan Azcarate -Aguerre	BK BPI and Facade Economics
Alexandra den Heijer	BK Public Real Estate and Campus Management
Zeno Winkels	Valorisation Centre TUDelft / Climate-KIC
Marleen Hermans	BK Public Commissioning
Hendrik Ploeger	BK Geo-information and Land Development
Monika Chao-Duivis	BK Building Law
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Hubert Linssen	The Green Villlage
Sacha Silvester	IO Sustainable Design and User Interaction
David Keyson	IO Social Contextual Interaction Design
Marcel Reinders	EWI Pattern Recognition Laboratory
Kelvin Berghorst	CRE Strategic Campus Management
Rob Weststrate	CRE Manager Maintenance
Johan Hogervorst	CRE Maintenance
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