From Product to Product-Service System

The demarcation of producer responsibilities

in the transition from linear to circular service system.

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Executive Summary

Context

In the construction industry of today, buildings are seen as finished products rather than ongoing processes. The business model of facades as a product service system is a promising strategy to change these practices. A pilot project at Delft University of Technology sparks the interest of Alkondor Hengelo, to explore their tasks and responsibilities as pioneers in this new way of supplying facades. Suppliers would retain the ownership of a leased PSS façade and guide a project through its entire service life and beyond, managing materials in a circular way. The two main challenges were identified as 1. Going from a linear model to circularity, and 2. The ongoing involvement in a PSS instead of handing over their product. The first steps of implementing the façade leasing model have been taken, however the full strategy yet needs to be outlined, to understand how value is added for suppliers and clients and where technical barriers are found.

Objective

Ideally, a PSS would optimize façade performance and provide all services that are needed to do so. This adds value for the client and creates a steady source of income for the supplier. As the pathway to a full PSS is best approached in smaller steps, it should be defined: What set of tasks would the façade supplier take on in a basic stage of servitization, and what could be added on to form a more advanced service agreement? For façade suppliers, it is important to make the best use of the investment into their product, as they would not only be acting as producers, but also operate and safeguard the product and its performance throughout the entire cradle-to-cradle life cycle. Therefore, it should be designed for optimal operation and output during use, and designed for circularity, to achieve a high residual value after the first use. Different design criteria and considerations are therefore given, as a reference for future designers of circular facades as PSS.

Main Findings

A hypothesis was made, that the final form of a PSS strategy for facades would include a performance guarantee. This is a complex task, because in current practice, the indoor environmental quality and energy consumption is rarely studied after the completion of construction. The proposed task would not just focus on receiving feedback on the effect of an energy retrofit: If the supplier could use the façade as a performance-delivering tool and create a reliable prediction of its resulting performance, he or she could market the guarantee of this valuable outcome. It has been found, that there are multiple challenges involved with this endeavour: The IEQ and energy performance is a product of all internal and external factors of a building, not just the façade. The supplier needs to control the most critical factors (building systems and dynamic parts of the façade) to direct the overall behaviour.

In the design of circular PSS facades, the residual value of facades after their first service life is the main driver in linking environmental and economic interests. It was identified, that PSS facades should be independent of the building they encase, in both an economical and constructive way. Their design should make them flexible and adaptable to new reuse scenarios. Further research could be done on the reuse on component level.

Acknowledgments

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Table of Content

1. Introduction

In this thesis, the challenges and potentials of designing facades as performance-delivering tools within the system of façade leasing are explored. In the strategy of this circular business model, the façade supplier is thought to retain ownership of his or her product, while the building owner receives a guaranteed performance for a leasing fee. The service offered by the supplier includes all operational tasks such as maintenance and solutions for the end of service life. The thesis builds on previous publications of the interdisciplinary research team at TU Delft, where it is argued that “a Product-Service System approach to façade design, construction, operation, and renovation could accelerate the rate and depth of building energy renovations”[1] It is also anticipated that a PSS paves the way towards a circular façade construction industry, saving material resources, as well as optimising the performance of façade products, to achieve energy-efficient buildings. With the Dutch governmental aim of enforcing a circular economy[2], and eliminating Co2 emissions by 2050 [3], a clear goal of the building industry should be the energy renovation of the existing building stock, to increase its performance, while applying any needed materials in a responsible circular way.

The supply-side innovation in facades is explored, looking at new concepts in terms of design, production and long-term operation, fit for a performance-delivering system. Together with the façade specialist company Alkondor Hengelo, the ongoing pilot project of the Civil Engineering Building (CiTG) at TU Delft is taken as a learning opportunity, of discovering new design and operation strategies. The project is experimental in its unprecedented form of a product-service façade retrofit. Actual potentials and constraints apply, that come with the new business model and interaction of all its stakeholders.

In changing the practice of façade construction from a product-oriented, to a product-service system, multiple aspects of the current model require rethinking. A change in the overall scheme sets a chain reaction of new requirements in various sub-systems in motion. Besides the managerial side of financial and legal issues, “an integral PSS approach would completely redefine the way in which systems are designed to interact with each other by, for example, increasing standardisation and reducing compatibility issues. It would also restructure the supply chain in terms of contractual obligations.”[4]. As the main responsibility for the performance of a leased façade lies with the supplier, most tangible design changes will occur in their department. We need to ask: How well do current façade products and their management throughout their service life and beyond, fit into the new system? And where is redesign needed? All the changes in the physical building components are a result of a new constellation of stakeholder interaction, their motives, interests and operational strategies. The main question of this thesis is how far the supplier’s responsibility and influence go, considering different stages of product service systems are possible, and different steps would be taken to reach them. Part of this thesis is the unravelling and visualising of these interrelations, finding where demarcations lie and assessing both risks and benefits of strategies.

[1] (Azcarate Aguerre, Den Heijer, & Klein, 2017, p. 2)
[2] (The Dutch Ministry of Infrastructure and the Environment and the Ministry of Economic Affairs, 2016)
[3] https://www.government.nl/topics/renewable-energy/central-government-encourages-sustainable-energy
[4] (Azcarate Aguerre et al., 2017, p. 8)

Context and Background

Alkondor Hengelo

Alkondor Hengelo is the main external consultant for this thesis. The façade specialist company have been an external consortium partner of the façade leasing research project previously and in the present. They are involved with the first pilot project, in which test panels were mounted on TU Delft´s EWI building in September of 2016 and are the façade supplier for the new project of retrofitting the CiTG building. From their multidisciplinary team, Martijn Veerman joined the dialogue to find new strategies of how a supplier can manufacture and operate a leased façade, as he is the specialist for circular facades at Alkondor Hengelo. The practical expertise helped to highlight the challenges of the new business model, as seen from the supply-side. Both tangible and non-tangible parts of the PSS will be subject to redesign and reorganisation. The key question of “how will it work?” was discussed as well the integration of promising ideas such as building systems and smart devices, because with more responsibility for the performance of the product comes the initiative of experimenting with the integration of functions, that were not previously sought after by the architect or client. The continuous revenue of a product-service system provides a more stable financial setting, to invest in innovative systems that have not yet been tried and tested. On the other hand, new responsibilities are added on the supply side, and therefore the demarcation needs to be defined, taking the companies experience and knowledge into account.

The CiTG pilot project

Figure 1: CiTG Delft. Source: Author´s own.

The Faculty of Civil engineering and Geosciences of TU Delft, or "CiTG", requires an energy retrofit, due to its lacking current performance. It is the second façade leasing project at TUDelft, after the previous demonstrator on the EWI building in 2016. In the EWI project, the desired effect was described by Jeroen van Winden as to "really make all people around the table think about the realization of the concept the idea to start a so-called pilot project came up. The idea of a real project would make communication with everybody more concrete and would generate better results for the research." [5] Four different panels were mounted on the existing EWI façade, as a physical platform, visualizing the unprecedented idea. The design was not conceived as the future of the entire building´s façade. The building was merely chosen as a host, contrary to the plans for the CiTG building, which is meant as a real case of an energy retrofit.

Figure 2: EWI Delft. Source: www.tudelft.nl

The new project at the CiTG building on the other hand is meant to be used both as a pilot project and an actual energy renovation of one side of the building. The CiTG building is an interesting case study, because of its key features:

- Part of a university campus (Client=CRE/TU Delft),
- Large scale,
- Relatively old underperforming building stock,
- Uncertainty about future lifespan and use of building,

[5] (Van Winden, 2016, p. 12)

- Two longitudinal facades: one has been treated with common, minimal methods; the other is to be treated as a leased facade.

The building is featured as one of the case studies of the doctoral thesis “Re-Face” (Ebbert, 2010), because it “can stand representative for a large portion of the market”. In his work, Thiemo Ebbert develops different strategies for the refurbishment of office facades, to help give planning teams an overview about the challenges in office refurbishment and navigate through the field of refurbishment options. Many aspects of “Re-Face” are relevant for this thesis, and although the current refurbishment strategy of the CiTG East Façade using a PSS model does not directly relate to the proposals planned by Ebbert, they give food for thought and insight on the CiTG building.

About the CiTG: The building is part of the campus of Delft University of Technology. It was designed by the architecture office *Van Broek and Bakema* in the 1960s. In recent years, the desire of the university and municipality to preserve the building in its characteristic brutalism stood juxtaposed to the building reaching its end of technical lifespan. That said, a careful refurbishment is needed and has been planned for some time being, as already Ebbert mentions “The University is planning to refurbish the building in 2010”. But the decision is apparently not an easy one to make, as in 2016 the renovation had officially been put on hold, plans of large-scale renovations had been excluded and the building was staying put for “at least the next ten years” ("Civil Engineering faculty building gets ten year lease of life," 2017). In the same web entry, it is stated that:

> “Maintenance activities will be focused on achieving a functioning building for the next decade. In cooperation with Facility Management & Real Estate service a framework has been drawn up of must-have requirements for an adequate environment for teaching, working and research. The first steps will be towards improving comfort and climate control in the building (which many colleagues find less than satisfactory) and a better use of meeting rooms and workspaces.”

Beginning in the summer of 2017, the west façade facing the Mekelpark area was stripped of the old cladding, containing hazardous materials, and maintained in an overall minimal way, including “the installation of new ceiling panels, new exterior blinds, painting of the balcony railings and replacing the casement window stays”("Detailed planning of activities to the western facade including asbestos removal," 2017). These measures certainly keep up the aesthetic of the building, but do not largely improve its technical performance. This case study is therefore a good example of old, underperforming building stock that needs an energy renovation to meet modern standards and goals for the future, but due to the limited lifespan of the rest of its components, it seems uneconomical to treat the façade in an impactful way.

Renovation

Many buildings like the CiTG are stuck in a phase of uncertainty about their treatment until they are demolished and replaced by an entirely new construction. Large scale renovations are often deemed unprofitable due to the associated financial investment needed, compared to the remaining service life of the entire building. This can mean years or decades of unsatisfied users, dealing with uncomfortable conditions in the spaces they occupy daily. It might seem like the users are the only party affected by disruptive factors such as overheating, glare or badly ventilated rooms, but bad comfort conditions are directly reflected in the productivity of occupants such as students or employees, making it an even more critical, quantifiable problem for building owners and organizations such as TUDelft in this case, as their success is linked to the productivity of building users. A healthy and comfortable indoor environment can have economic and societal benefits in increasing productivity and decreasing the amount of sick leaves of occupants. (Bluyssen, 2013) Therefore, a solution is needed, to renovate buildings which no longer meet modern technical standards, such as the CiTG. As Ebbert states, "(…), many buildings are demolished, which are still structurally good. Such demolition is not only a waste of capital and embodied energy. It also leads to a loss of architectural identity. Current practice is lacking innovative and practical refurbishment concepts for office facades, which support the refurbishment of offices on a wider basis, as well as the indication, to which extent these are applicable to different existing façade types". (Ebbert, 2010, p. 10)

An energy renovation not only improves the indoor environmental quality of a building for its remaining lifespan but can potentially even increase this lifespan. Choosing renovation over the replacement of the entire construction saves valuable components such as the structure, which can be durable for longer, from meeting a premature end of life. Additionally, an obvious reason for energy renovation is related to the goals set by the Dutch government, to eliminate CO2 emissions by the year 2050 (The Dutch Ministry of Infrastructure and the Environment and the Ministry of Economic Affairs, 2016), and banning office buildings of energy labels below class C from the year 2023 (Prendergast, 2016). The specific deficiencies of the CiTG and its current façade construction lie in the poor thermal properties: single glazing, thermally unbroken steel profiles and additional cold bridges of the concrete structure result in a high energy consumption for heating purposes in winter. This challenge should be tackled for both ecological and economic reasons. Reducing CO2 emissions is a governmental concern, but additionally stated in the universities own goals of improving the energy efficiency by 30% by the year 2020 (Ebbert, 2010). Ebbert even states that in the year of his thesis in 2010, "Currently, the CiTG faculty building consumes (…) 18% of the University´s total energy consumption.", and that the largest part of heat losses occurs through the non-insulated façade.

The most frequent remark of occupants on the other hand, seems to be related to the overheating during summer. As the buildings active climate control does not include cooling, it is critical to keep thermal gains as low as possible, to improve this situation. The retrofit proposal therefore replaces single panes of glass by insulating multipaned glazing, in thermally broken aluminium frames, while a new highly durable shading system is used to reduce overheating hours. The design of this new east façade will be further explained and discussed in later chapters.

Learning from the CiTG

The case study of the CiTG building is focussed on testing a project with real financial, legal and contractual constraints, as a proof of concept and further testing for the business model of façade leasing. This forms a test scenario for the stakeholders of the project, to gain a foothold in this new environment within the construction industry. The aspects of the project that are further analysed and discussed in this thesis are related to the physical façade, its construction and effects. An inherent goal of façades as PSS is to construct in a circular way, where materials are managed carefully by one supplier throughout their lifecycle, maximising the output of the product. The lifecycle of leased facades is no longer tied to one building. We can design them according to new rules, creating an advantageous construction that is as long-lasting or easily updatable as needed, to optimize them as performance-delivering tools, with multiple service-life cycles on different buildings. The CiTG is a fist attempt at such a project and it shows that we can go even further in matters of design and construction of PSS facades. The service life of the pilot project façade is not sure to end with its application on the CiTG. A purpose of this thesis is to explore whether the reuse of panels is possible.

Figure 3: CiTG Delft. Source: Author´s own.

Additionally, the extent of service included in the supply of the façade is assessed. The PSS renovation of the CiTG east façade covers maintenance requirements, but more advanced forms of PSS could be developed, including a multitude of services. The details of this endeavour are not clear yet: Can we provide result-oriented services such as a performance guarantee? Will we reach goals, or how far are we from being able to do so? These challenges related to the technical implementation are explored with the CiTG as a case study at hand. It will form the subject for paradigmatic simulations and calculations. Results then add to the body of research of the overall topic and could inform facade suppliers such as Alkondor in their approach.

Problem Statement

In current practice, almost all façade builders' tasks are related to planning and construction up to the on-site completion, while maintenance is rarely an integral part of the business. This relates to the fact that "The general tendency to look at buildings as "finished products" rather than "ongoing processes" leads to an overall short-sightedness when defining the most efficient operation and end-of-service scenario design for the construction and the materials that compose it." (Azcarate-Aguerre, 2014; Azcarate Aguerre et al., 2017, p. 43) To provide for the product-service system of façade leasing, two main changes would have to be accounted for by façade builders: 1. Going from a linear model to circularity, and 2. The ongoing involvement in a PSS instead of handing over their product. For the latter, the new tasks and responsibilities of producers have not yet been defined. While the idea of leasing facades and adding services to the supply system is generally discussed and deemed as promising in literature, it is lacking a definition of what the business model could include, and which benefits, and risks might be involved. An overview of the challenges and possibilities is needed by suppliers and further researchers, to make progress in the implementation of circular PSS for facades.

From Linear to Circular

Moving towards an environmentally, societal and economically stable future, the façade construction process needs to be rethought by all actors, most importantly the parties taking up the responsibility of managing the lifecycle of façade products. For façade leasing, the role of facilitating circularity is taken by the façade builders. The business model gives an incentive towards supplying circular facades, because companies hold both the power and responsibility of applying processes and products, redesigned to optimize the loop. The new circular business model requires strategies for an ongoing circle of design, construction, assembly, maintenance, use, monitoring, disassembly, updating, reuse, reprocessing, and repeating the cycle. The extended period of involvement with a project and its afterlife means thinking multiple steps ahead. Every element needs elaborate preparation, including materials and handling. When done correctly, suppliers could benefit from maximizing the value of the raw materials used in their products, by optimizing their functionality during use with proper care and maintenance and unlocking the potentials of residual value in the stages after the first service life. The latter can include the reuse of components, producing income from a second service life, or getting a head start in the second-hand market, anticipated for a circular economy of the future.

Long-Term Involvement

The largest new task of the façade builder in a leasing model is to retain ownership of the materials, while supplying the client (owner of the building) with the desired performance. In doing so, the interests of both parties change compared to a standard construction method. Traditionally, the supplier would produce the façade according to an architect´s or main contractor´s plans, using preselected systems to manufacture what he or she is asked to. In the new scenario, the revenue no longer comes from product sales, but from setting up a system that will live up to agreed-on performance expectations.

As there is no handover date of the façade product and responsibility, reaching performance goals at a single point in time is not sufficient. Regular monitoring, maintenance, replacements and updating are needed to keep up the service. For those purposes, monitoring tools can be applied to measure temperature differences, CO_2 levels, humidity, lighting of indoor and outdoor areas as well as moveable parts such as sun shading systems, windows, ventilation grills and (integrated) building systems such as mechanical heating, cooling, ventilation etc. This is useful for the following reasons:

Keeping track of outer influences, inner heating or cooling loads, as well as to user behaviour, which can explain numerical measurements and their fluctuation. The recorded data is then used to plan maintenance service, such as replacing gaskets to restore optimal airtightness, or replacing shading elements after a certain operative quantity. The second reason is, that multiple parties are interested in keeping track of how well the buildings skin works: the supplier ("when do I perform maintenance to avoid a performance drop?"), sub suppliers and architects ("how well does my design really work? What could I optimize to keep up with my competitors?") and the user/client ("Am I getting the indoor comfort that I am paying for?").

Relevance

The successful implementation of façades as circular PSS is especially relevant in finding new solutions for the much-needed energy renovation of our large stock of underperforming buildings. Energy retrofits are to be performed within the next decades, in order to reach the goal of eliminating CO2 emissions by 2050. A large share of CO2 emissions is produced because currently energy is wasted to heat and cool buildings with below-standard thermal envelops. Although technological solutions are available and the construction industry is not standing still in terms of renovations, we are not moving fast enough. Two main steps should be taken, to ensure real progress is made in time to sustain our future: The rate of renovations needs to be drastically increased, and the implementation of innovative technologies must be promoted and made economically accessible to building owners. Although new technologies should be developed further on to make facades with even higher energy performances possible, the lack of technological solutions is arguably not the reason why current practice is not the refined solution needed to tackle the vast amount of renovations. The idea of designing a standardised or modular façade solution to cover the renovation of a large amount of buildings efficiently has been researched and results can be found in literature. It is a valuable approach which is not far from what is considered in designing leased facades. But to form a holistic concept, not only the construction needs to be rethought, but also the practices in the industry. New ways must be found of how to finance, design and build, and equally important, treat products during and after their service life. With facades as PSS, a promising business model has been developed. In this thesis, some of the missing links in terms of technical, organizational and operational solutions are tried to be found, in hope to further the implementation of facades as circular product service systems.

Objectives

The objective of this thesis can be described in different parts: The steps in the transition of façade supply strategies, from product to product service systems are to be elaborated. First, it should be made clear to the reader, what main changes are made, comparing current practice to the proposed new business model, and how an incentive is given, to simultaneously transition towards a circular façade construction. Then, the idea of adding services to a previously product-oriented supply strategy is analysed in more detail by defining different types of PSS for facades. As the pathway to a full product service system is best approached in smaller steps, we should define: What set of tasks would the façade supplier take on in a basic stage of servitization, and what could be added on to form a more advanced service agreement?

For façade suppliers, it seems vital to make the best use from the investment into their product, as they would not only be acting as producers, but also operate and safeguard the product and its performance throughout the entire cradle-to-cradle life cycle. Therefore, it should be designed for optimal operation and output during use, and designed for circularity, to achieve a high residual value after the first use. Different design criteria and considerations should therefore be given, as a reference for future designers of circular facades as PSS. Especially the most advanced, fully result-oriented PSS model holds a high level of uncertainty. Namely, providing a performance-guarantee for facades, in terms of energy performance and indoor comfort of rooms enclosed by the envelope, is promising but is possibly the most complex to implement successfully. Therefore, a case study building is used as reference for a computer simulation and discussion of different outcomes, to provide a quantitative base, to understand the risks for different stakeholders, thus minimizing the uncertainty of offering a performance guarantee. The reader should be given an overview of factors which could influence the gap between presumed façade performance and the actual outcome, on the example of the CiTG building on the TU Delft campus. Lastly, some methods of how to narrow down the expected range of performance are proposed.

Research question and design question

Main Research Question:

- **(Main RQ) What are the points of demarcation related to energy performance and indoor comfort, along the pathway to facades as PSS, and how can they be specified?**

Sub-questions are:

- (RQ1) What is the difference of PSS models to traditional facade procurement?
- (RQ2) Which new tasks and responsibilities does the façade builder take on in shifting towards PSS models?
- (RQ3) Which critical factors present an issue in guaranteeing a certain range of energy performance and indoor comfort of the CiTG east façade?
- (RQ4) What technical and managerial aspects can help the implementation of result-oriented PSS facades?

Main Design Question:

- **(Main DQ) What is the effect of the PSS approach on the design of facades?**

Sub-questions are:

- (DQ1) How does the PSS façade design compare to a standard construction?
- (DQ2) What design criteria emerge from supplying facades as PSS?
- (DQ3) In which way can the design of PSS facades contribute to a more circular facade construction?

Methodology

In this section, the research approach for this thesis will be explained. In the problem statement, multiple challenges in the field of facades as product service systems were touched upon. The scope of this work is defined, and strategies are set up to gather and process information needed to form conclusions and answer the research and design questions. This thesis is the product of conversation with the façade supplier Alkondor, while further research was done to take interests of all actors into account. The objective of this thesis is to take some of the questions that arise from the supply side in this new business model and inform leased facades of the future.

The existing theoretical model of facades as product service systems is taken as a basis, to now explore the physical implementation. The development of the new business model developed by the TUDelft research group progressed in a usual way: First, a general problem was detected (a large building stock that needs renovation and the current construction industry not being fit for circularity) and an overarching idea emerged, to try and solve it (form economic opportunities that speed up the rate of renovation and provide a system that ensures materials are managed from cradle to cradle). At this point in time, the economical side has been explored further than the tangible part of the product service system: the physical façade and its materials, as well as the effects that it has on the building it encases. The goal of this work is therefore to give an overview of the challenges at hand and form a bridge between the organizational aspects (financial, legal etc.) and built elements, where it is needed right now, to progress a step further towards successfully designing facades as product service systems. The goal is to form a reference for future research which will be needed to reap the full potential of facades as product service systems. The scheme shows the method of how the wide topic of *designing facades as product service systems* is approached.

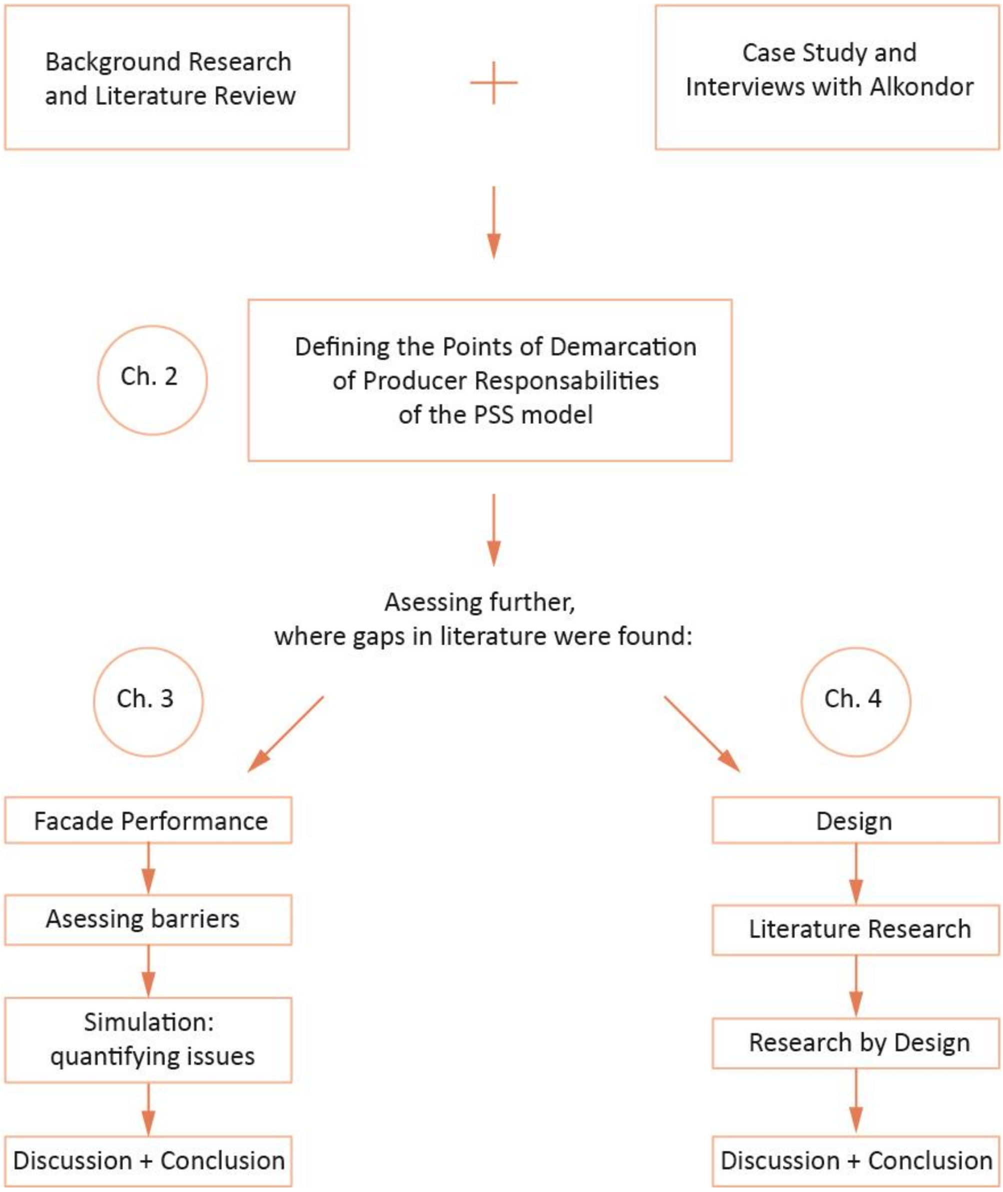


Figure 4: Methodology Scheme. Source: Author´s own.

Research tools

Literature: The first step of understanding the topic of PSS and façade leasing in depth is to study the existing literature. The available publications of thesis, papers and articles are an important source of information.

Interviews and occupant´s data: The more practical method of gathering information on the façade construction industry and façade design is to conduct expert interviews. Consulting with the main group of actors surrounding the CiTG project was a useful starting point. Alkondor Hengelo was the main interview partner, while occupant´s data of the CiTG building provided some valuable additional insight.

Plans and simulations: For the process of answering the beforementioned design questions, plans of the project were used as a basis of research through design. As the answering of research and design questions requires quantitative results, computational simulations were made in Design Builder, a tool used to assess environmental performance. The environmental benefits of the façade leasing model can be divided into two categories: Reducing the energy consumption of buildings and reducing the waste of raw materials. A successful façade design constantly weighs out both categories within design decisions, but for the sake of simplification for this methodology, it translates to the three aspects of *Circularity, Performance* and *Design*. The background of building technology formed a useful basis to try and bridge between the numerical output, needed to form agreements between stakeholders, and tangible input, namely the physical facade manufactured and applied by the supplier.

Literature Review

A literature review was conducted, using publications about the following topics:

- PSS and Façade Leasing
- Energy Performance and Indoor Comfort
- Façade Value and Real Estate
- Façade Renovation
- Façade Design and Construction Concepts

The Results of this review largely influenced the discussion and conclusions of this thesis. The complete review can be found in the appendix.

2. Façade Construction: Current practice and innovative alternatives

Façade Leasing

Why should we add “service” to a product system?

The topic of façade leasing or facades as circular product service systems revolves around a proposed innovation in the field of the façade industry. The new business model should increase the rate of energy renovations of facades by making them financially accessible to building owners. This is done by the supplier retaining the ownership of the product, supplying its performance as a service for a steady leasing fee. This way, the barrier of a large initial investment by the building owner is overcome. To progress from a basic leasing contract towards a more result-oriented service system would mean that a set of services is added to the financial leasing contract. Services would be carried out before, during and after the operational phase of a façade application.

In his thesis “*Façades as a Product-Service System: The potential of new business-to-client relations in the facade industry”* in 2014, Juan Azcarate-Aguerre gives an overview of perfomance criteria of common interest of stakeholders, as basis of façade value. In a section about business-to-client relations, he addresses stakeholders benefits of façade leasing, namely the following:

- For the client, there is no large initial investment in a physical product. They could feel free to explore new technologies, without having to worry about the financial investment in an upgrade.

- The producer exchanges the task of supplying and keeping up a functional product-service, with the long-term relation to the client and their ongoing leasing payment. Additionally, they hold the market share of their used products and can make use of the residual value.
  (Azcarate-Aguerre, 2014, p. 20)

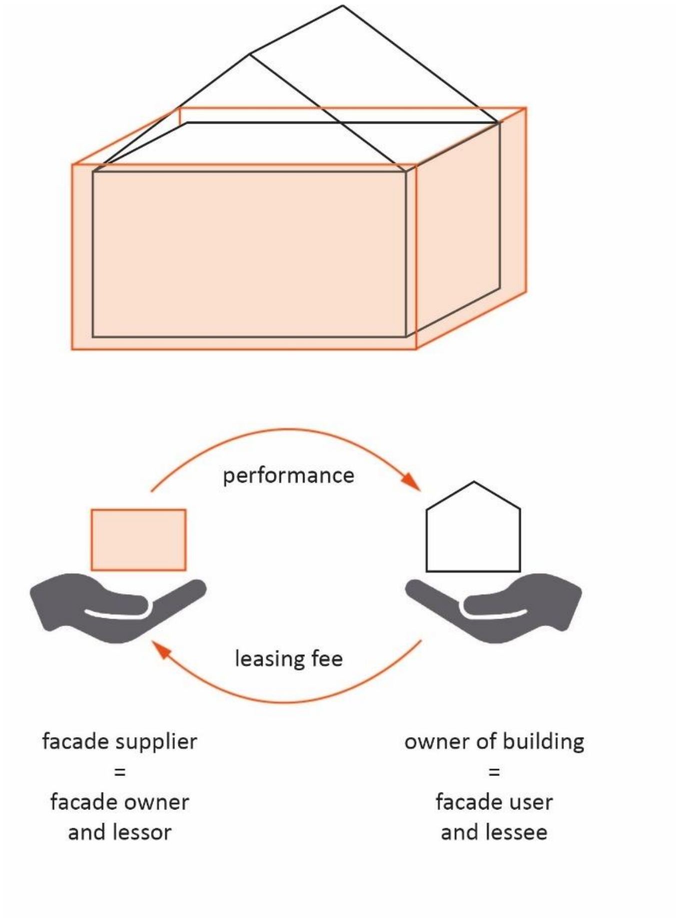


Figure 5: Facade Leasing explained. Source: Author´s own

Where does "service" start?

Reviewing the current tender procedures and the frequency of their use is a valuable basis for the setup of processes in new business models that imply a main role of the supplier in providing both the leased façade and related services. To define where service starts, it is interesting to first look at the tasks of façade suppliers in current practice.

Current practice: In his 2013 dissertation "Integral Façade Construction. Towards a new product architecture for curtain walls", Tillmann Klein maps out the currently employed construction process of facades, as well as future challenges that come with the changing market. He argues that stakeholder roles will change, and to tackle future challenges, a development towards product-based architecture for the diverse types of integral façade constructions is needed. A hypothesis is presented, arguing that the structure of design and construction processes is "blocking the development of new constructional solutions"(Klein, 2013, p. 39), and an analysis is needed. The current situation is described as the following: "Basically, the entire building process is divided into separate crafts which are planned by different planners such as structural engineers or buildings service engineers and are also executed by different companies. The underlying idea is that the architect guides the entire process much like a conductor" (p.24). The separation of crafts leads to problems, once a façade becomes more complex, with new systems to help reduce energy consumption. "These are problems that are rather new and challenge the traditionally separated building disciplines" (p.27). With increased technicalisation and integral approaches, new building processes and task distribution are needed. The current tender options are listed (Klein, 2013, p. 52):

1 Open tender: The façade is tendered on the basis of extensive specifications. (Basically, the façade builder has no influence on the design.)

2 Builder involvement: The builder gets involved in the architectural design (he/she might even get paid for this). After that he/she competes with other companies that are also asked to submit a quotation.

3 Direct contract ('building team'): The façade builder is involved from the beginning, and then negotiates a price and gets the job.

4 Functional specifications: The tender document specifies functions only. (Can you make a façade that can do this and that, and how much will it cost?)

In an open tender process, the supplier has next to no influence on the physical façade, and therefore the design for performance is entirely up to the architectural designer or other contracting entity. In other words, the responsibilities are clearly split between different crafts. The open tender process is currently used in most processes, according to interviews with stakeholders (Klein, 2013). Tender processes with more façade builder involvement on the other hand relocate more of the decision making towards the executing party, merging the interests of constructing a façade and ensuring its qualities, which can lead to a better technical result. However, the process shifts away from the architectural designer. "On one hand, it offers valuable technical input, making sure that the façade design is technically and financially solid, but on the other hand the builder naturally has an own agenda that might not comply with the one of the client or architects. Thus, there is a mutual interest but also a potential conflict." (Klein, 2013, p. 57). Without going into more depth on benefits of different tender processes, some of the interview results are informative for this thesis, as stakeholder task division is a large topic. More specifically, the role of the architects, clients and suppliers must be rethought to provide a circular business model for façades as product services.

Façade Leasing and PSS: The terms "Façade Leasing" and "Product Service System" might be associated with the same field of innovative business models, but they do not automatically mean the same thing. A financial façade lease in its basic sense simply means that the supplier would retain ownership of his or her product, to temporarily provide it to a customer in exchange of a leasing fee. A PSS on the other hand does not automatically imply any leasing transaction. Although most PSSs feature leasing in one way or another, there could theoretically be systems of products that are owned by the customer in a traditional sense, with a service tied to them. Azcarate-Aguerre presents such a model in his design theory of visualizing different strategies of "value engineering" that could be used in facades as product service systems: "Rolls Royce has been chosen as the related brand because of its history of providing a "single investment" policy. This means that the person buying their cars wouldn´t have to worry about service (as service expenses were included in the original cost), (…)" (Azcarate-Aguerre, 2014, p. 73).

Although he presents the case for a different purpose, it is here mentioned as an example of a product sold in a standard way, but with the added value of promised service. It could be argued, that this is simply a guaranty (which does not yet make a PSS), extended in time and supported by the reputation of Rolls Royce as a luxurious and reliable company. However, the service component is clearly existent, although only the intangible value of trust and comfort would set the model apart from standard product guarantees.

The lines between leasing and product service system seem blurred, because ownership and responsibility are inseparably related in the traditional understanding of products equated with properties. In simple terms: “If I own something, I take care of it. It is in my own interest to get the best use and value out of my property.” In a leasing situation however, the ownership differs from the usual situation (stays with the producer), while the responsibility may be shared between client and producer or taken fully by either side. A PSS without the component of leasing can be simplified as a guaranty. That means, the ownership is handled in a traditional way, while the responsibility is assigned to the non-owning party. In theory, a warranty could even be provided by a third party, who did not sell the product, but has knowledge and experience related to it. Of course, these different business models originate from different objectives and to achieve various benefits to supply and demand side. But for the service of facades, the product related goals are clear: achieve the best performance and keep it up for as long as possible. The importance of handling facades properly is high, because of their complex nature, and the large range of performance as a possible result of one construction. The service including maintenance and operation could be described as the influence that we have, to achieve better output from an input. The high risk involved with “not caring” (no maintenance, standard operation with no further reflection), shows the need for service.

But where does it start? It starts with an incentive to care about the product, beyond the usual 5-year product guaranty. This incentive can be found in the leasing model. The supplier extends the direct contact to the client and therefore to the perfomance of the product. In other words, “Façade-leasing as a form of product-service system keeps suppliers committed, throughout the building´s service-life, to safeguard optimum perfomance in operation, while actively stimulating clients to adopt innovative technical solutions.” (Azcarate Aguerre et al., 2017, p. 2) The logical first steps to safeguard said perfomance is to ensure the correct on-site application and connection to other building elements. Further, regular maintenance can be taken on by the producer, to supply a product of consistent quality: The façade needs to be kept clean and materials intact, with all mechanical parts moving properly. But how to deal with an automated shading system? The dynamic factor of shading operation would go beyond the fixed physical components of a façade, digging deeper into the topic of optimizing climate design. So we would ask:

How far does service go?

Juan Azcarate-Aguerre (2014) mentions the positive impact on sustainability, due to the better use and reuse of products, compared to the current economy without clearly assigned responsibilities. A chart is given, comparing the information and material flows of traditional purchase/leasing models, to a PSS scenario. (Azcarate-Aguerre, 2014, p. 29):

An interesting thought related to façade performance can be followed up from this graphic representation: The PSS tasks are visually divided in two groups: 1. The physical “building climate technologies” and their financing, management, control, maintenance, ownership and recycling, and 2. The “service delivery” with a fixed result of indoor climate conditions, and the shift of responsibility and risk management from client to supplier. It is described that “In an FIBC (Façade-Integrated Building-Climate Service Provider) scenario, on the other hand, all financial, technological and human resources required to deliver the final service (indoor-climate values) are centrally managed by the service provider. The building and its owner are therefore at the end of the supply chain, as they simply hire the service of maintaining this indoor-comfort level; Outsourcing everything implied in delivering it to a third-party with a full, specific experience doing it.” (Azcarate-Aguerre, 2014, p. 28)

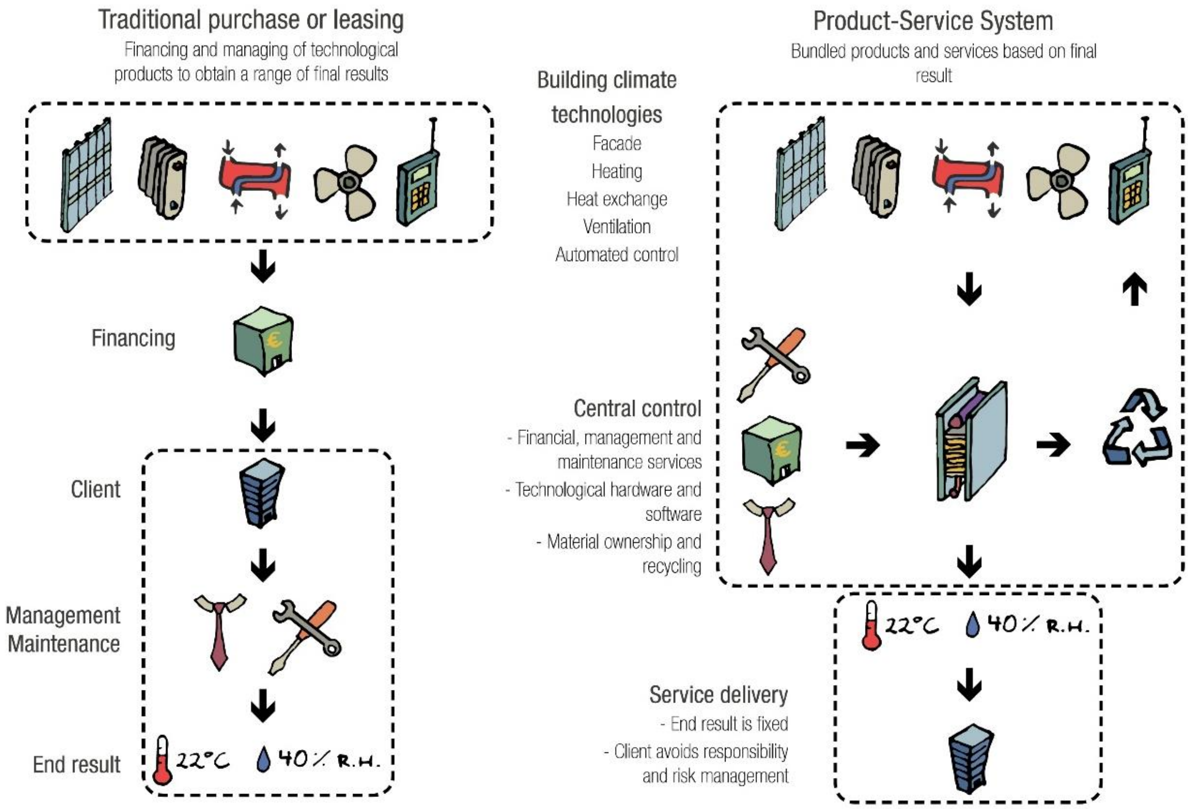


Figure 6: "Information and material flow in a traditional purchase/leasing scenario (left), and a product service system scenario (right). Source: Azcarate-Aguerre (2014), p. 29

In dividing the tasks into two regions, the nature of indoor comfort (second region) as a result of all factors in the above region is visualized. However, it is not entirely clear if the supplier in this scenario gives a guarantee for certain indoor comfort conditions, or if it is said that the building owner is simply released from the task of façade handling and accepts results without further reinforcement in form of any measurable performance indicators. What if the results of these two scenarios differ, due to the different point of demarcation? In this thesis, the range of demarcation in possible PSS models will be given and possible effects are discussed.

An overview of general types of PSS systems provide a guidline to define the steps of service provided for facades. The work of Tukker (2004) revolves around the factors that determine whether different types of PSS business models are successful in providing firstly added value, and secondly incentives for sustainable behaviour. He states eight types of Product service system models, which are organized as different stages of servitization, ranging from product related (1) to functional result (8), as represented in the scheme below.

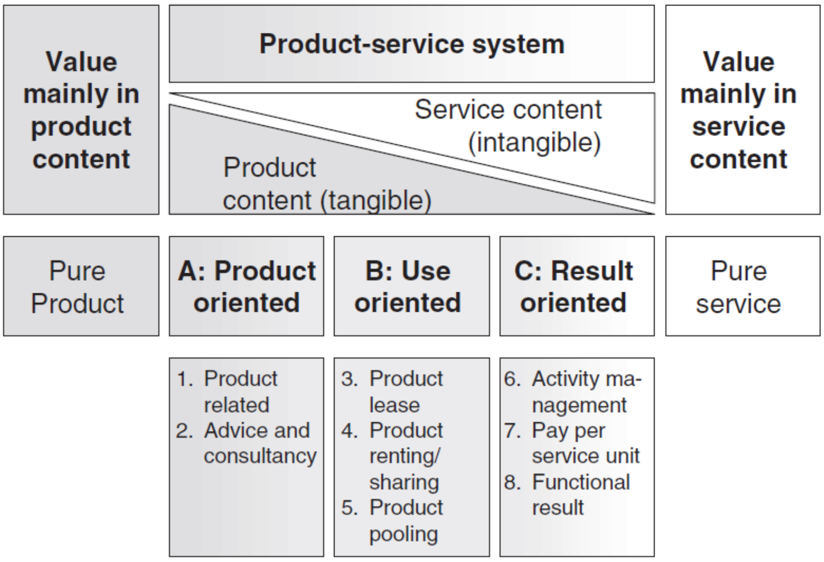


Figure 7: "Main and subcategories of PSS" Source: Tukker (2004), p. 3

Categories of PSS: Three main categories are used to describe the main focus of the eight types. The first category consists of models which divert only slightly from traditionally sold product, by offering some basic related services. The main step taken in the second category is the retention of ownership by the supplier, while the models are still characterized as product-centred. Only in the third category, the focus shifts towards the service, as the product used as a tool to achieve an aggreed-on result is no longer pre-determined. This shows the beforementioned idea of using a leasing model as an incentive to add the service component to a product system. He concludes, that with the advancement towards defining the service as a main value, the freedom of providers in "fullfilling the true final needs of a client" is increased (Tukker, 2004, p. 4). This can bring technological innovation and added value for both parties. The subcategories named by Tukker could be matched to their implementation in PSS of facades:

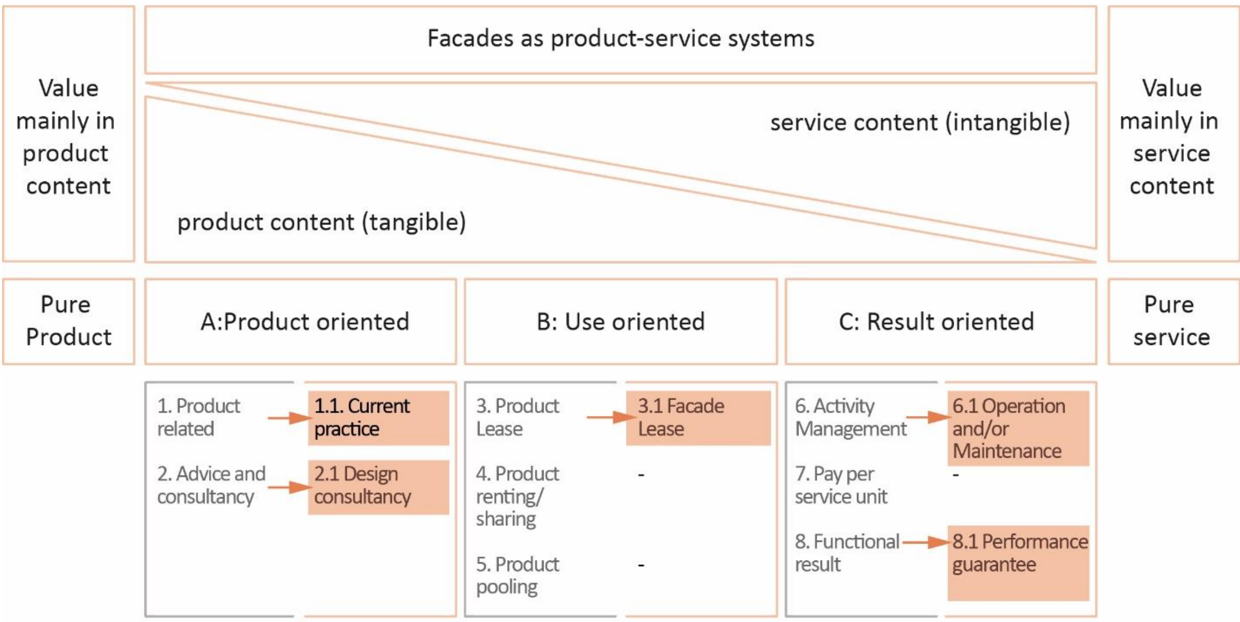


Figure 8: Characteristics of different façade supply strategies. Source: Adapted from Tukker (2004) and Klein (2013).

Categories of PSS for facades:

1. Product related: Tukker describes this category of product-related services: “This can imply, for example, a maintenance contract, a financing scheme or the supply of consumables, but also a take-back agreement when the product reaches its end of life.”(Tukker, 2004, p. 3). This is probably the logical first and most realistic step to take, however it is not too different from current practice in the façade industry, because this kind of PSS is not service- or result oriented.

2. Advice and consultancy: “Here, in relation to the product sold, the provider gives advice on its most efficient use.” (Tukker, 2004, p. 3) For the supply of facades, design consultancy can be a service offered by suppliers. The “efficient use” can also be consulted on, however this would be part of maintenance and operation as a separate service package.

3. Product lease: In this basic form of leasing without further add-ons, the lessee has full access to the product as well as the responsibility for it. This means that theoretically any third party can be assigned the tasks of maintenance, monitoring and consultancy. However, splitting these tasks could lead to challenges related to the value of the product, as the supplier has retained ownership and is therefore entitled to a certain level of care and upkeeping of it. This is especially important for the residual value of the façade and has major effects on the track record of the supplier company, as he of she has less influence on the results.

4. and 5. Are seen as not applicable for facades.

6. Activity management: To give purpose to “acticity management”, the discussed service needs to be taken from the task portfolio of the owner of the building, or a sub-department. For example, a university´s facility management could currently be responsible for the cleaning and maintenance of facades. Although it is unlikely that this entity has an in-house maintenance crew, they are probably currently responsible for the scheduling of that activity. The façade supplier would take over this planning task and/or the actual maintenance.

7. Pay per service unit: This type of PSS uses the “service unit” to measure how much of the service was taken advantage of. A well known example of this system are copier products, where the lessee pays for the number of copies, scans or prints that are made. The actual mashines are a primary investment made by the supplier, and they stay in his or her ownership. For subcomponents, the “service unit” could be a single opening of a window, or the closing of a shading system. The problem with charging by unit here, is that the user would be driven to minimize the use, diverting from a sensible operating schedule. It seem like this system would not be beneficial, because the service unit here has a direct effect on façade perfomance, whereas for printers, the quality of one single printed sheet is not typically effected by a lower of higher amount of prints made.

8. Functional result: For the category of “functional result”, Tukker mentiones “Typical examples of this form of PSS are companies who offer to deliver a specified “pleasant climate” in offices rather than gas or cooling equipment (…)” (Tukker, 2004, p. 4). This example sound very close to what could be imagined as a final stage of service for leased facades as PSSs. The façade supplier would provide a specified indoor climate and related energy perfomance. If this could be achieved, it would be highly beneficial for all stakeholders, as well as for the goal of cutting Co2 emmissions by keeping energy consumption low. But as mentioned before, it is difficult to determine how to meet the rather abstract demand.

Or rather: could suppliers ever meet those demands? It is a matter of defining a realistic range of energy and climatic performance, and building a strategy of optimizing when goals are not reached.

While it is rated as a favourable development to move towards service-focused models, it is also stated that “abstract demands are often difficult to translate into concrete (quality performance) indicators, which makes it difficult to determine what they have to supply, and difficult for the clients to know whether they have got what they asked for.” (Tukker, 2004, p. 4).

What is the Value of Service?

Value is here divided into two parts: the tangible value, which a client can rationally calculate and asess whether to choose a PSS over a traditionally owner product, and the intangible value. The latter cannot be quantified as savings in terms of financial input, resources or time, but is best described as a “priceless experience”. Although it is not quantifiable, Tukker states that the intangible value often plays a decisive role in successful PSS business models. Looking at the supply side costs, the intangible costs associated with risk premium and uncertainty is added to the tangible production costs. Linking these costs and values, Tukker states that a system “makes sense if the tangible added value of the PSS for the user is higher than the (extra) production costs for the provider, or if a cost deficit is more than compensated for by the intangible added value that the user attributes to the PSS”(Tukker, 2004, p. 6).This relation is graphically represented in the figure below.

Figure 9: Diagram of possible cost and value for supplier and client. Balance should be achieved for successful business model. Source: Author´s own, informed by Tukker (2004)

An interesting observation made by Tukker is that savings in production costs can apply for some PSSs such as in the model of carpooling, because in comparisson to personal car leasing, more people can make use of just one provided vehicle. Although this does not directly translate to the model of façade leasing, another form of savings can apply: Provided the residual value is high enough to reuse the elements, the subsequent use could result in an additional return on the investment. Looking further into the key economic aspects of different models, it is stated that for the final stages of PSSs, Tukker concludes that

> “However, since the provider promisses a result on a high level of abstraction, agreement on perfomance indicators, and the level of control in achieving this perfomance, can be an important (if not prohibitive) problem (which translates to a low score on the risk premium issue). Capital costs could be low, but transition costs high. This model leaves the highest degree of freedom with regard to innovation.” (Tukker, 2004, p. 9)

Sustainability of PSS models: Answering his second research question about the sustainability aspect of product service systems, Tukker considers the change in technological systems and impact reduction of socalled Product Related Services (1) minimal, while Product Lease (3) models might even result in negative ecological effects due to careless use of products by customers. Product Leasing and sharing (4) is considered to have a positive effect, as well as the product improvement that comes with Pay Per Unit (7) models. **Functional result (8) is named to have the highest potential in impact reduction, as "This provider will therefore try to do so (deliver result) in the most costeffective way, which bears the promise of a search for radical innovations" (Tukker, 2004, p. 12)**. He states that models 4, 5 and 8 have the highest potential for innovation and sustainability. As a general silver lining to this work, it can be concluded that PSS models have a tendency to have a higher positive impact in economical and ecological terms, but with the tradeoff of a higher uncertainty because the specifications of these new models need defining, and the supply of a result instead of a product holds inherent risks for the supplier.

Conclusions of chapter 2

Main RQ: What are the points of demarcation related to energy performance and indoor comfort, along the pathway to facades as PSS, and how can they be specified?

The main goal of facade renovations is to increase the energy performance while securing a comfortable indoor environment, because on one hand, CO2 emissions should be reduced, while on the other hand, we are building for people who occupy these buildings. To achieve a maximum of performance, the combination of a product (the façade) and service (taking care of that façade) is needed. **To define the demarcation of producer responsibilities, there are multiple subsequent steps to consider, which together form a full result-oriented PSS.** As previously discussed in this chapter, it is important to define where service starts, and how far suppliers can go. The scheme below shows sub sequential services which can add on to each other.

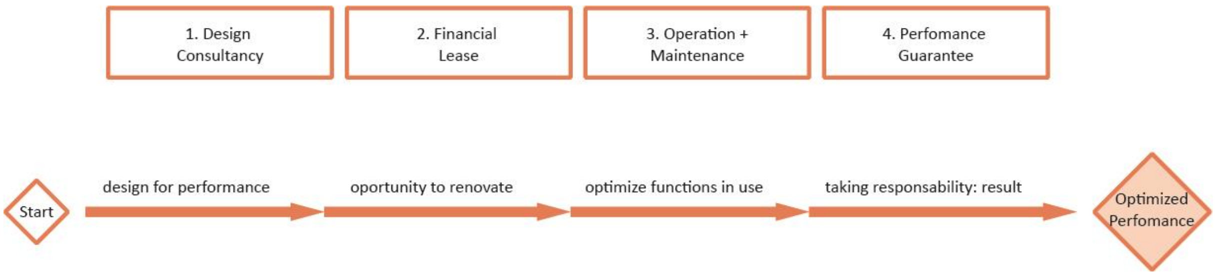


Figure 10: Scheme: Demarcation of producer responsibilities for facades as PSS. Source: Author´s own.

1. **Design consultancy:** Service can start before a leasing system is implemented.
   It is already a part of current practice: Design consultancy might be given to architects and clients during today's façade construction projects, and architectural details are converted to manufacturing drawings by the supplier. But this practice can become a larger part of interdisciplinary design. When switching to a circular PSS, the supplier´s experience of constructive matters such as the component´s interfaces and the assembly and disassembly process become an important part of design. While the stakeholder´s experience with looking at buildings as ongoing processes and material cycles as circular entities is typically limited, the builder is the actor with the most knowledge about the dynamic nature of the building process per se. This process has a larger role in the overall lifecycle of façade components, when they are meant to be reused.

2. **Financial Lease:** the financial lease is the plainest version of leased facades. It entails a predefined financial strategy package. The client is offered a contract for a façade renovation without any large initial investment on his or her part, but a steady leasing fee instead. The leasing period and type of façade are agreed on. Without any add-ons, the client would still

need to make investments for maintenance and manage the operation of the façade. Although this is not an impossible model, it is not very beneficial to any of the parties, because the client does not receive a complete, worry-free service package and needs to invest in maintenance separately. The supplier would be left with the insecurity of who would maintain the product, which is kept in his or her ownership, and is confronted with the risk of premature depreciation, possibly resulting in a lower residual value.

3. **Maintenance and Operation:** This service package is a good addition to the plain financial lease. It adds value for the client, who might be willing to pay a higher leasing fee if it includes a secure maintenance and operation plan. The supplier obtains a new side to their business, receiving payments that add to the desirable steady income. But most importantly, such a PSS contract ensures that maintenance is performed in required increments, to reduce the risk of performance loss of the façade. Propper maintenance can mean that the level of performance does not significantly drop from day one to the end of the leasing period, because any deterioration or damage to the materials and systems is counteracted consistently by the company that holds the most knowledge about the product and its weak points or presumably short lived parts. Additionally, technological solutions can be used to monitor façade functions. This minimizes the response time and optimize the process of maintenance by planning bulk-maintenance when it is assessed to be useful.

4. **Performance Guarantee:** Looking at all the above-mentioned services, it seems as though an ideal package can be offered using different methods to incentivise renovation and make full use of the façade´s potential to produce a good result for the indoor climate and energy performance. The supplier could make use of his or her achievement, by marketing the actual façade performance. This would be done in form of a performance guarantee: Measurements are continuously taken in the office to quantitatively determine the indoor comfort conditions such as temperature. Reaching agreed-on values would verify to the client that contractual obligations were met by the supplier. **But there are some barriers left to overcome before this strategy can be implemented successfully. These challenges can best be described as the uncertainty about reaching performance goals.** Currently, there is no strategy available to safely predict a certain (range of) indoor climate conditions, in consideration of energy consumed to climatize spaces. This is discussed in chapter 3.

RQ1: What is the difference of PSS models to traditional facade procurement?

Traditionally, facades are acquired by building owners, in form of a physical product. This product is currently specified by an architect of main contractor, who commissions a façade supplier to build according to plans. The façade supplier is typically consulted on design choices or technical matters only in the final stages of the project development, leaving limited options of influencing the outcome.

The product service system is a result-oriented model, where the physical façade is no longer sold, but leased, along with an indispensable service component. The critical point is, that no materials are sold. The physical façade is used as a tool by the supplier to deliver performance.

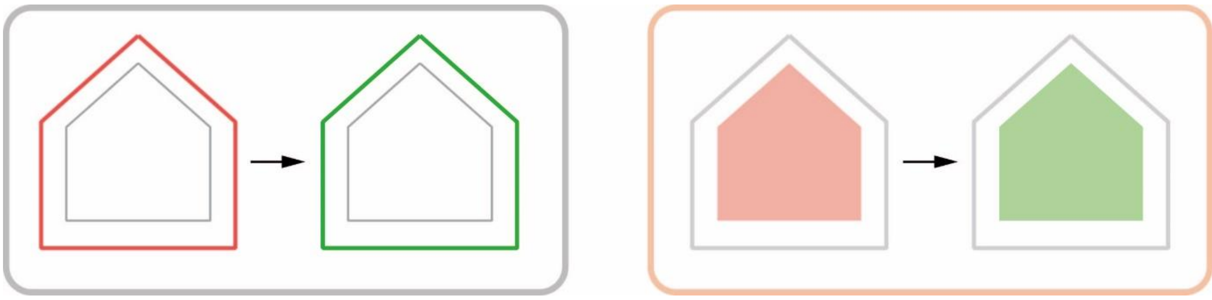


Figure 11: Goals of facade procurement models: Current practice is product-focused (left) while PSS are service and result-oriented (right). Source: Author´s own

The tender process will change because the value shifts from the point of hand-over (end of construction) towards the period after construction. In a market of multiple facade suppliers competing in a tender process, their ability to select and use a façade to achieve the best possible performance will be the deciding factor. What would be marketed is a product-service agreement that can offer the client a low-risk solution to optimize their building´s indoor comfort and energy performance. A balance of leasing costs and value would determine which supplier is selected by the client. The supplier taking responsibility for result-optimizing tasks, as well as the result itself, adds value for the client.

The model of facades as PSS brings the client and the façade supplier closer together, without a general contractor as a conductor. Because the physical façade is not sold, the investment in materials and human resources to form the façade as a product is up to the façade supplier. He or she needs to manage investments accordingly acquiring not only material resources wisely. The façade supplier would benefit from expanding the company staff by professionals familiar with the new tasks involved with the PSS model. He or she will make executive decisions on designing, building and operating a façade to meet the client´s result-oriented requirements.

RQ2: Which new tasks and responsibilities does the façade builder take on in shifting towards PSS models?

Additional service components included in a PSS package, mean more long-term responsibility, and with that, the supply side will be interested in efficiently designing, producing and using the product, which becomes a performance-delivering tool.

Designing a performance-delivering tool

The supplier will take on a larger role within the design-process. Along with the existing tasks of this phase, the aspect of reverse engineering for demountability is added for a circular PSS model. The façade builder will benefit from an extended design department in their own company.
Design-related questions and tasks will be discussed in chapter 4

Covering accounting, administration and legal requirements of façade leasing

The practice of leasing instead of selling façade solutions requires added attention on accounting, administration and legal issues of the new business model. A worry-free leasing package can be an attractive offer for clients. However, the supplier will need to integrate different types of professionals into their team of staff and collaborating actors. The financial investment of an external party could be sought out to make the leasing model more feasible for all stakeholders. The lifecycle assessment of materials and products is an essential task for the success of this model of long-term supplier involvement.

Centralized operational tasks

An office-based team of professionals should keep track of the output during the operational phase. Data that is recorded in buildings must be analysed and the requirement for optimization of the façade is to be reviewed. The feedback from measurement devices helps balance the indoor comfort conditions and energy consumption of mechanical climate control systems. Additionally, monitoring equipment should be linked to the off-site operations team, in order to schedule maintenance services.

On-site operational tasks

A reliable maintenance crew should be informed about the scheduling of services. An in-house maintenance team or long-term collaborating party is beneficial because knowledge can be shared over the entire lifecycle of a façade. Some larger replacements and updates might be required in less frequent intervals. In addition to the maintenance and operation of the façade, the set of on-site tasks includes user communication by skilled professionals. Receiving first-hand feedback by the users of the building gives valuable insight into how the indoor comfort conditions are perceived and what could be optimized to satisfy the occupants and keep the energy consumption low.

3. Façade Performance

Defining performance

The business concept of façade leasing leads to a different setup of stakeholders´ tasks, ultimately integrating more of the responsibilities taken along the path of design, construction and operation into the hands of one party: the façade supplier. A product service system potentially closes the gap between theoretical input and real output. Designing and handing over the product to a customer who must deal with the consequences and setbacks does no longer work when switching to a PSS. New questions need to be answered, related to defining, designing for, and achieving performance of facades.

In the PSS of façade leasing, a final puzzle piece of the service component could be the delivery of energy performance and indoor comfort, or "façade performance". Therefore, it is essential to define what this term entails. The performance of a façade can be described as its characteristic to fulfil its purpose. **Energy performance and indoor comfort are the effects that we want to technically optimize to produce good conditions for users, while minimizing the environmental impact. The contribution of the façade to these effects is what is referred to in this thesis as "façade performance".** Even through multiple other factors could be added to the definition (such as aesthetics or ease of operation), the term is simplified for this purpose. It will be further described, why façade performance is not exactly equal to energy performance + indoor comfort, and which difficulties there are in defining how well a façade really performs.

Façade functions: A common basis for these explorations is the interrelation of built façade elements, their functions, outputs and the resulting performance. To better distinguish between these, the "black box" idea is used, as referred to in *Integral Facade Construction* (Klein, 2013, p. 103):

> *Simplified, Eekels and Cross as well as others describe functions in form of a 'black box'. It contains all the functions that are necessary for converting the inputs into the outputs. In contrast to a property that a product has independently from the goal of the user, functions can be described as requirements that a product has to fulfil.*

A function can be fulfilled by different elements, that would serve the same purpose: the output. At the same time, one element can have more than one function. Functions can be categorized as primary or secondary, technical or emotional and positive or negative (a negative function can be an inevitable biproduct of a system, or different actors can see a function in different ways). A series of elements and their outputs together create the total theoretical output of a façade. A façade made of elements that together fulfil all required functions, should in theory perform well, mainly creating a safe and comfortable environment for the user, relying on minimal support of energy requiring building systems, while excluding the risk of damage to the construction over time (by water, corrosion, etc.).

Factors that influence IEQ: Because the façade is the boundary between interior and exterior, experienced by users from both sides, influenced by factors of exterior as well as interior sources, the resulting outputs are determined by more than just the actual façade. It is not a detached element with invariable boundary conditions, but constantly influenced by the changing weather conditions and interior factors such as building services and user behaviour.

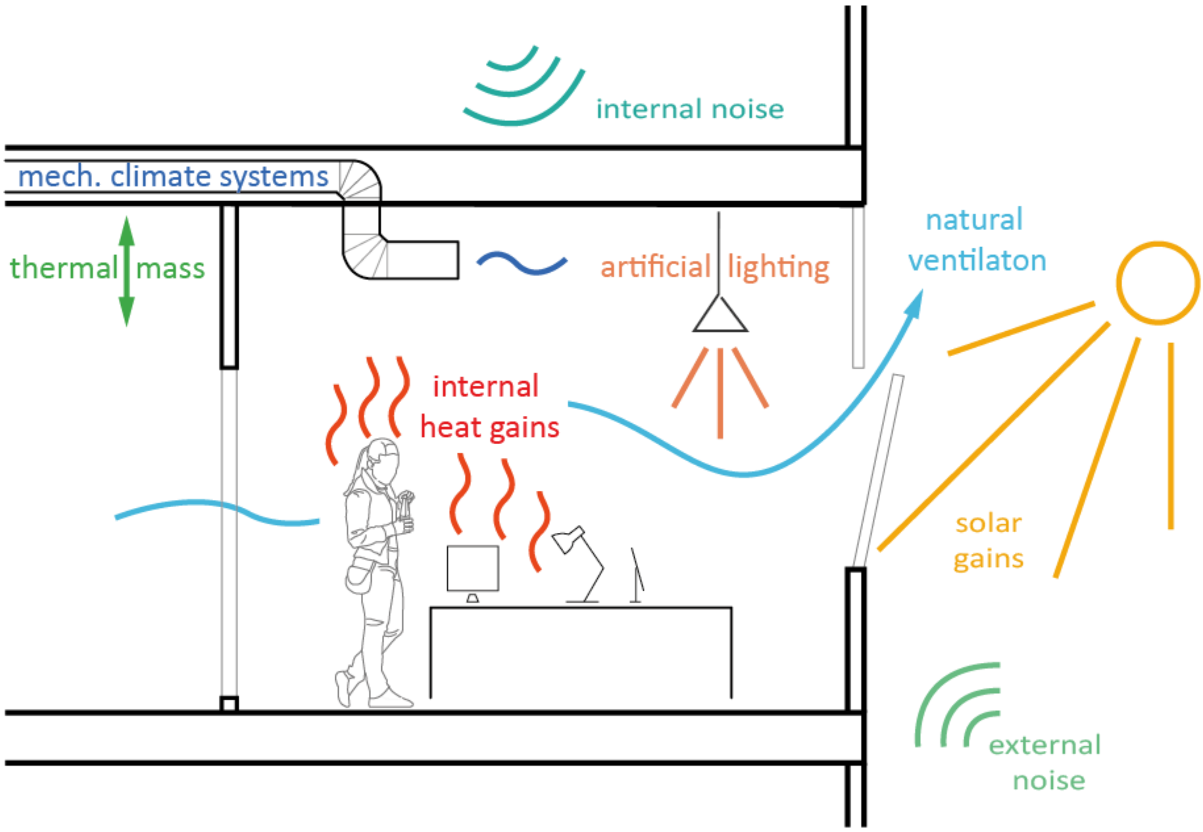


Figure 12: Factors influencing the Indoor Environmental Quality. Source: Author´s own.

This is one of the key considerations of the research of this thesis. Because of the complex combined effects of different building factors, of which only some are façade-related, it is difficult to guarantee indoor comfort and energy performance for a façade supplier. However, it is not impossible, especially if a **range** of performance is agreed on. It is favourable to keep it as narrow as realistically possible, to fulfil the purpose of a true result-oriented PSS. Exactly how much risk is involved with guaranteeing results that might be affected by factors other than the façade, is concluded in later pages of this chapter.

Guaranteeing Performance

Guaranteeing indoor comfort and good energy performance is a step into uncharted territory of the built environment. Although guidelines and certifications for buildings of high climate performance exist, the missing link between plans and actual performance is the incentive for stakeholders to fulfil requirements without accepting major setbacks. What is missing, is a relationship between supplier and building owner that reduces the likeliness of actors settling for solutions that largely deviate from the predicted outcome. A result-oriented PSS for facades clearly defines the demarcation of producer responsibility to supply a certain result, and therefore taking care of everything that can be optimized to achieve it. The result is the selling point in marketing the supply solution. The client is offered the highest added value that a product could entail: the security of achieving a predicted effect. However, next to the implementation of a business model where stakeholder interests align and clients would be willing to pay for extra services, there are still a lot of uncertainties about the technical possibilities. Can we guarantee indoor comfort and energy performance? How would we verify it? And what happens if the endeavour is not successful? Or on the other hand: what happens when it is?

The major difficulties of guaranteeing "façade performance" lie in minimizing the differences between predicted performance (planned, designed), measured performance, and user-experience. This will be elaborated in the following pages. Additionally, an exact range of indoor comfort and energy performance is not just difficult to achieve, but to verify. How is performance measured? An important effect of supplying a result oriented product service system is, that the fulfilment of the performance guarantee is tested by taking measurements in the building to obtain performance indicators: The indicators of indoor comfort (for example temperature and CO2 levels) are measured, to see if desired values are achieved. In a purely naturally climatized building, without HVAC systems, this would more directly indicate if the façade is performing well. However, heating and cooling equipment is used in most non-industrial buildings, such as offices, retail and housing. Therefore, the energy consumption of these systems must be added to the equation of assessing façade performance under real conditions, as underperforming facades would still reach good results of indoor comfort when using the required energy to heat of cool them. Using both measurements of both climate conditions and energy meters could form a starting point. This is again an argument in favour of system integrated facades, because HVAC systems would be detached from other energy-consuming devices in the building, therefore providing more accurate results of how much energy is needed for mechanical climatization.

But making the best of the current situation (of non-integrated facades), measuring indoor comfort in combination with a conscious use of energy for HVAC systems is a good first step. In fact, it is a large step forward, from average current practice, where hardly any feedback is given to suppliers, manufacturers and designers, about how well their product is performing. Mostly, even the building owner is not fully aware of how comfortable the indoor environment is for the inhabitants or office workers, or how the energy consumption relates to the façade functions and operation. Feedback is a useful component of any supply system that is not purely product oriented. When we start actively caring for the result of building products, we need to understand how we our plans were put in action. Information about the building´s indoor comfort can be obtained by numerical measurements in the building, and user-feedback. The results are not just interesting for the application on the building at hand but can form a point of reference for all supply-side stakeholders, to inform future projects, as well as the reuse of a façade. It could create the basis of a steeper learning curve for all parties involved.

The Performance Gap

In the complex construction of a building, the predicted performance can largely differ from the actual measured performance. A certain output may be sought after during the design phase of a project, but when measurements of temperature, air quality, lighting and acoustics are taken, the results are unlikely to match the assumptions. As stated in S.R. Kurvers et al, 2009, values are influenced by the dynamic weather conditions such as temperature, sun and wind, and the dynamic processes going on inside the building. Ventilation, heating, and cooling as well as the occupancy of the building and thereby produced heat loads can affect the results. Another variable factor is user behaviour and the operation of sun-shading and operable openings. “There is still no recognized research or measurement protocol, to examine, if the indoor climate assumed during the design stage equals the practical results.” (Kurvers, Van Den Ham, Leijten, & Van Der Linden, 2009). Working towards the goal of a more energy efficient, sustainable built environment, this is evidentially a large concern. In the current construction industry, there might be a missing link in terms of interests and responsibility for the performance of buildings and their components.

To tackle the issue of the so-called “performance gap” in façade design, two actions need to be taken:

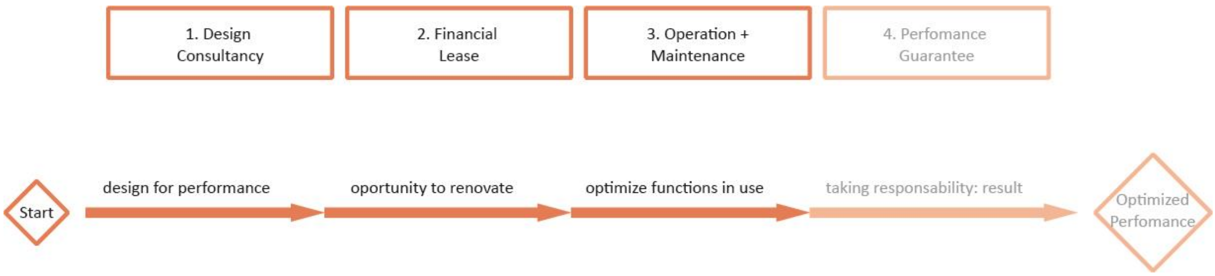


Figure 13: PSS Points of demarcation, related to the operational phase. Source: Author´s own.

Firstly, a managerial one: Creating a more continuous chain of responsibility, from the design to manufacturing and assembly and most importantly beyond, to the entire operational phase. This requirement covered in the business model of façade leasing. It ensures the interest and dedication to realize façade constructions, that perform in the way they are planned to.

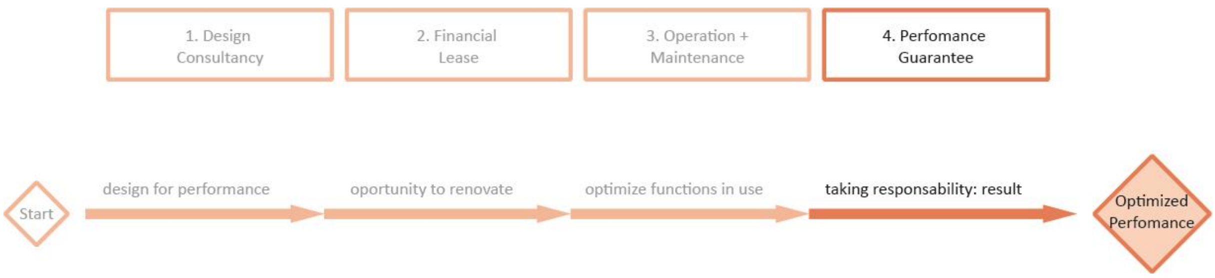


Figure 14:PSS Points of demarcation: The performance guarantee. Source: Author´s own.

- The second consideration is closely linked to the first one but is set in the field of building technology and is yet to be defined. In this work, the following question is therefore treated: **How do we guarantee performance?** This entails highlighting the main factors that form the performance gap, both on the theoretical side and on the side of actual processes taking place in the built construction. The latter will be quantified, to point out their level of influence on comfort (linked to user satisfaction and productivity) and energy consumption (linked to sustainability and finances). The next step is to find possible solutions of minimizing the deviation from the predicted performance. This could be in form of tangible “smart building” tools or methods of cooperation between building owner and users with the façade supplier, including education, communication and consultancy.

Factors of indoor comfort and energy demand

Reasons for deviations between assessed and measured performance in the finished building can originate in the setup of the assessment method, namely the "construction principle" of testing or simulation, as stated in (Kurvers et al., 2009). They can be listed as the following:

- Inaccuracies in measurement, due to placement of devices.
- Occupancy level and rate
- Interior heat loads
- Light diffusion
- Sun- and light shading and their operating systems
- Ventilation amount
- Cooling performance
- Weather conditions

Additional deviations can come from characteristics of the design, which for a façade renovation project can be divided into two categories: Pre-set design (existing building features) and the design of the new façade. The gap in performance related to these factors could originate from slight deviations from plans to actual execution, or larger differences in design of the assumed model to final constructed circumstances.

Pre-set design:

- Exterior construction (as e.g. Exposed Floor plate edges) as predetermined limitation of thermal boundary and airtightness of new façade,
- Interior layout (boundaries such as dry walls, defining the volume of spaces)
- Interior materials of exposed surfaces (interior walls, ceilings, floors),
- Furnishing and predetermined appliances of existing building,
- Building systems (HVAC) and air flow in existing building.

Design of new façade:

- Insulation properties of Spandrel panels and window: U-value and g-value, LTA and R-value,
- Characteristics of exterior and/or interior sun-shading system (g-value and LTA).

Measurable characteristics that influence indoor comfort are:

- Temperature
- Air purity
- Humidity levels
- Ventilation and draft
- Lighting and glare
- Acoustics

Additionally, one more subjective quality is the level of influence that the user has on the operation of systems, such as windows, ventilation grills, shading devices and heating and cooling systems. The ability to actively control one's environment has a direct effect on the level of satisfaction of users. Besides the option to manually override systems that are assessed by users to not operate according to their preference, users also make decisions based on their own working schedule, which can hardly be predetermined to match a programmed sequence. “Occupants have their own considerations and can manage these trade-offs by themselves, e.g. by opening windows only when they go out for lunch.” (Kurvers, Raue, Van den Ham, Leijten., & Juricic, 2013, p. 4)

Measuring Indoor Environmental Quality

As performance and indoor comfort are made up of many different aspects, there are multiple test methods and units of measurement involved to cover all of them. The following list attributes a unit of measurement to the different characteristics:

- Temperature: Degrees Celsius, measured with a thermometer [C°],
- Air purity: mainly CO2 levels, measured with instruments based in infrared, electro-chemical or electro-acoustical mechanisms [ppm],
- Humidity levels: rel. humidity, measured with an (electrical or mechanical) hygrometer [%],
- Ventilation and draft: velocity of airflow measured with an anemometer [mph],
- Lighting and glare: brightness and quality of light measured with an illuminance meter in [lx]. Measuring lighting from artificial sources can be complicated, because a direct comparison between products and their spectral coverage is difficult.
- Acoustics: reverberation time and sound insulation, measured with a measurement-grade microphone, creating a frequency response by plotting [dB] against [Hz] frequency. An energy time curve can quantify the reverberation time in a room (amplitude against time).

Consumer risk and producer risk

Deviating from predicted comfort conditions can be defined in different ways: Conditions can either be unfavourable for all actors, when measurement results show the effect of an underperforming construction, and occupants state to experience an uncomfortable indoor environment. An agreement can also occur when numerical values show positive results, reflecting the occupant’s satisfaction. **But it is not unlikely, that the human perception, which is ultimately the most important indicator, and conclusions made from measurement data do not align**. **This results in either producer risk, or consumer risk.** In the case of a PSS for an office façade, the latter is made up of at least two groups of actors: the building owner and the users.

According to Kurvers et al. 2009, producer risk might occur when the IEQ of a space is tested and quantitatively defined to be below agreed-on standards of comfort conditions, while users do not feel said lack of performance. It is also possible, that it is a result of inaccurate measurement data. The producer might invest in fixing problems that are not subjectively detected by the occupants, whose opinion should ultimately count. Consumer risk on the other hand can occur when users feel uncomfortable in the indoor environment, while tests with measurement equipment show theoretically satisfying results. That means that consumers (occupants and building owner) pay for a performance that they do not experience positively. The interest and risk of users and building owners might not always align: For example, an increased use of energy is mainly a risk of the building owner, because neither the façade supplier nor the user have a direct part in paying energy bills and an assessment of only indoor comfort would still achieve deceivingly good results (even through for example heat losses are high, and are counteracted by an excessive amount of heating).

Kurvers et al. state that the chance of achieving a correct assessment is called the distinctiveness of a test. The goal is to minimize producer risk to max. 5%, and the combined risk of producers and consumers to below 20% (Kurvers et al., 2009). It is also mentioned that this is an especially important requirement for service contracts. The solution in case of facades as PSS could be:

- Firstly, to take three types of information into account when assessing how well a façade is performing: Occupant´s feedback, measurement data of indoor conditions, and the energy consumption.

- Secondly, it is helpful to understand how different factors influence the indoor comfort and energy consumption, and what kind of risk is involved: The level of deviation from the presumed outcome, and who is affected (façade producer, building user or building owner).

Handling consumer risks and producer risks is most certainly a limitation of the studies in this thesis. The issues of narrowing down those risks is an issue that goes beyond the scope of this thesis, because this is a very complex topic in an intersection of social and technical field studies, that has not yet been unravelled fully in literature. The only practical approach of solving these issues would be to use upcoming pilot projects of PSS facades as links between researchers and façade suppliers: Monitoring the IEQ in spaces and a professional user-communication strategy could provide researchers with data to work on an issue that concerns not only façade suppliers of a PSS, but the construction industry in general. A PSS scenario presents the opportunity to do so, because the assessment of measured and experienced comfort is already part of the business model, while experts on consumer risk and producer risk might be looking for data to fuel their studies. When progress in their research is made and shared, façade suppliers of the PSS benefit in exchange, by optimizing their supply strategy.

Narrowing down the range of uncertainty

We have an uncertainty about how close we can get to reaching a certain range of performance and we would like to minimize that uncertainty. A "range of performance" means that we have an ideal IEQ in mind (which should be comfortable for the majority of inhabitants, as the predicted mean vote), but know that in a real scenario it is almost impossible to continuously reach this value (for example 22°C during every hour and day of the entire year). Firstly, a thermally comfortable indoor environment is not necessarily characterized by one strict temperature point, but users will be satisfied in a wider range, which is defined by factors such as the outdoor temperature, relative humidity, as well as their metabolic rate and clothing value. A weighed annual assessment can be given, of how often the temperature exceeds the comfortable temperature range, how far, and under which outdoor circumstances. It is used, because assessing user satisfaction is not a dual system, but different levels of comfort can of course be experienced. For a small number of days of the year with extreme outdoor temperatures, it might already be accepted during the design phase, that the range of thermal comfort will temporarily be exceeded, so that the construction does not need to be over-dimensioned in terms of airtightness and insulation, if it is sufficient for all other days of the year. **Summing up, acceptable thermal comfort is set as a range rather than one point.**

The question for facades as result-oriented PSS is, if we can safely guarantee that the indoor comfort of a room (while tied to its energy consumption) will be inside the range that was defined during the design and contractual phase. The current barrier is the uncertainty about this matter. Considering all the challenges mentioned in sub-chapters above, it is important to define the effect of different factors that result in a (currently unexpected) deviation in performance. **Converting the uncertainties to risks that can be pre- assessed makes it possible to include them into the planning of the business model**

and to set up tools and approaches to minimize their influence. The goal of the next subchapters is to make some first assessments and discuss subsequent conclusions.

Simulation

Simulation methodology

Can we guarantee façade performance? This is a question that is both complex and broad. Complexity can be tackled by taking one step at a time, and therefore it is aimed in this thesis, to try a first approach: The CiTG project will be taken as a case study of the behaviour of an exemplary office room and its façade. A simulation will be performed to make basic assumptions of how the indoor climate and energy consumption could change after the retrofit. This is a procedure that might be used in current practice, and one that could be imagined to be useful in setting up a result-based agreement for a PSS leasing contract. But because, as mentioned before, there is a multitude of factors that could make the actual situation divert from an assumption, a second simulation is used. Here, multiple alternative scenarios are set up, applying different changes to boundary conditions: Decreasing or increasing occupancy, changing the rate of natural ventilation (people might open windows more frequently), inner heat loads (due to a change of equipment), or even the thermal mass properties (what if carpets are stripped away and the bare concrete is exposed).

Limitations of the simulation method:

How the multitude of all performance indicators are combined and relate to the users' experience is still not fully known. For the method used in this thesis, one part of this range of factors was chosen: Temperature is the main criterium looked at in the Design Builder simulation. Ventilation and air purity levels, for the purpose of this thesis only, are set as biproducts that influence the thermal conditions. Lighting is only used as an indicator of solar radiation entering the room, through the shading system, while acoustics will be entirely excluded from the scope of the analysis. Acoustical insulation is an important property of a façade, even more so for a building located in an area with high outdoor noise levels. The acoustical insulation property should be set for the façade elements and should apply when all openings are shut. A passive ventilation concept can be chosen wisely in using elements developed to serve both ventilation purposes as well as insulating requirements, namely ventilation grills as an addition or alternative to regular window openings. But overall, the interrelation between acoustical comfort and other aspects is minimal, compared to thermal comfort, which is influenced by most other decisions made in balancing different aspects of indoor environmental performance.

➔ The performance indicator of **indoor temperature** was chosen for the assessment of the simulation. The amount of overheating in summer months was assessed, with a maximum **comfort temperature set at 25 °C, as a main performance criterium**.

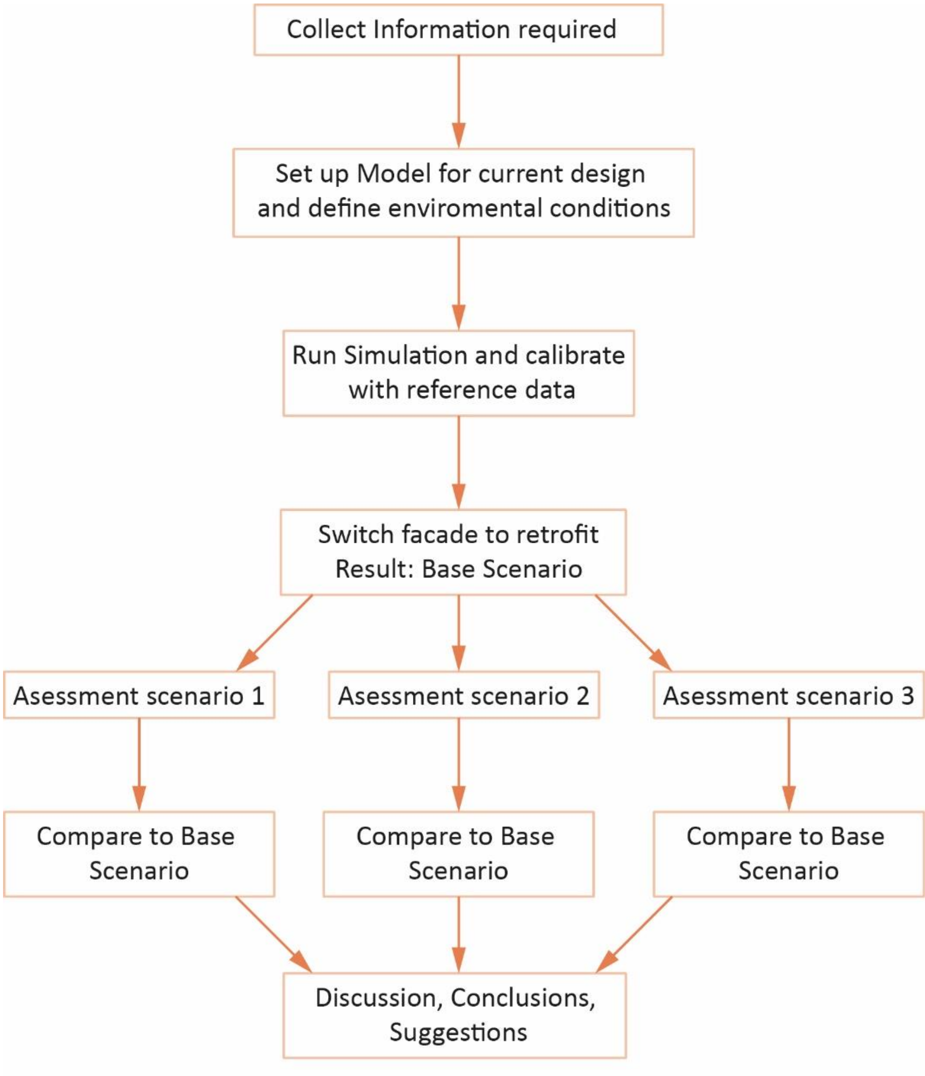


Figure 15: Research by Simulation Methodology. Source: Author´s Own.

Simulation stages: The simulation consists of multiple stages: First, a one-room model of a representative CiTG office space is set up, using dimensions and materials as built, before the retrofit. To validate the results, steady-state hand calculations are used. To explain which design days and according weather data was chosen, the second stage is best described first. It should be mentioned, that average daily temperatures were input into both simulation and hand-calculations for this first stage.

Stage 2: In the second stage, the model is tuned and calibrated to match the real measurement data from the indoor environment of the CiTG building. The Delft-based company OfficeVitae offered to share data from any day during the approximately one-year period of ongoing measurements, including temperature, CO2, humidity and lighting. First, the annual report was used to find a representative office, that did not show any extreme values in positive or negative direction and seemed to be occupied in an average pattern. The east-facing office number 20 of the 3rd floor was chosen. To receive indoor measurement data of this office, three days were chosen beforehand (to minimize the otherwise overwhelmingly large amount of data): A hot summer´s day, a medium day, and a cold winter´s day. The months of September 2018, October 2018 and January 2019 were selected. Because OfficeVitae applied their devices mid-September of 2018, that was the hottest month for which data was available. Specific days were selected by searching for an average representation of the entire month: 27. Sep. 2018, 18. Oct. 2018 and 28. Jan 2019. A daily average of weather data for these days was input into stage 1 of the simulation, while real, non-constant values were used for stage 2. Weather data was gathered from the Dutch meteorology institute KNMI (www.knmi.nl).

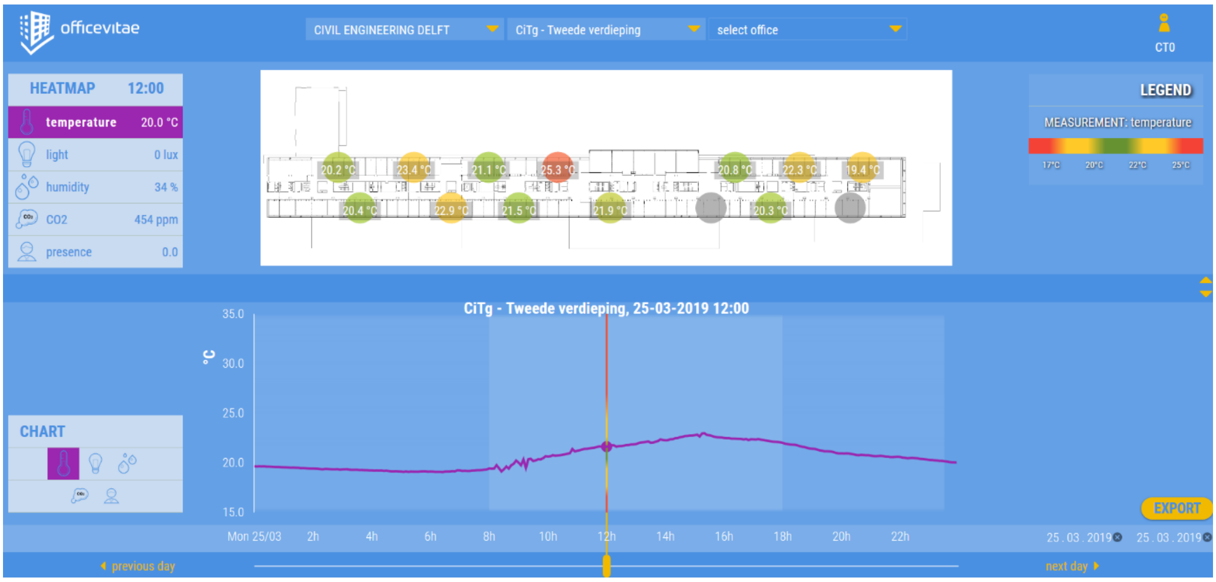


Figure 16: OfficeVitae website, IEQ measurement of CiTG. Source: https://app.officevitae.com

For approximate occupancy schedules of the office, the indoor measurement data was analysed, using CO2 and temperature levels to assess presence and calculate the ventilation rate. These assumptions were later tweaked to match simulation results to real indoor measurement data.

Stage 3: In stage 3, the façade is "retrofitted" by changing its characteristics in the model. Results of indoor temperature are noted. This is the base-scenario is supposed to represent the performance that designers and suppliers might assume when setting up a performance-guarantee PSS contract. Next, multiple alternative scenarios are simulated, to show how the results can deviate. Most importantly, these results are then discussed, to form conclusions about the supplier's risk, along with the twofold consumer risk (user and building owner).

Input data

A one-room model with inner dimensions of 6,5m x 3,6m and a height of 4,1m and an additional block forming a suspended ceiling space, is drawn from two horizontally stacked blocks. It represents a typical office, located on the second floor, in between other similar offices, along the east façade. The adjacency to the surrounding offices (north, south, above and below) was represented by “mirroring” the thermal behaviour of the main room, by using adiabatic settings. The adjacency to the corridor was also simplified as adiabatic, because it is well heated. Naturally the focus lies on the exterior wall, as it includes the façade panels, where the heat transfer between inside and outside occurs. The following chart shows characteristics of room dimensions and U-values of the existing façade.

Properties (before retrofit)	Value	Units
room width	3,6	m
room depth	6,5	m
room height	4,1	m
floor area	23,4	m²
heat loss area	14,8	m²
facade area	14,8	m²
volume	95,9	m³
U concrete	2,8	[W/m²K]
U glass	5,8	[W/m²K]
U window	5,8	[W/m²K]
U spandrel	2,7	[W/m²K]
U facade (c+w+s)	4,5	[W/m²K]

It should be mentioned, that triple glazing was assumed for the simulation, contrary to the double-glazing solution used in design related discussions in chapter 4. The design of the CiTG east façade retrofit was not yet finalized when the research of this thesis started. Initially, triple-glazing was still under discussion, and was therefore used as an input in this chapter´s simulations. Later, it was decided that a double-glazing variation was to be chosen, which I then adopted for the final stages of the thesis. This was not found to be problematic for the outcome of this thesis, as the performance related simulation and design related detail drawings are not interdependent.

The images show visualizations of the design builder one-room model.

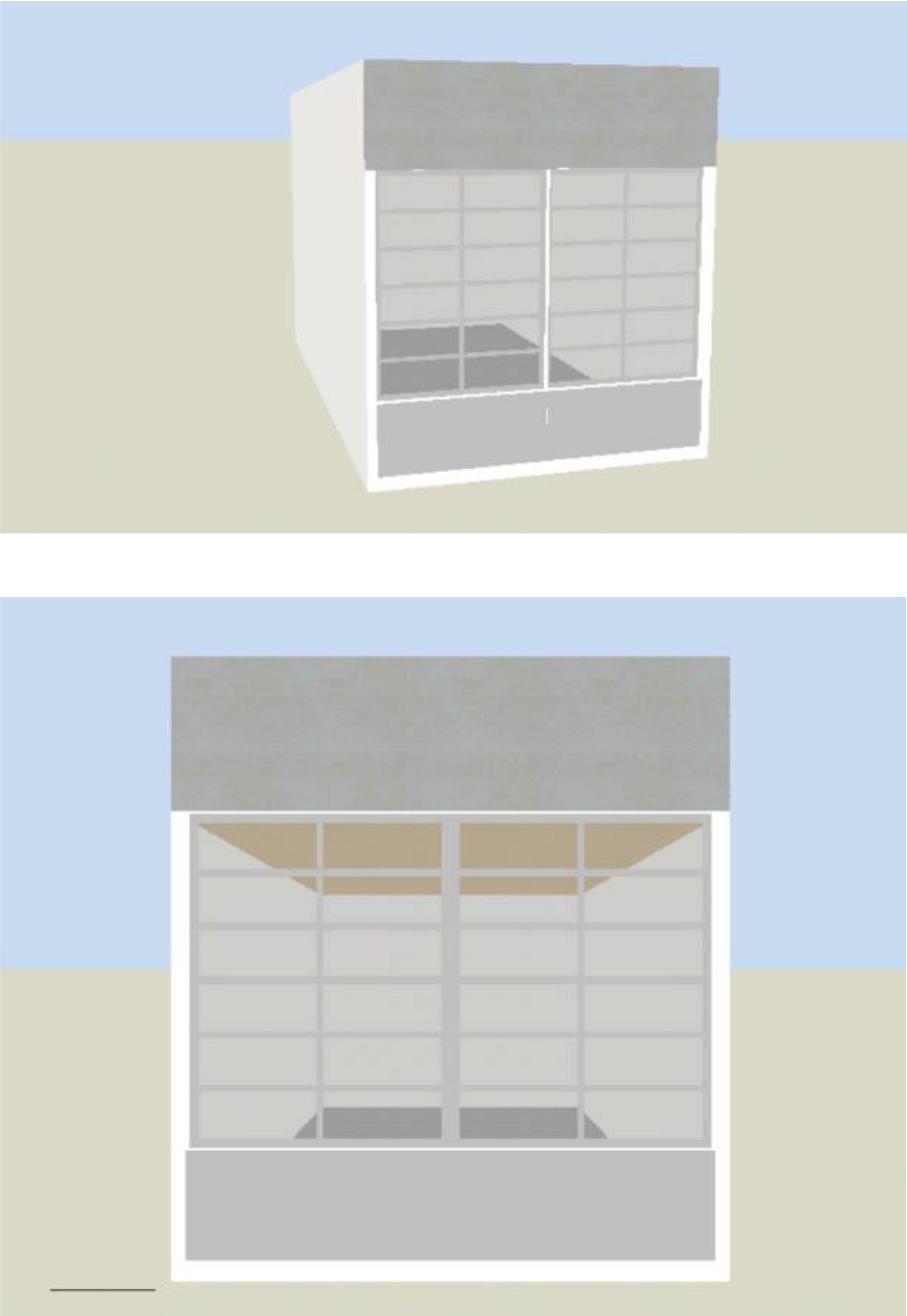


Figure 17: Design builder visualization. Source: Design builder; Author´s own.

The existing ring beam was modelled as a concrete wall with a thickness of 57cm (which does not include the additional outer prefab element), so that the façade could then be added as an opening.

The frame, glazing and spandrel area were approximated: The surface areas of different materials were simplified in geometry. The actual position of elements, or type of frame (fixed/operable) were disregarded, to produce a simple replica of total surface area per material (frame≈1,1m²; spandrel≈1,1m²; glass≈3,3m²). The figure below shows the layout of the built construction (left) and the model (right).

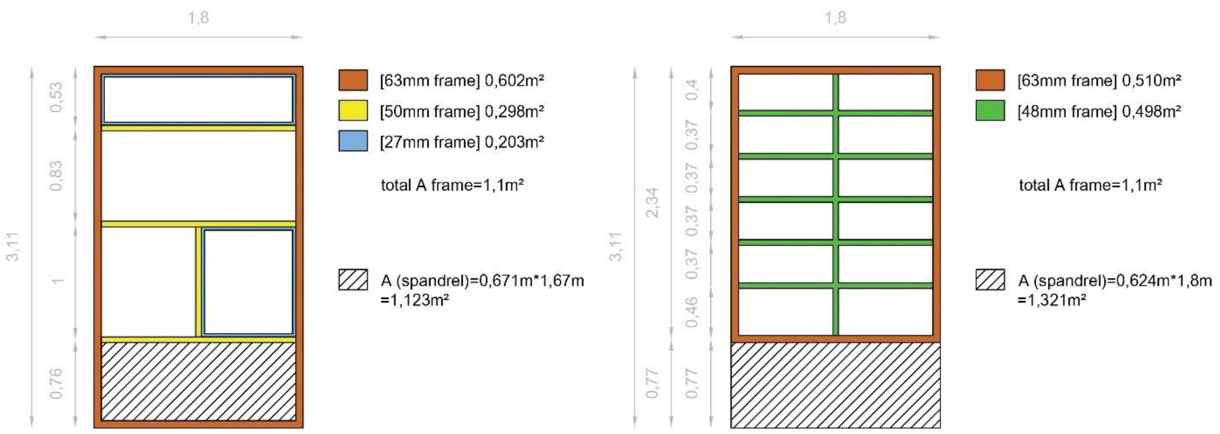


Figure 18: East Facade Panel: Approximation of Surface Areas. Source: Author´ s Own

Thermal bridges: Special attention was paid to the construction of not only the façade, but the remaining building components interacting with the outside air. Although design builder automatically takes the individual thermal properties of surfaces into account, the effect of thermal bridging needs to be input manually, using Psi Values derived from a *Therm* FEM model. The linear thermal bridging coefficients for lintels and sills of windows can thus approximate the effect of the isotherms along non-insulated concrete elements and façade panels.

Linear thermal bridge coefficients have less of an influence in the thermal calculations of an underperforming façade (before the retrofit). However, when a retrofit is performed, the effects are relatively high, because weak points between the existing structure and the updated façade panels become apparent. For a PSS scenario, the supplier is confronted with new aspects of their products, namely the combined effect of façade and existing building. When a performance guarantee is planned, the influence of large thermal bridges must be considered to achieve more exact predictions. ^

Psi Value (from Psi-Therm 2D)	PSI [W/mK] pre-retrofit	PSI [W/mK] post-retrofit
Lintel above window	-0,02	0,32
Sill below spandrel	0,30	0,32

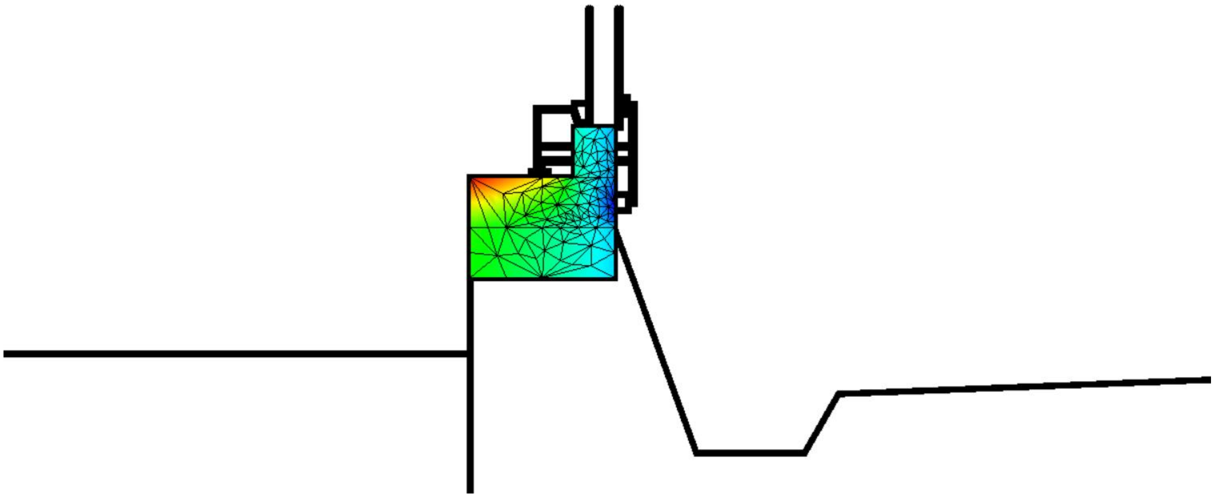


Figure 19: 2D PSI Therm model of thermal effect of lower spandrel connection.

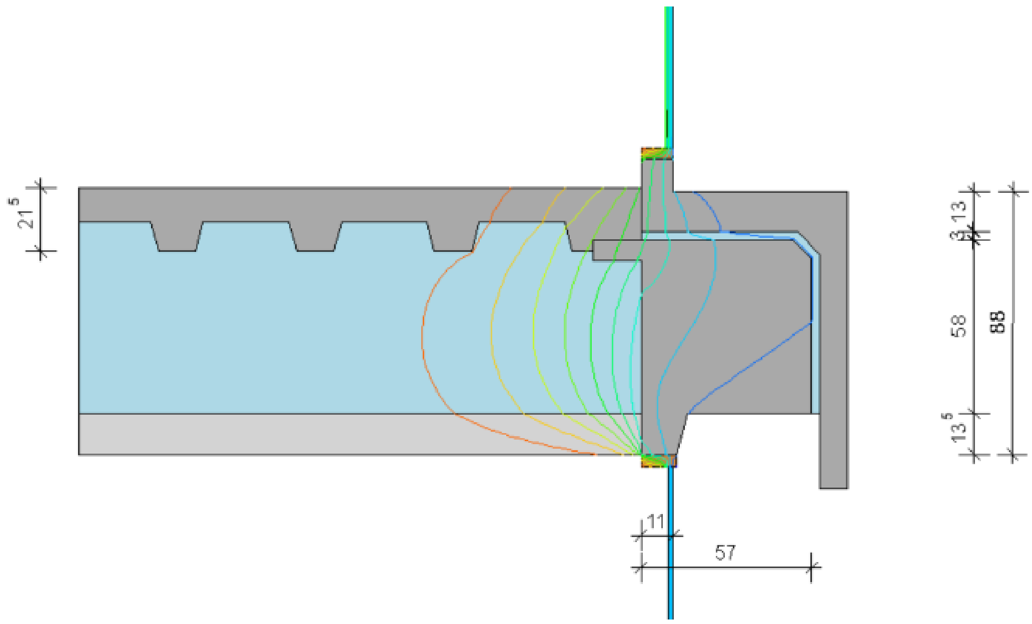


Figure 20: Larger overview of the effect of thermal bridging,

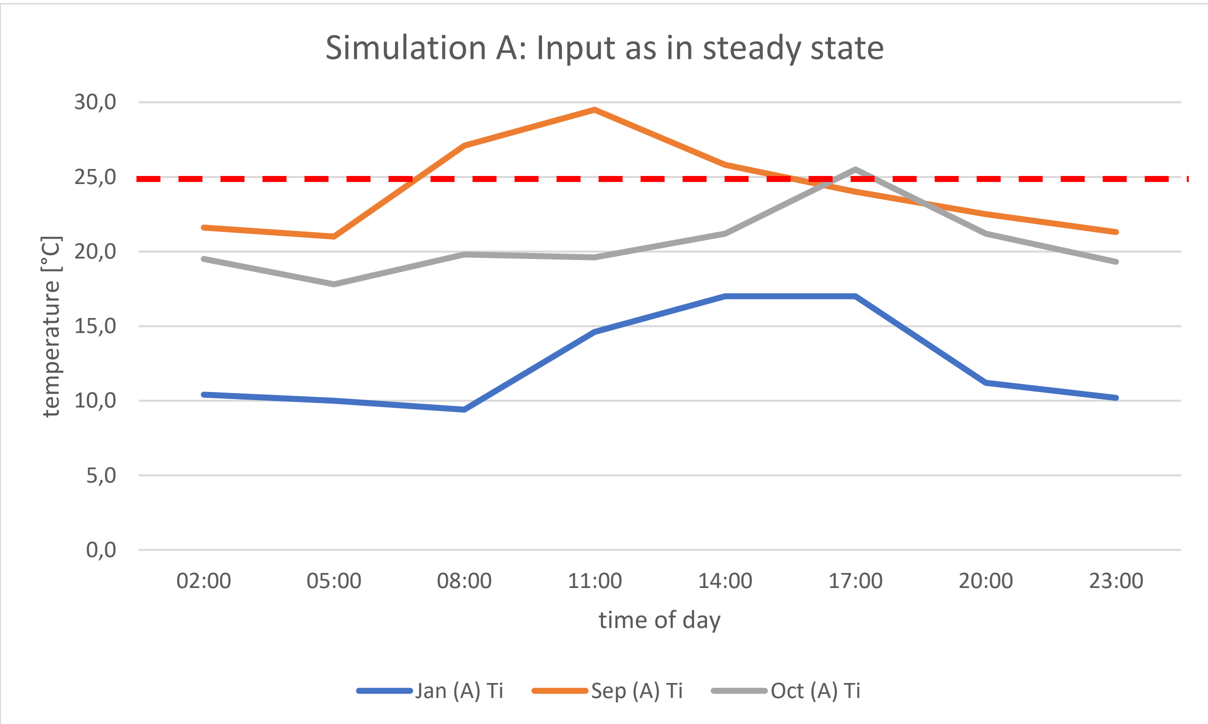
originating from the connection to the large, non-insulated concrete ring-beam.

Validation

Simulation results were compared, and successfully validated using a steady state heat balance equation (found in the appendix). The daily average of indoor temperatures matched hand calculations quite closely.

General note for tables and graphs: For a better comparison of results, a critical maximum temperature of 25 degrees is marked, so that the level of critical overheating in summer can be easily identified and compared with other scenarios.

A	time	Jan (A)	Sep (A)	Oct (A)
		Ti	Ti	Ti
	02:00	10,4	21,6	19,5
	05:00	10,0	21,0	17,8
	08:00	9,4	27,1	19,8
	11:00	14,6	29,5	19,6
	14:00	17,0	25,8	21,2
	17:00	17,0	24,0	25,5
	20:00	11,2	22,5	21,2
	23:00	10,2	21,3	19,3
	Average	12,5	24,1	20,5
A	Before tuning: values as in hand calculation; no shading; no HVAC. Ac/h=0,7; Qint=30W/m²			



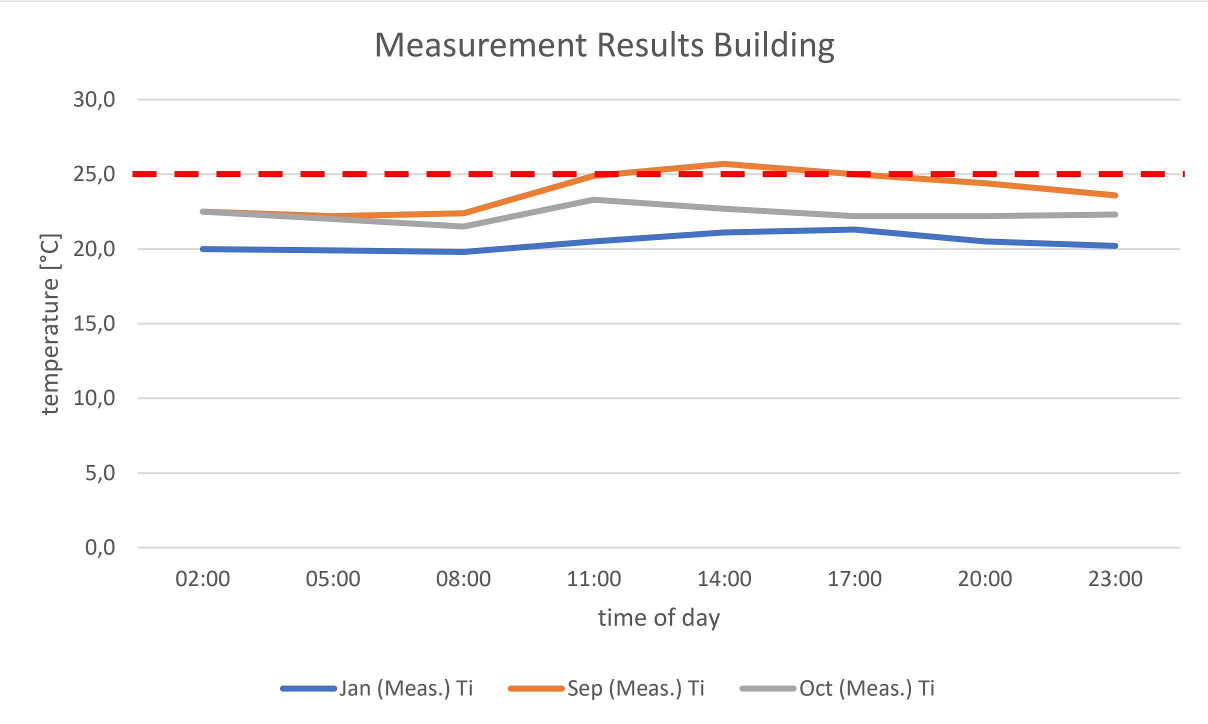
Tuning and comparison to real measurement data of the CiTG

After the model was validated by comparison to steady-state hand-calculations, the results (referred to as “Simulation Results C”) were compared to real measurement result of the pre-retrofit CiTG office. The target values were the daily averages of the real measurements. The hourly values were used to adjust the ventilation, occupancy and shading schedules, for tuning purposes.

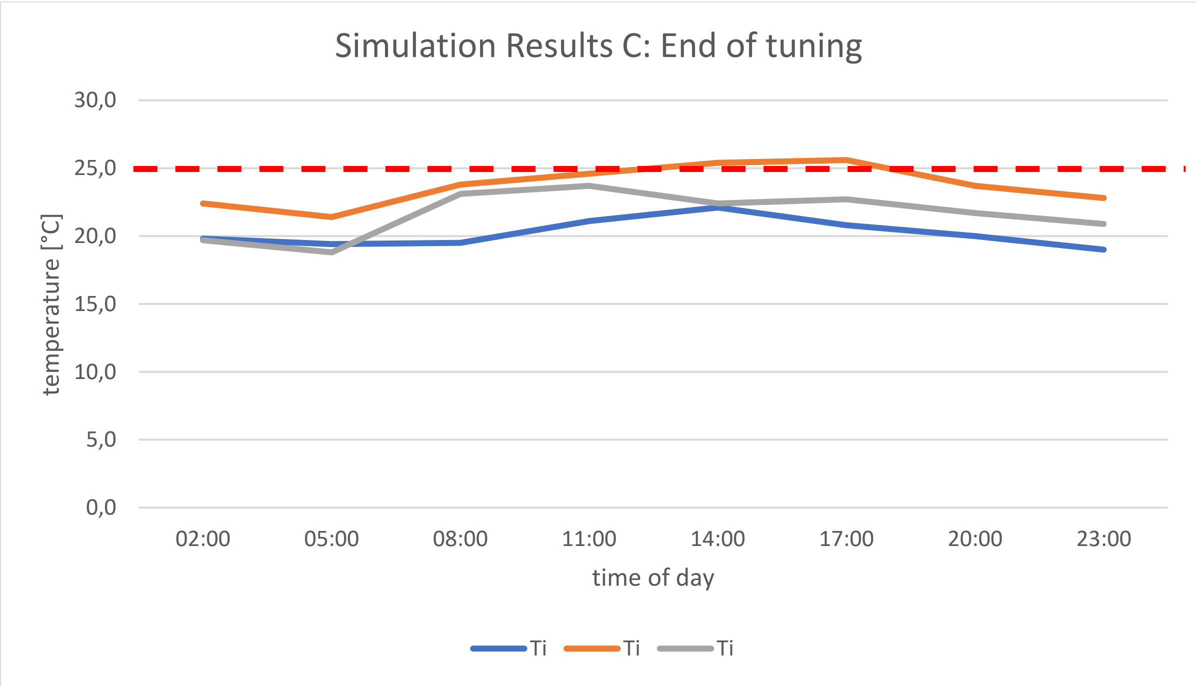
Tuning input: This was done in two steps: First, shading was added (positioned inside and a schedule was set), and a ventilation rate of 0,35 was assumed by analysis of the measurement data (comparing CO_2, lighting and temperature). The internal heat loads were defined as a standard value for the office size, of Q=30W/m².

Simulation results C were then achieved by changing the shading schedule (using temperature and lighting of measurement results as reference for tuning) and the ventilation schedule was rid of night cooling, while the rate was set higher during occupied hours. These changes provided a close enough match of simulation and measurement results, in order to progress further. The following charts and graphs show both data sets for comparison.

Meas.	time	Jan (Meas.)	Sep (Meas.)	Oct (Meas.)
		Ti	Ti	Ti
	02:00	20,0	22,5	22,5
	05:00	19,9	22,2	22,0
	08:00	19,8	22,4	21,5
	11:00	20,5	24,9	23,3
	14:00	21,1	25,7	22,7
	17:00	21,3	25,0	22,2
	20:00	20,5	24,4	22,2
	23:00	20,2	23,6	22,3
	Average	20,4	23,8	22,3
Meas.	These are the measurement results of indoor temperature, taken in the existing office, pre-retrofit.			



C	time	Jan (C)	Sep (C)	Oct (C)
		Ti	Ti	Ti
	02:00	19,8	22,4	19,7
	05:00	19,4	21,4	18,8
	08:00	19,5	23,8	23,1
	11:00	21,1	24,6	23,7
	14:00	22,1	25,4	22,4
	17:00	20,8	25,6	22,7
	20:00	20,0	23,7	21,7
	23:00	19,0	22,8	20,9
	Average	20,2	23,7	21,6
C	Weather data changed to real hourly values. Shading scheduled, No HVAC, changed ventilation schedule: No night cooling, higher rate during occupied hours.			



Modification of model: The retrofit. Inputs and changes

The retrofit was simulated by inputting new components for the glazing and profiles. A more effective shading system was added, and natural ventilation schedules as well as the heating schedule and setpoints were updated.

Properties (after retrofit)		
U glass	1,6	[W/m²K]
U window	1,4	[W/m²K]
U spandrel	1,3	[W/m²K]
U facade (c+w+s)	1,5	[W/m²K]

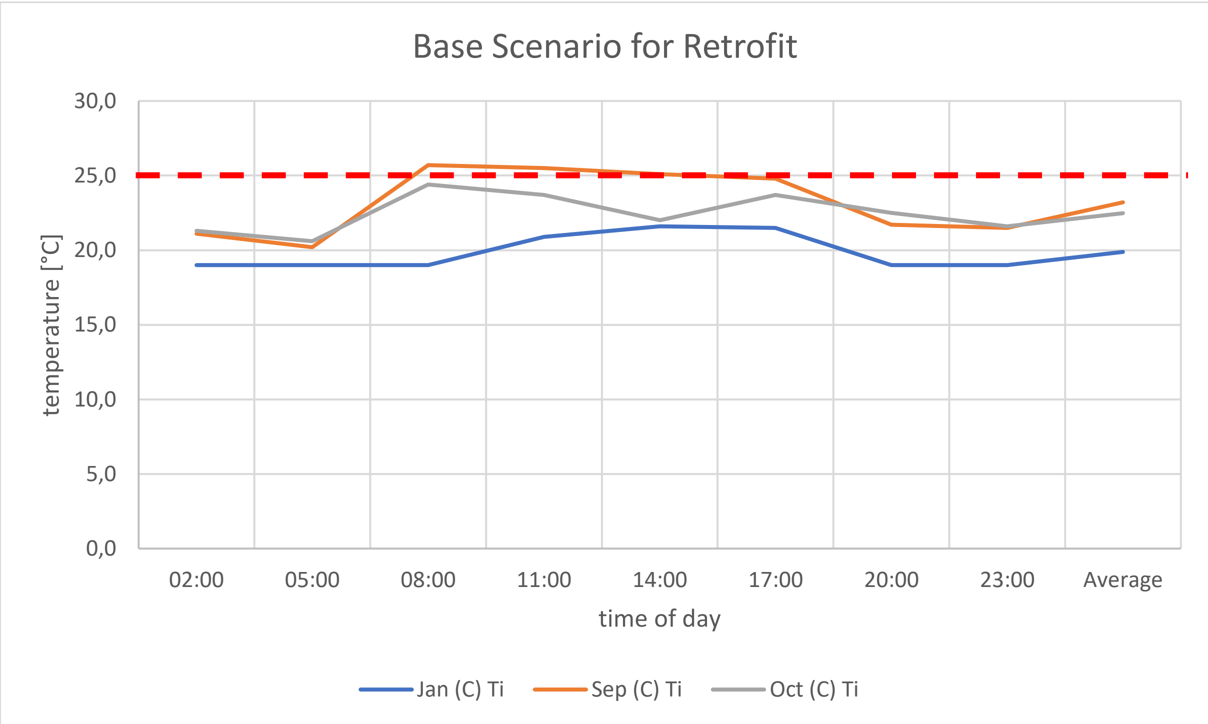
Base results of retrofit

The following simulation results were used as the base scenario of the retrofit. It represents a scenario that stakeholders would use for reference as a possible outcome of indoor comfort, to partially assess façade performance. The winter-case was not fully assessed, because the space is heated, and therefore results will stay in a somewhat steady range, related to the chosen setback, even when parameters are changed. A simulation for the heating demand of the space must be compared side-by-side, to see the effects of changing factors during wintertime. This again shows the fact, that HVAC systems and their use of energy are defining in a way, that no reliable assumptions about the façade during winter months can be made, if the schedule and effectivity of the heating system are uncertain.

The summer scenarios however show results that are unaffected by mechanical air conditioning, because there are no cooling systems in the CiTG. Hence, the months of September and October were the focus when comparing alternative scenarios. The results in the base scenario show, that overheating is already an issue during summer months.

During the time I did my research and simulations, the design decisions for the upcoming retrofit of the CiTG were changed by the design team: A double-glazing solution was chosen over the triple-glazing that was input into the simulation model. A higher U-value would mean, that more heat can escape during the summer situation, while more heat is lost in winter. For the triple-glazing solution, an even higher amount of night-cooling (larger openings or cross-ventilation through the corridor and opposite sided rooms) might have been a solution to lower the indoor temperature during summer months. For the purpose of this thesis however, the base result is not optimized further, because only the deviation from the base results are essential to determine.

Base	time	Jan (C)	Sep (C)	Oct (C)
		Ti	Ti	Ti
	02:00	19,0	21,1	21,3
	05:00	19,0	20,2	20,6
	08:00	19,0	25,7	24,4
	11:00	20,9	25,5	23,7
	14:00	21,6	25,1	22,0
	17:00	21,5	24,8	23,7
	20:00	19,0	21,7	22,5
	23:00	19,0	21,5	21,6
	Average	19,9	23,2	22,5
Base	BASE SCENARIO RETROFIT: Input of retrofit characteristics as mentioned. Ventilation schedule adjusted for September: Natural night ventilation added.			



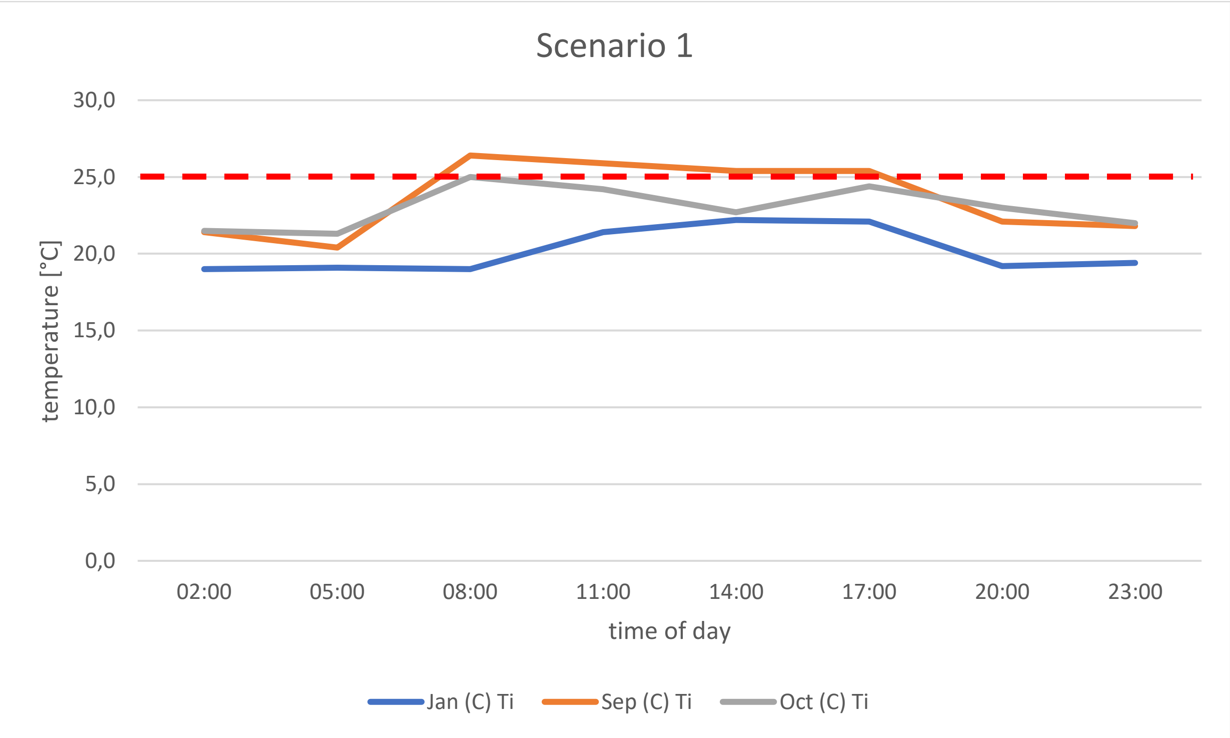
Alternative Scenarios: Inputs and considerations

For the façade supplier to provide a performance guarantee, the risk of different alternative scenarios needs to be assessed. That way, the necessary technical and managerial aspects can be planned, in order to produce a high performance façade. The knowledge about unexpected deviations can be informative during the design phase of hardware and software components. Additionally, it can be used to optimize the operational phase. For the following scenarios, one parameter was changed at a time. Each scenario shows the effect of a single changed factor, namely: Occupancy (S1), internal heat loads (S2), ventilation (S3) and shading (S4).

Discussion of simulation results

Scenario 1

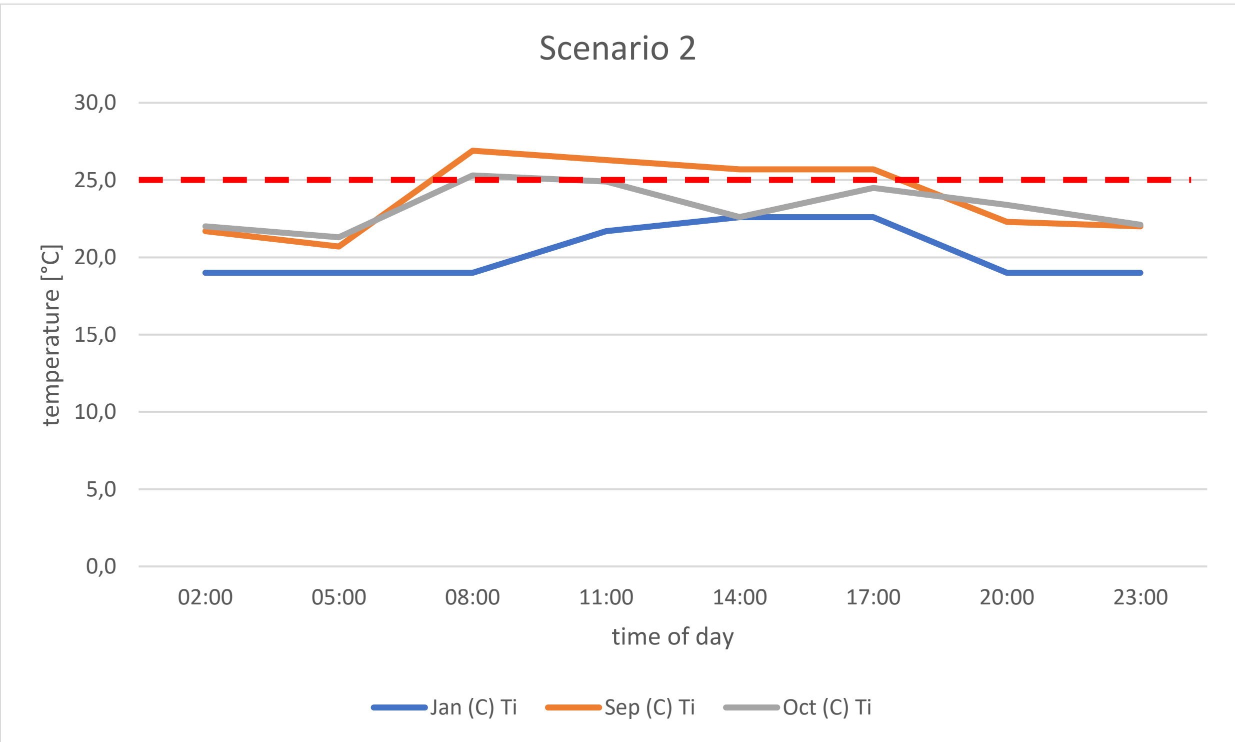
S 1	time	Jan (C)	Sep (C)	Oct (C)
		Ti	Ti	Ti
	02:00	19,0	21,4	21,5
	05:00	19,1	20,4	21,3
	08:00	19,0	26,4	25,0
	11:00	21,4	25,9	24,2
	14:00	22,2	25,4	22,7
	17:00	22,1	25,4	24,4
	20:00	19,2	22,1	23,0
	23:00	19,4	21,8	22,0
	Average	20,2	23,6	23,0
S 1	SCENARIO 1: **Occupancy** changed: 3 occupants instead of 2. No additional Office equipment.			



With higher occupancy, the indoor summer temperatures rise only slightly. Even though temperatures do not dramatically exceed the range of comfort, the scenario might be falsely understood when only looking at temperature values. It is very likely, that CO2 and humidity levels become higher than planned, which would result in some sort of occupants reaction (opening a door to the hallway, in order to cross-ventilate, which forms in different conditions than planned, and might even result in acoustical problems, not detected in simulation or by measurement equipment). Although these are just assumptions, such considerations can be researched by questioning occupants about their experience, to prevent a high consumer risk of the supply strategy.

Scenario 2

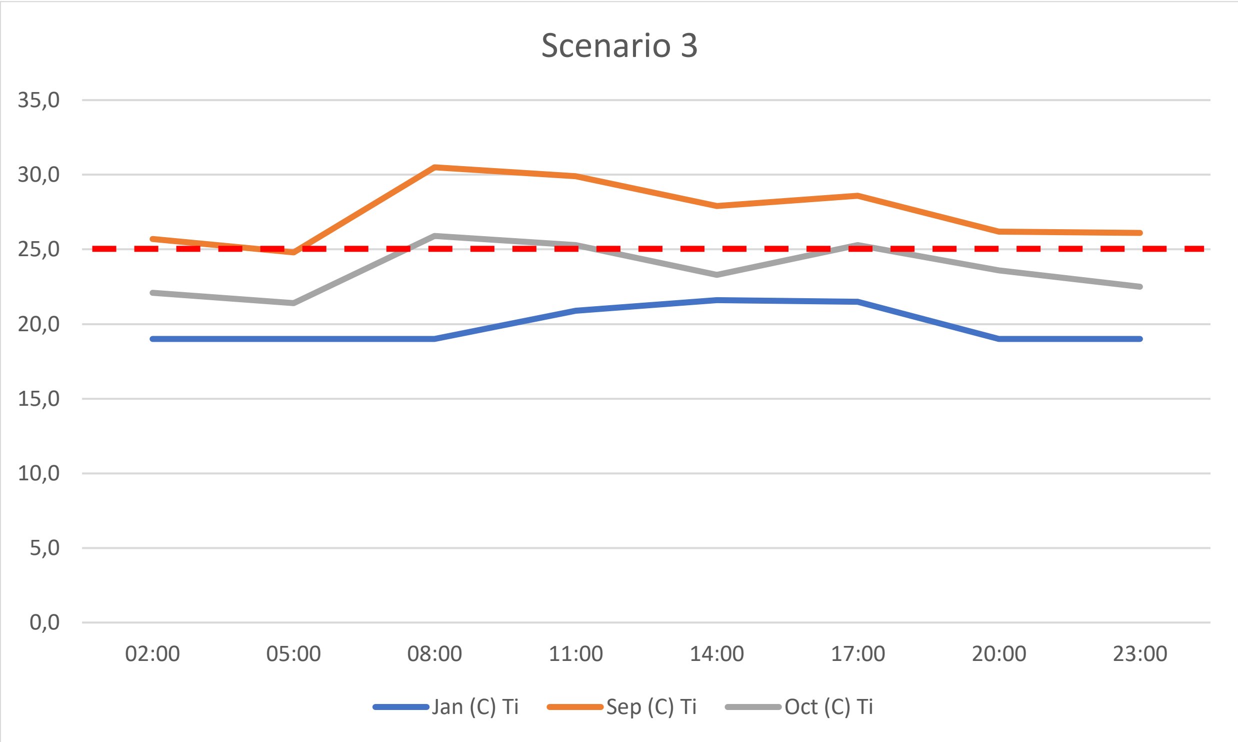
S 2	time	Jan (C)	Sep (C)	Oct (C)
		Ti	Ti	Ti
	02:00	19,0	21,7	22,0
	05:00	19,0	20,7	21,3
	08:00	19,0	26,9	25,3
	11:00	21,7	26,3	24,9
	14:00	22,6	25,7	22,6
	17:00	22,6	25,7	24,5
	20:00	19,0	22,3	23,4
	23:00	19,0	22,0	22,1
	Average	20,2	23,9	23,3
S 2	SCENARIO 2: **Heat load** by office equipment increased, from 20W/m², to 30W/m².			



A difference between assumed and actual internal heat loads can result in overly high temperatures in summer or lower temperatures in winter. In this case, the summer temperatures are increased. This could be a result of old, inefficient PCs or appliances of a small pantry. Additional heat loads may be unknown in the design phase, or while setting initial shading and ventilation schedules. In this building, this effect can be counteracted. However, the required quantity of shading and ventilation must be enabled in the design, so that these options are available.

Scenario 3

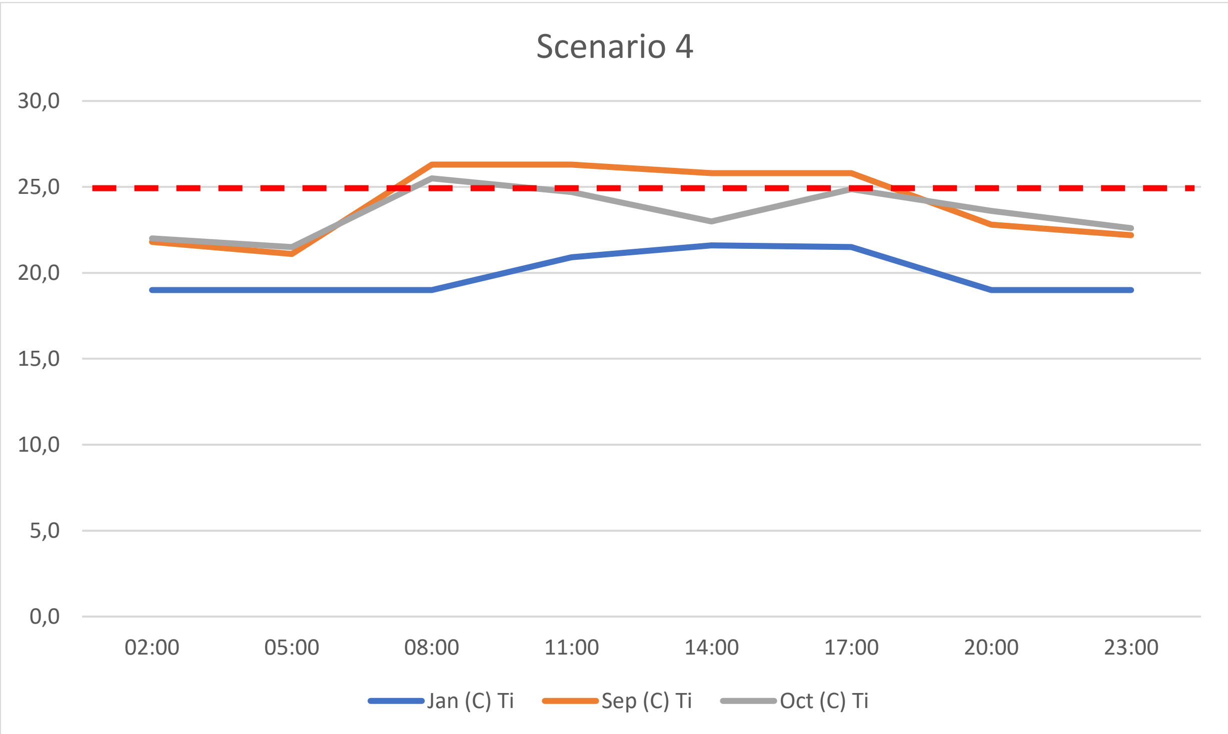
S 3	time	Jan (C)	Sep (C)	Oct (C)
		Ti	Ti	Ti
	02:00	19,0	25,7	22,1
	05:00	19,0	24,8	21,4
	08:00	19,0	**30,5**	25,9
	11:00	20,9	**29,9**	25,3
	14:00	21,6	**27,9**	23,3
	17:00	21,5	**28,6**	25,3
	20:00	19,0	26,2	23,6
	23:00	19,0	26,1	22,5
	Average	19,9	27,5	23,7
S 3	SCENARIO 3: **Ventilation** schedule changed: Only ventilated from around noon to the end of working day.			



This might be the case when an optimal ventilation schedule is disregarded. Occupants may arrive later during the day or use ventilation openings when the indoor temperature is already high. When using night cooling to decrease the overheating hours in a space, the thermal mass (as the concrete ceiling here) can be used in an optimal way. The ventilation during night hours is missing in this scenario, so the thermal mass potential of the existing concrete structure is not used.

Scenario 4

S 4	time	Jan (C)	Sep (C)	Oct (C)
		Ti	Ti	Ti
	02:00	19,0	21,8	22,0
	05:00	19,0	21,1	21,5
	08:00	19,0	26,3	25,5
	11:00	20,9	26,3	24,7
	14:00	21,6	25,8	23,0
	17:00	21,5	25,8	24,9
	20:00	19,0	22,8	23,6
	23:00	19,0	22,2	22,6
	Average	19,9	24,0	23,5
S 4	SCENARIO 4: **Shading** schedule is changed. A situation is simulated, where shading is applied too late in the day.			



Here, the use of shading is scheduled in a different way: It is only applied from 9:00-16:00, instead of starting earlier in the morning. (Note: No shading was applied in January in any simulation). These few additional hours of morning sun can have a negative effect on the indoor temperature. When shading is not scheduled efficiently in the hottest months of the year, indoor comfort levels which were previously already on the upper limit of the range, now exceed it.

Conclusions of chapter 3

RQ3: Which critical factors present an issue in guaranteeing a certain range of energy performance and indoor comfort of the CiTG east façade?

In this thesis, the performance indicator of the indoor temperature was chosen to quantify indoor comfort in a very simplified way. The following three factors were seen critical in guaranteeing the IEQ and energy performance of the CiTG east façade:

From the simulation, it was apparent that it was important to control ventilation and shading correctly.

- **Ventilation:** The ventilation rate and schedule have a very defining effect on the indoor temperature of the simulated CiTG office. The building has a concrete structure and therefore a high thermal mass. In scenario 3 the room was only ventilated during later working hours of the day, but not during night-time. The effect of night-cooling could not be used to cool the concrete or delay the rise temperature during the day. Generally, ventilation can be considered an important factor for most buildings. The air change rate of natural ventilation is also affected by changing wind speeds, which can hardly be predetermined. The openings used for natural ventilation also form a unique dynamic in an otherwise thermally and acoustically closed envelope.

- **Shading:** The ineffective use of shading systems is not an unlikely situation. For the CiTG building, a simulation was made considering no shading during the morning hours before nine o´clock. The effect was not dramatic and is comparable to the effect of some added heat loads of appliances. However, this scenario is only a mild misuse of the system, and still temperatures exceeded comfort levels. It can be derived from scenario 4, that worse cases are possible, especially for south-facing facades (in comparison to the east/north-east facing CiTG façade).

The factors of user behaviour and occupancy of spaces were assessed to be less influential on the indoor temperature of the CiTG. It should however be considered for all simulated scenarios, that only one factor was altered at a time. In reality, multiple factors could form a combined critical scenario. Additionally, it was concluded that mechanical climatization, while not included in the simulation, would play a large role in balancing the IEQ and energy consumption. This is especially influential for the winter months in Delft.

- **The HVAC systems of a building:** Mechanical heating, cooling and ventilation largely alters the performance indicators of a room, such as indoor temperature, CO_2 and humidity levels. They are used to improve the indoor comfort, but by doing so, the real façade performance cannot be assessed. The problem is that the environment is controlled actively by consuming an unknown amount of energy. Even though most facades in northern European countries will need mechanical heating during the winter months, an efficient use in combination with a high-performance façade is required to reduce life-cycle costs and environmental impact. Guaranteeing a range of "façade performance" is not possible when such a large unknown impact is made by HVAC systems.

RQ4: What technical and managerial aspects can help the implementation of result-oriented PSS facades?

To help implement result-oriented PSS facades, where a performance guarantee is given, different technical and managerial solutions can be applied. It is important to narrow down the range of uncertainty about how well the outcome will match predictions. In doing so, the indoor comfort and energy performance are automatically optimized.

- **Keeping in touch:** A constant "dialogue" is needed, to understand the results in quantitative form (measurements) and user-feedback. User-communication is important to minimize consumer-risk. Knowing how well the built façade is serving its purpose is a step of resolving problems during the occupational phase. This includes the use of monitoring and measurement devices, and professional conversion of data to useful information.

- **Taking control**: The façade supplier in a result-oriented PSS should take control of dynamic façade elements, by automating passive ventilation and shading systems. The HVAC system should be controlled by the supplier- The best option would be to integrate them into the façade. Systems could be independently monitored, operated and maintained, managing an effective interrelation of active and passive systems.

- **Optimizing:** A leased PSS façade is a process- not a finished product. Therefore, the results need constant reviewing, the operation of the façade will need to be optimized. As mentioned in RQ3, some of the dynamic factors might not align with expectations. The design of the façade should be made to be flexible to change and therefore less prone to failure under different conditions of weather of usage. Design a "robust" leased façade, with the following characteristics, derived from Kurvers et al. (2013):

    - Enable user control
    - Choose passive systems over active systems
    - Minimize maintenance requirements
    - Split heating from ventilation systems

- **Collaborating:** Transitioning towards the supply of facades in a circular PSS is not a simple endeavour. It will need the combined knowledge of different professionals to be feasible and successful. Some crafts can be integrated into the façade supplier´s internal pool of staff, as mentioned in RQ2. Suppliers should additionally collaborate with experts and companies who focus on related topics of technical, architectural, economic and social fields. Reaching out for advice outside of the construction business might be beneficial, considering that PSS models have been implemented in other fields of work.

4. Designing facades as circular PSS

Redesigning facades for circular PSS

Designing facades for a circular product service system is an important topic of interest in this thesis. The scheme below, previously shown in chapter 2, includes "Design Consultancy" as an early point of demarcation, along the pathway to facades as PSS.

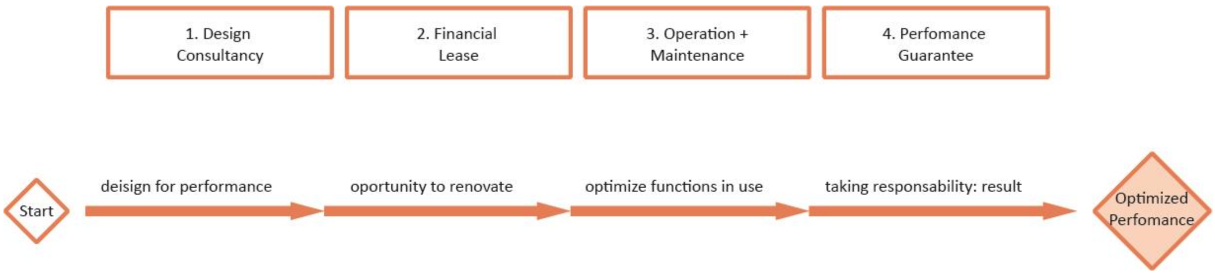


Figure 21: Points of Demarcation of producer responsibilities. Source: Author´s own.

The scheme is used to name consecutive points of demarcation, where "design consultancy" can either be an independent task, serving as the first way of adding value to the supplier´s offer, or as part of an add-on scheme including one or multiple of the progressive steps, leading to an overall optimized performance. The design considerations span a much wider range of tasks, which can be summarised as part of the following categories, subsequently in this chapter:

A - Design related to the operational phase
B - Design related to the assembly, disassembly and reassembly.

In part B, the question of reuse of facades on a component level is explored. The scope of research is limited to a component scale only, rather than looking at smaller divisions such as elements or building materials.

The CiTG case study project is used for reference in the research through design process, to discuss: How can we reuse the CiTG, as an exemplary study to get an idea of PSS facades in general? What would the most beneficial approach be? What are the barriers?

A- Design related to the operational phase

The façade designers of a product service system would be faced with questions beyond the scope of regular building projects. The operational phase becomes an added period of responsibility for the supplier when tasks such as façade operation, maintenance and even the guarantee of performance are integrated. In a product service system, the optimization of the façade in the design phase grants access to a well-functioning tool in all later stages.

In the previous chapter, different "tools and aspects" were already discussed, which could help optimize façade performance. The following three aspects are crucial to be considered during the design phase.

- Monitoring
- System integration
- Robustness

Firstly, Measurement devices must be applied in the spaces encased by the leased façade, to provide numerical feedback as performance indicators. This is an integral part of the producer-client relationship in the supply of facades as result-oriented PSS, where performance is guaranteed. Secondly, the task of monitoring the building is best automated, by applying different sensors to mechanical parts of the façade. This can give the supplier information about the current status of components, if they need maintenance, a different software setup, or must be replaced entirely. It helps to predict future maintenance requirement on an individual component level. A shading system for example could be assumed to have a service life of 10.000 cycles (shading rolled up/down) before it needs replacement. Applying this thought to a building with a large exterior surface area means that many service components can be compared to determine the best time to maintain in bulk.

Another consideration, discussed in literature, is the integration of functions such as heating, cooling and energy generation. Van Winden (2016) elaborates on the EWI pilot project, where multiple panels of different integrated functions are tested. Valdes Cano (2016) focuses on the use of building integrated PV systems in a leasing model, because it could promote energy generation on facades. As discussed previously, integrated building systems can help to implement the service of performance guarantee into the PSS model.

B- Design related to the assembly, disassembly and reassembly

Material loops and residual value

While the circular redesign of façade systems is needed to reach environmental goals of our future, there is an apparent gap between the available knowledge and the implementation of the practice. As mentioned before, a PSS scenario aligns environmental and economic interests of the involved parties. When suppliers retain ownership of their products, the implementation of circular practices are incentivised. A higher return on investment is possible, when a strategic effort is made to get the highest possible output from material input over a façade´s lifecycle.

Reducing material waste and value losses: This includes the beforementioned design for the operational phase, as well as the design for the assembly, disassembly and reassembly, implying multiple uses of products. Reusing products means extending their lifespan, therefore maximising the financial output as well as minimizing the environmental footprint and material waste.

A general guideline to reduce losses is to keep material loops as closed as possible. This means choosing to reuse over recycling. This principle introduces another correlation of financial and environmental sustainability: The higher the residual value of a façade and its parts after its initial use, the better. Making use of this remaining value shares the hierarchy of the "reduce-reuse-recycle" principle. The offer is more economical for the supplier and simultaneously reduces waste, when:

- The façade is designed to be efficient in material use, production process and performance once in use (general requirement of waste reduction),
- a product can be reapplied (most direct case of reuse),
- individual elements can be reintroduced in a different combination, e.g. shading motors applied in another project,
- building products can be resold (theoretically preferred over recycling),
- raw materials can at least be efficiently recovered to begin a new production cycle (recycling or if unavoidable: downcycling).

To reap the benefits of these different solutions, a holistic management of building products is needed. Efficient design is the first step towards reducing waste. In the field of façade design, most design choices are directly manifested in a measurable indoor comfort and energy use. Therefore, all decisions are to be made considering both the embodied energy and the building´s energy consumption throughout the time of use. Further, designing for disassembly increases the potential for reuse, and makes for a clean separation of recyclables at their final end-of-life. Additionally, material banks and passports are a promising way of recording material data, to provide their current and future owners with information about quantity, properties and quality. Tracking materials and their properties is one key to a continuous value chain. Building a new market for the reuse of materials helps realise and solidify their commercial retail value, consequently saving resources in form of raw materials, embodied energy and financial input.

Designing for a high residual value shares a direct overlap with the idea of circular facades. It can be argued, that the most direct reuse of a product would retain the highest possible value. It is favourable to minimize the requirement of additional material, energy and labour in between uses, as well as minimizing downcycling practices. An important consideration of façade leasing is the demounting and reuse of a product. **A reusable design would need to fulfil requirements of more than one building project. The product should be more widely relevant in the building market.** The figure below shows different levels of building products, which can be considered in reuse scenarios.

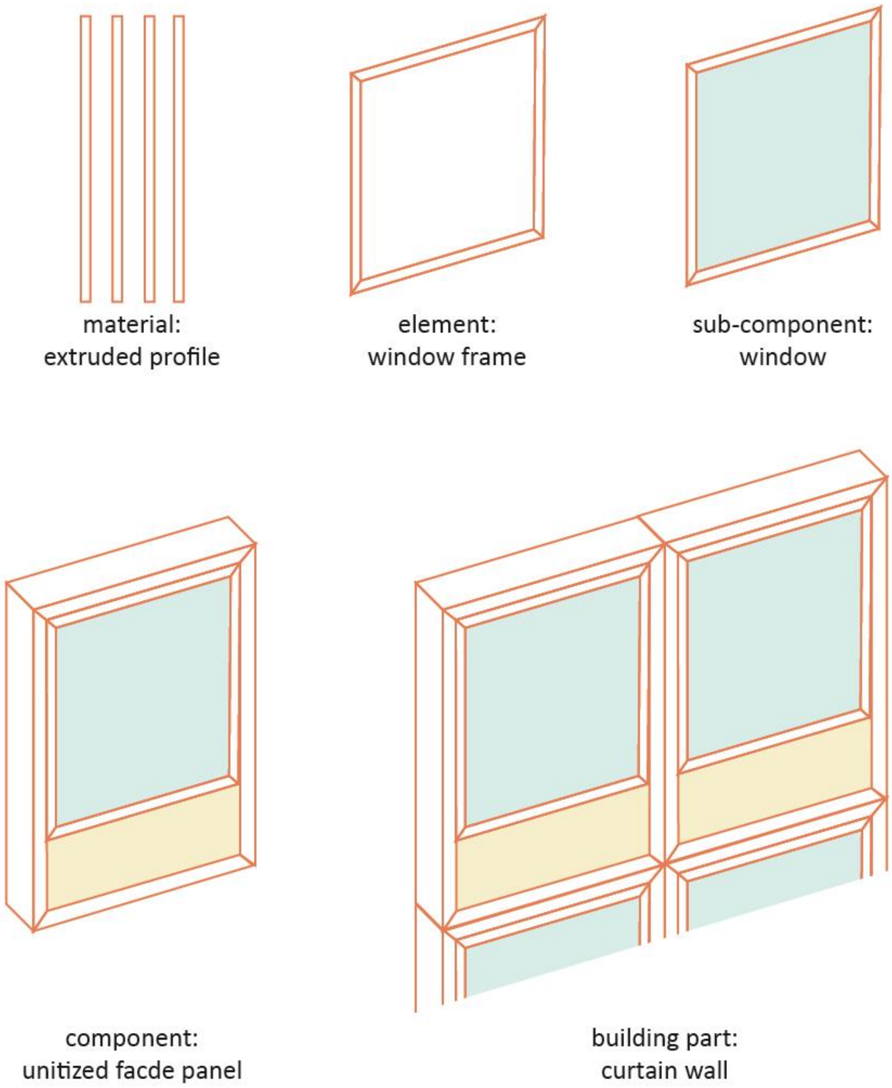


Figure 22: product levels for facades. Source: Author´s own, adapted from Klein (2013).

In this thesis, the idea of reusing entire façade components, as directly as possible, is explored. As mentioned previously, it is not an attempt to solve details of façade disassembly, or to cover all possible strategies of making a façade circular. **Rather, the relation between product service systems and the circular design of façades is addressed, in order to highlight opportunities and challenges for future designers and stakeholders.**

Reuse on component level

Why should we reuse PSS facades on a component level?

- It is the most direct form of reuse
- This type of reuse is made possible by a PSS. A long-term involvement of the supplier with the façade gives the opportunity of a more organized management of the façade components,

that is needed for this process. A holistic strategy of design, engineering and marketing is required.
- The investment into the design process and the labour costs of component building can achieve higher returns, when more than one use is made of the system as a whole. Otherwise, losses occur in premature disassembly of elements and materials.

The demounting of components and their direct reassembly on another building could be especially interesting for renovation projects of buildings with a limited remaining lifespan. A façade might be demounted in the foreseeable future, ahead of the facades end of life. The CiTG building could be an example.

The reason why the scope of this thesis was limited to the **reuse on component level** is that the strategy seems very specific to facades as PSS, and it was found to be only minimally discussed in literature. While reusable sub-components such as sun shading devices are already on the market and re-manufacturable insulated glass units are engineered in scientific research environments, the reuse of components is not yet being solved. Instead of detailed solutions of a single element, designed by the engineers of one producer company, the design of reusable façade components (e.g. an entire panel) requires taking a step back, and looking at the bigger picture. A façade supplier such as Alkondor Hengelo generally acts as the midpoint of a multitude of sub-suppliers, combining different products to something that is more complex than their sum. **In manufacturing a component, elements are converted from commercial products of competitive market value to a customized building unit. Usually, this unit holds value for the owner of one specific building only - where the façade is assembled and becomes obsolete after the first service period.** In current practice, the functional value of the façade components after the first use is not reflected in the market value, because the item is seemingly irrelevant for any potential clients. There are currently no façade owners offering used façade components, because no solution has been developed to implement the concept.

A product service system brings together multiple designers and engineers, forming an interdisciplinary setting. Both the required knowledge and a common incentive is given to explore whether a leased façade could be designed to be used multiple times on different buildings.

In a research through design approach, the following questions were explored: Can we reuse the panels of the CiTG east facade, as an exemplary study to get an idea of PSS facades in general? And what would the most beneficial approach be? What are the barriers?

The Typology of the CiTG façade

To clarify the comparisons made to the case study building, the main characteristics of the façade should be explained. The east façade of the CiTG is currently designed to be:

- Panelised in components of around 1,8x3,1 meter
- Inserted in between the concrete floor and the edge of the ring beam
- Covering four regular floors and one top storey
- Made from components with the following sub-components (bottom to top): spandrel parapet, double window with one fixed glazing and one operable part, one fixed glazing unit and one operable glazing for ventilation.

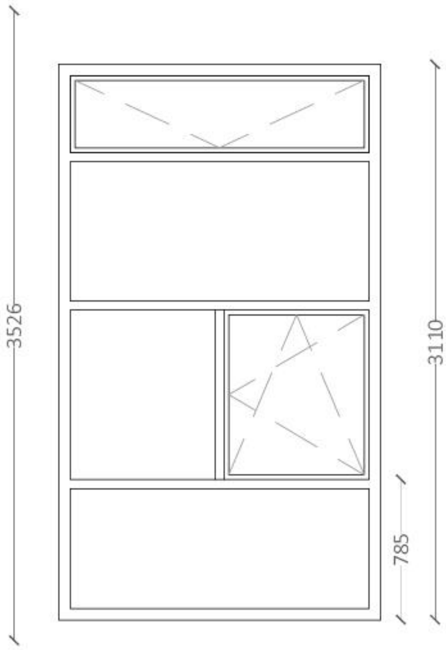


Figure 23: Elevation of the CiTG east facade retrofit panel. Source: Author´s own.

Figure 24: Pre-retrofit facade of the CiTG Delft. Source: Author´s own.

The CiTG building has a typology in vertical direction, which can be characterized as the panels being placed "outside structure" (Ebbert, 2010, p. 9), because the vertical elements of the load bearing structure of the building are located internally . The panels are integrated between the structural ring beams, and therefore confined in height dimensions. Sizes and location of the CiTG panels can be seen in the sketches below. In the CiTG, two panels of 1,80 x 1,80 are meet in a connection to an aluminium mullion.

Figure 25: CiTG Delft. Source: Author´s own.

The physical retrofit of the CiTG was a source of inspiration and information for the questions of this thesis. Designing circular facades entails a multitude of different sub-solutions on different scales. If façade components are made to be demountable, providing a flexible leasing tool, and materials are managed by their supplier throughout their lifecycle, the first step towards making a leased façade circular is taken. The façade supplier can make use of the entire possible service life of the façade, without being tied to the lifespan of the building. In a case such as the CiTG, the building needs a retrofit, but its remaining lifespan might be limited. The supplier could make use of another application of the material value, by demounting and remounting the façade onto other buildings, either in form of another retrofit, or even as a cost-reducing alternative for new projects.

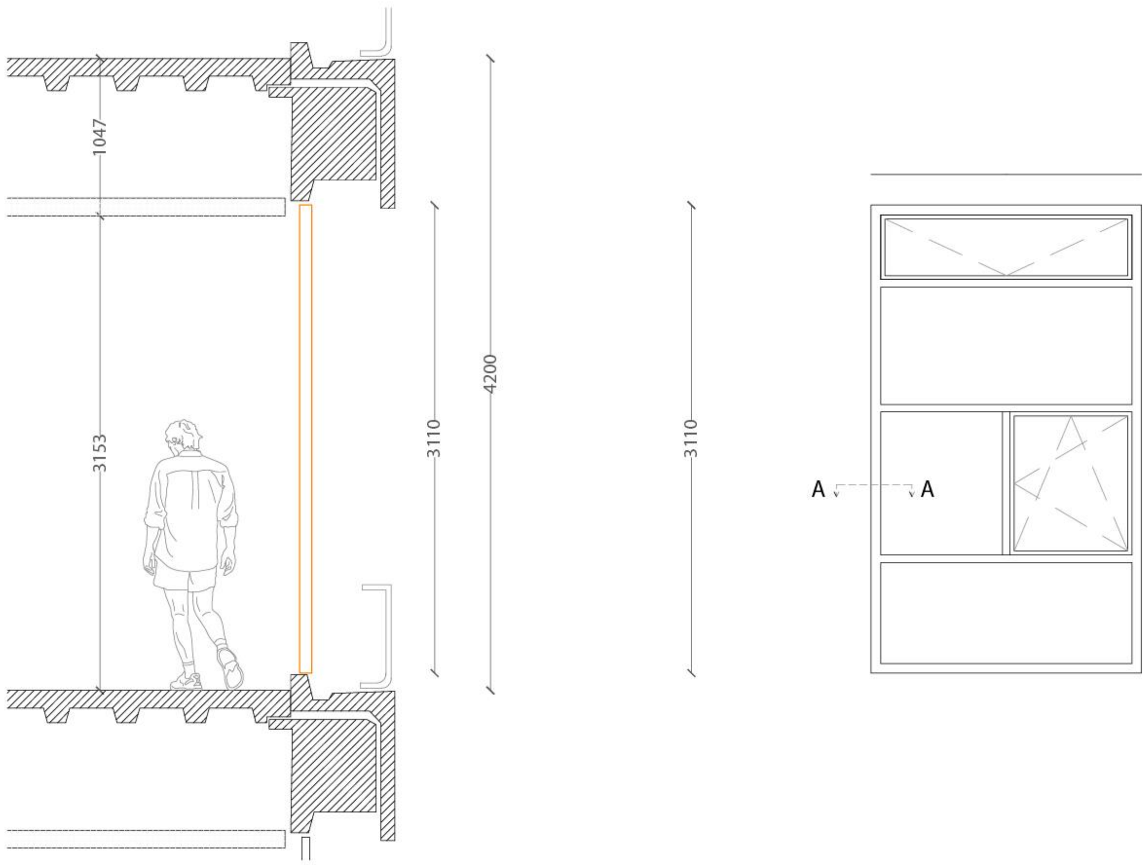


Figure 26: Section of CiTG and elevation of facade panel.

Source: Author´s own, derived from Alkondor Hengelo drawings and Ebbert 2010.

Method of design: Besides literature research, the design questions of this thesis were answered using a research through design method. Three steps were taken, to get an understanding of the reuse possibilities of the CiTG façade panels:

- Firstly, a rough overview was retrieved by reviewing various campus buildings for their similarity in typology to the CiTG facade, to see whether a suitable match was found to reapply the façade panels.
- Secondly, a more systematic approach was chosen, to find an existing building of the corresponding façade typology, by looking into Alkondor´s project portfolio. The *Hogekamp UT Enschede* was chosen for analysis.
- Lastly, a draft of an exemplary new building project was used, to explore the reuse of the CiTG façade on a standard office typology of today.

Reuse on TU Delft campus

A small field study was made on the campus of TU Delft. Impressions of faculty and education buildings were gathered, to study a representative group of buildings with similar function as the CiTG, in its surrounding area. They were assessed on their façade typology, according to the framework of Thiemo Ebbert (2010), and a general assumption was made, whether it would be possible to easily apply the leased façade panels which are to be used as part of the CiTG retrofit pilot project. The idea is, that the panels are given a second service-life purpose after the first 15-year leasing contract ends. In case the contract is not extended for the CiTG, panels might be mounted on another building that needs a retrofit. Only buildings with somewhat regular shape of the façade were looked at, to limit the search. This field study is of course only a small first assessment and is more relevant to the overall discussion in this thesis, than to find a perfect second application.

Reuse assessment: It was concluded from a quick look at these buildings surrounding the CiTG, that the reuse of the panels was not easily possible. Interestingly, the possibility of reuse was excluded because of a range of factors, quite evenly distributed amongst the buildings. Below, a summary table is given, of these reasons and the amount of buildings that they applied to. Two factors were more common than the others, which lead to the considerations:

- Are the CiTG panels too high, at 3,11m? It seems easier to add multiple smaller parts, than overcoming the challenge of a too large panel.
- Is the opaque spandrel that is part of the CiTG panel a barrier for the use on buildings with existing parapets? (The existing parapet should not be doubled up by the closed part of the CiTG panel, otherwise there cannot be any glazing on eye level of the users). This could be solved by making the infill parts flexible to changes, to make them opaque o transparent when needed.

Critical difference in typology	**Applies to X amount of buildings**
Position of façade to structure different (curtain)	2
Clearance of openings less high than CiTG	3
Clearance of openings higher than CiTG	2
Clearance of openings less wide than CiTG	2
Clearance of openings wider than CiTG	2
Column obstructing clear opening width	2
Existing fixed parapet	4

Faculty of Technology, Policy and Management

Faculty of Industrial Engineering

Faculty of Mechanical, Maritime and Materials Engineering

Applied Sciences

Dreamhall

Education Building 35

Faculty of Mathematics and Computer Science

Bouwcampus

Reactor Institute

Faculty of Applied Sciences (Van der Maasweg 9)

Faculty of Aerospace Engineering

Reuse on an existing building with similar typology: The Hogekamp UT Enschede

Figure 27: Hogekamp UT Enschede. Source: www.alkondor.nl

After touring the campus and getting a first look at reuse possibilities, it became clear that the search would have to be made more systematically. To broaden the radius and receive an experienced overview of which buildings might prove to be a good match, Alkondor Hengelo was consulted for advice. In the company's project portfolio, a building with a seemingly similar typology was found and chosen for analysis: The Hogekamp UT in Enschede. The building shares a distinct similarity of a ring beam and prominent concrete service platform.

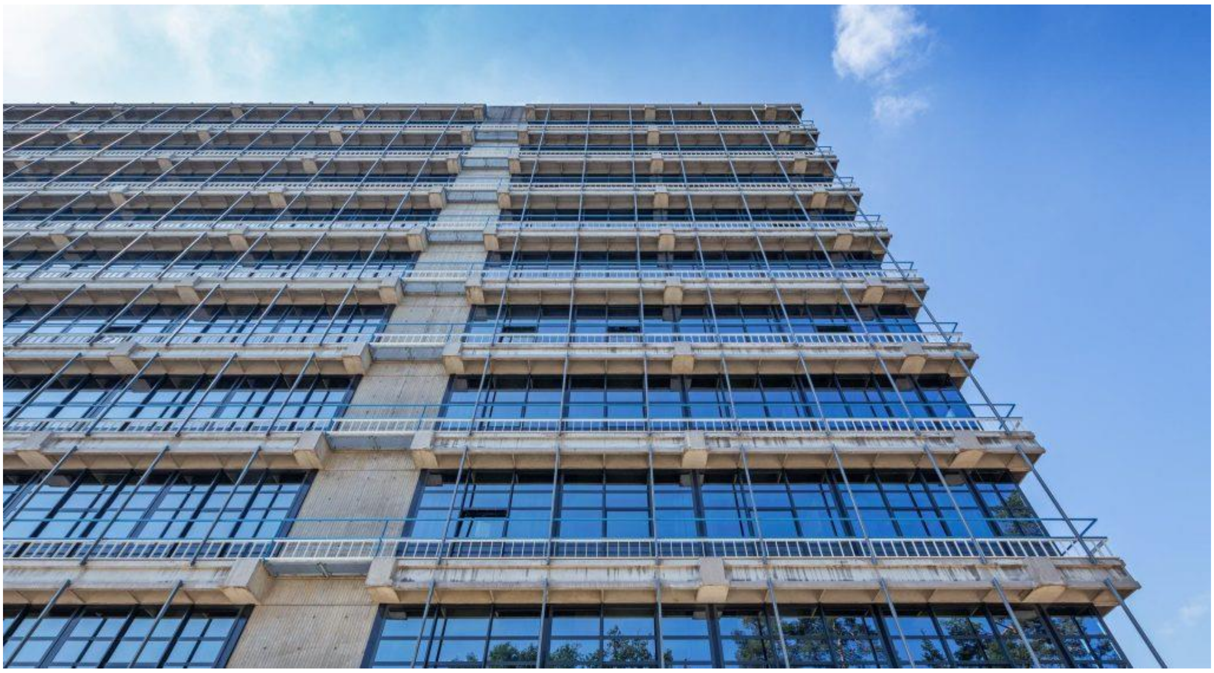


Figure 28: Hogekamp UT Enschede. Source: www.alkondor.nl

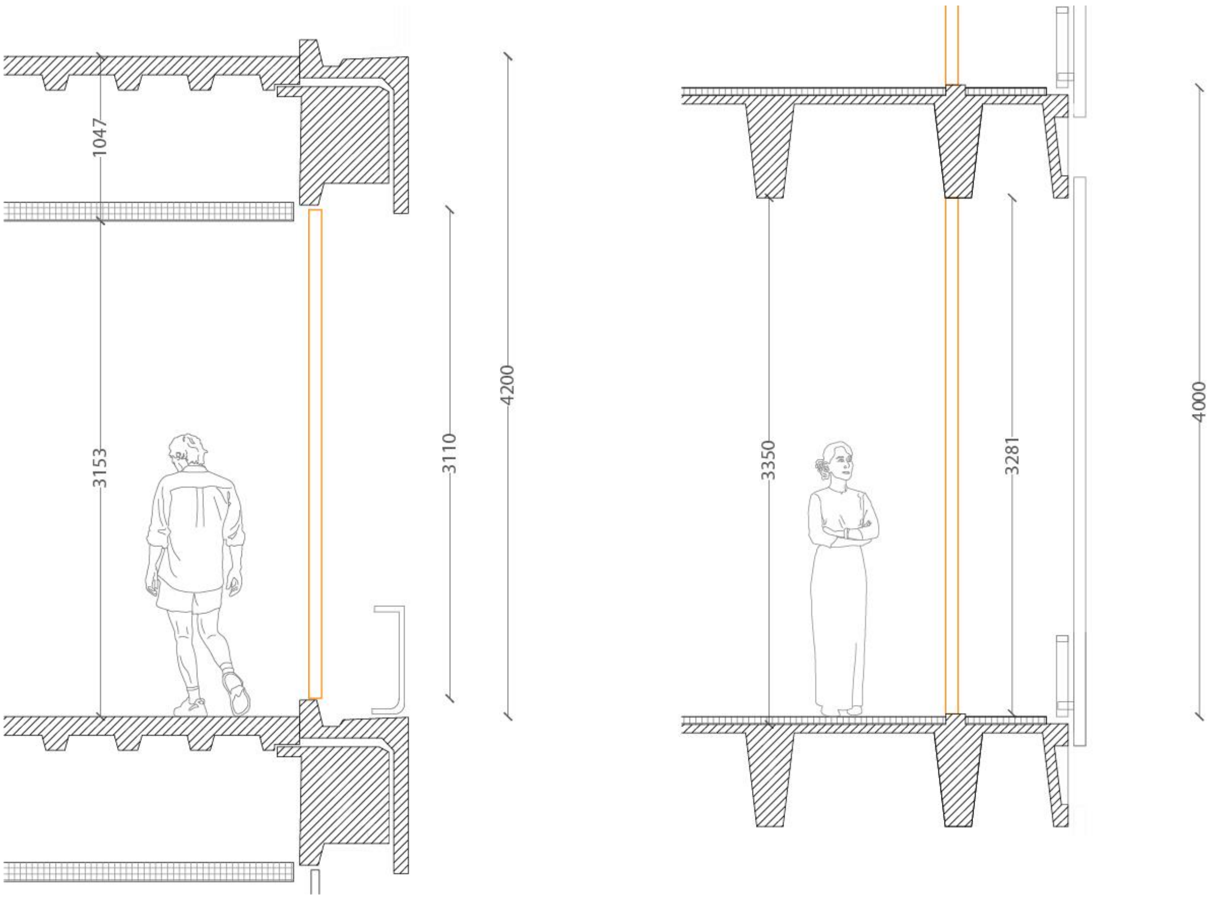


Figure 29: Sections of CiTG (left) and Hogekamp UT (right).

Source: Author´s own, derived from Alkondor Hengelo drawings and Ebbert 2010.

The project was chosen for a theoretical purpose only, as it does not require a retrofit at this point. The existing façade of the Hogekamp UT was explored but is not presented in this thesis, because the focus in the research by design process here lies in determining a technical solution for reuse of the CiTG east facade. For that purpose, the concrete structure and existing line of insulation of the Hogekamp UT are the determining factors.

Reuse assessment: The Hogekamp UT shares the same basic grid dimensions of multiples of 1,8m. Although the floor-to-floor dimensions of the buildings differ by 20cm, the vertical clearance between the ring beams is more similar, with only around 5 cm difference. **Therefore, the façade could generally be reused in its original form.** Only minimal adjustments of the mullion connections to the concrete and a slightly larger version of the wooden connection pieces than used in the CiTG are needed, to bridge the height difference.

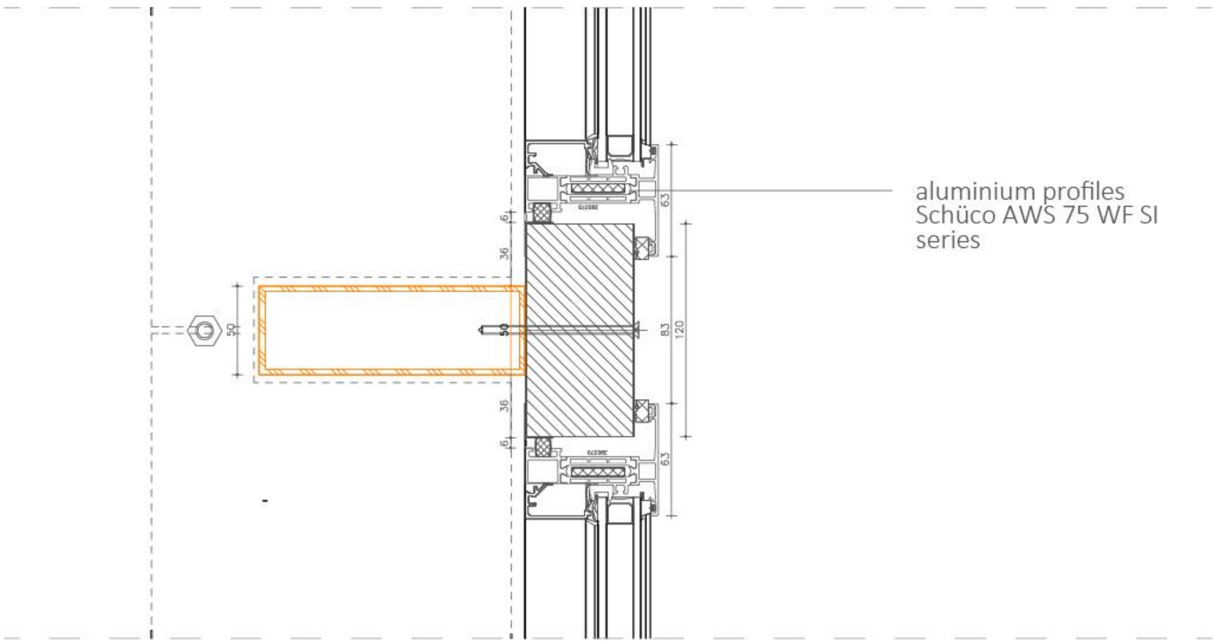


Figure 30: Detail CiTG retrofit design - horizontal section.

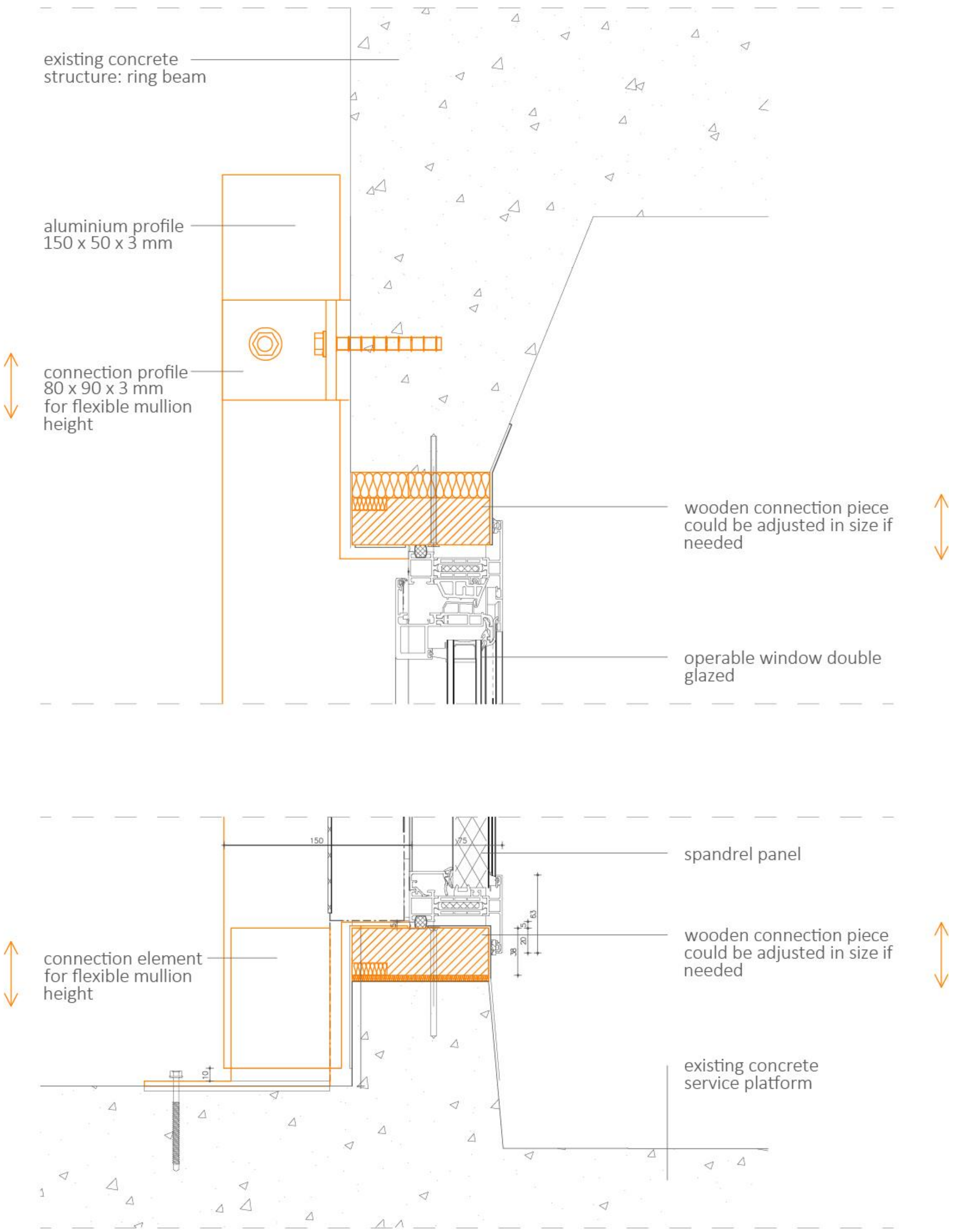


Figure 31: Detail CiTG retrofit design - vertical section.

Source: Author´s own, derived from Alkondor Hengelo drawings.

The potential of this single building however did not seem to answer questions of more universal reuse possibilities. Finding a building with a very similar building typology is not impossible to achieve for every façade that is produced, but unlikely to be a realistic solution in all cases.

Reuse on a new building of standard dimensions

In this next step, standard characteristics of today´s office buildings were determined. This reuse scenario shows how the CiTG façade components could be used on a new building, or any building of standard dimensions and construction. A new building project gives the opportunity to actively incorporate the reused components in early design phases. This would benefit a smooth technical and architectural integration.

The idea of reusing a façade after its first 15-year leasing contract, by applying it to an entirely new building is interesting, in terms of the managerial side. Either, a façade supplier could directly present an offer to an architect who is in the early stages of designing a new project, maybe even offering three dimensional BIM drawings of the previous application as reference. Or, architectural offices could look for suitable alternatives to traditional products, possibly benefitting the financial planning of their projects and turning further towards a circular economy and sustainable future of the built environment.

Horizontal dimensions: Literature was reviewed to pinpoint the most common dimensions used in office buildings in recent years. The horizontal grid of the structural elements and the rest of building products are usually in direct relation. Koorneef (2012) mentions a general grid-basis of 0,3 meters and that “What can be concluded is that the 1.8 meter basis for the office grid over the years has become the standard (…)” (Koornneef, 2012, p. 49). Facade dimensions would commonly be designed to correspond with the structural elements located on the outer perimeter, matching multiple façade component widths to one distance between columns.

By analysing the stock of office buildings in Amsterdam, Koorneef concludes that the most common characteristic is shared by 38% of office buildings: a grid of 7,2 meter of columns in parallel alignment to the façade, while 17% use a grid of 5,4 meters. Although the rest of buildings had other grid dimensions, this statistic will be used in this thesis, to represent the majority of office buildings.

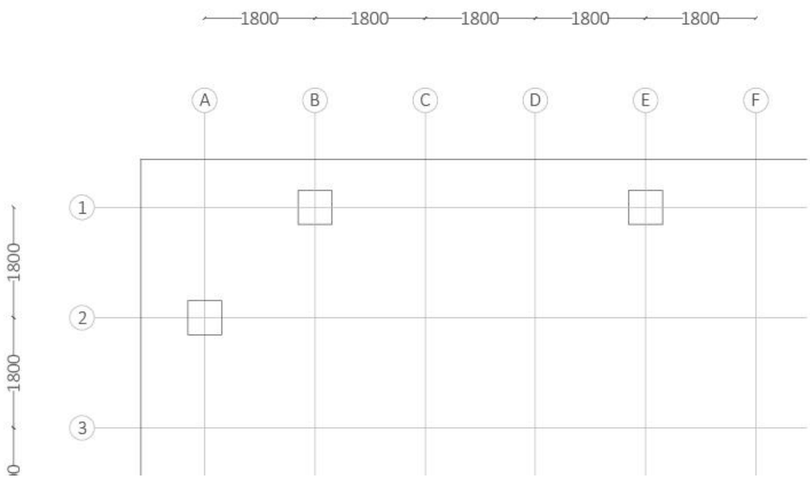


Figure 32:standard horizontal grid dimensions of office buildings. Source: Author´s own.

Vertical dimensions: Looking at standard vertical dimensions of office buildings, the floor-to-floor height as well as the clear finished floor height are determining factors.

Sarkisian (2012) states from a structural point of view, that “For office use, a 2.75 m (9’-0”) tall ceiling height nominally yields a floor-to-floor height of 4.0 m (13’-1½”), (…).” (Sarkisian, 2012, p. 86)

Additionally, Kohn and Katz make an aligned statement about office room heights: “The intended finished ceiling height, which is typically 2,6m or 2,75m although the trend during the 1990´s was to increase this height (…)” (Kohn & Katz, 2002, p. 35)

A vertical section of a standard building is thus derived and compared to the CiTG in the figure below.

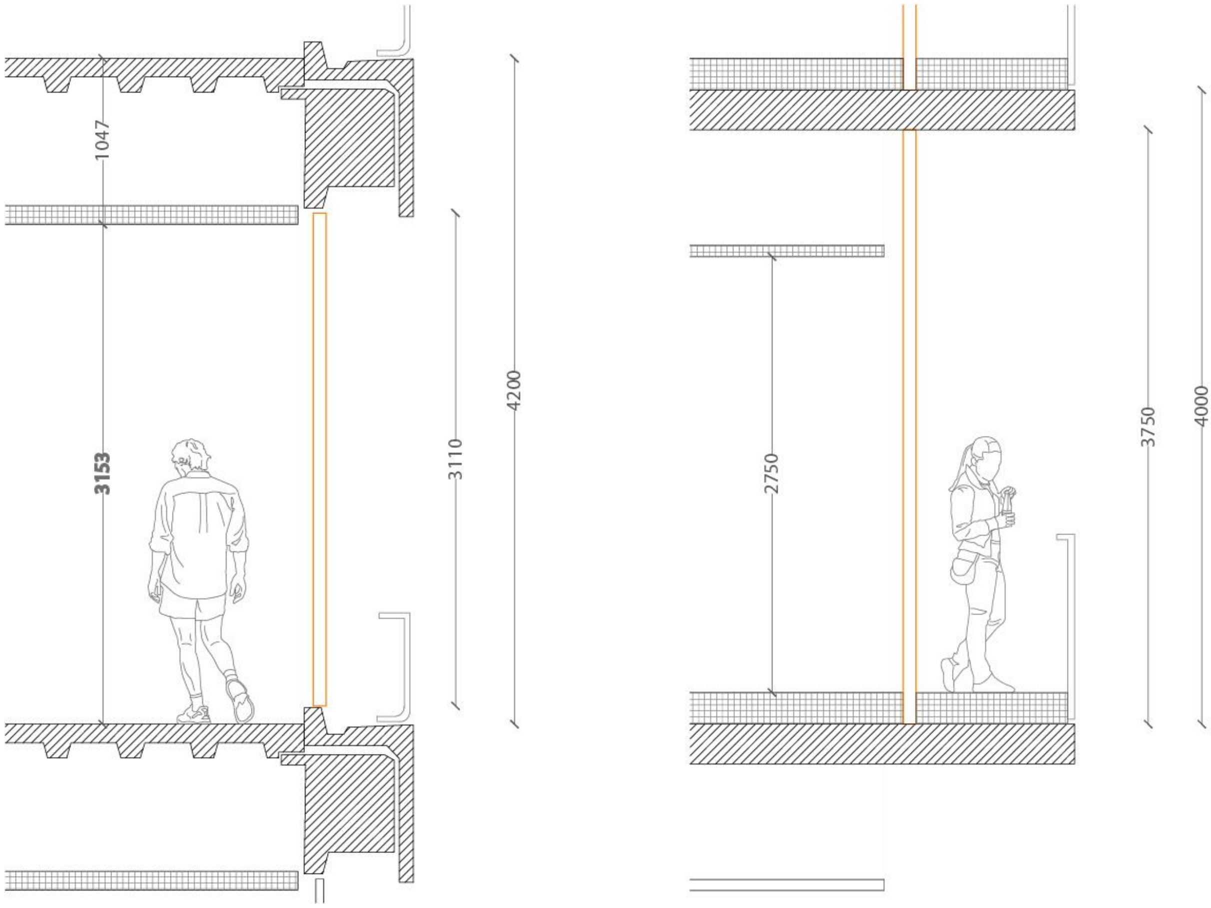


Figure 33: Sections of CiTG (left) and conceptual building with standard dimensions (right).

Source: Author´s own and derived from Ebbert 2010

An office building was conceptualized, which has standard vertical and horizontal dimensions, and a façade that is positioned between concrete floor slabs which form balcony spaces. This exemplary building is set to have a rectangular shape in plan and a structural system that frees the envelope from loadbearing walls or columns. A structural floor height of 25cm is assumed, with an added cavity floor solution for installation purposes. The ceiling is suspended to house lighting, mechanical installations and acoustical panels. A case is assumed, in which an architectural office or client would be interested in a PSS offer of leasing a reusable façade and integrating it into the design.

Challenges: An apparent challenge in using the CiTG façade components on a standard office building is related to floor edges and beam structures. In a case as shown above, the outer floor edge is free, without any ring beam narrowing the opening in building´s structure. The clear opening height is significantly higher than in the CiTG. The total height of a façade located between the floors would need to be around 60 cm higher.

Possible solutions: The solution to this problem can be found within one of two alternative strategies: **modularity or adaptability of components.**

A modular approach would first require standardization in buildings and facades. The height development of building parts would need to follow standardized increments. This would allow for a modular solution, where components would be pieced together as required. The interface between components would be a critical point of engineering.

Even though a set of modular components result in an overall adaptable façade, the term “adaptable” here refers to the internal adaptability of components. Components could be designed to adapt using scalable elements making a more gradual and less restricted height adjustment possible.

What was concluded from research so far, is that a modular approach seems theoretically favourable in terms of economic and environmental benefits, however it is currently only feasible for a limited range of buildings. Even for buildings of standard dimensions, differences in the composition of the building structure result in different requirements for a façade. Although the “one panel fits all”-solution does not exist, components can be reused with some adaptability.

Beurskens and Bakx (2015) adapt the *innovation curve* by Rogers (1995) (figure below). The authors discuss the issue “why the modular circular façade design is identified as a conceptual circular façade solution” and explain that “For example: the reuse of a ‘modular circular façade design’ on another building would still be very difficult, considering the wide range of variations in dimensions and connections and will therefore, almost certainly not fit at other buildings. Therefore, the ‘adaptable circular facade design’ solution, which can adapt to the required dimensions and connection locations would be the solution, in order to prevent the facade from becoming obsolete and turn into waste.” (Beurskens & Bakx, 2015, p. 80)

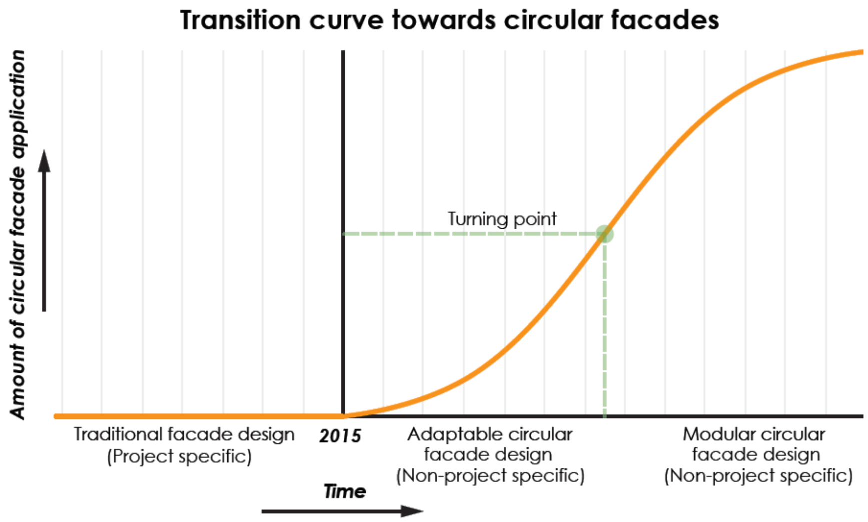


Figure 34: "transition curve towards circular facades (based on Rogers, 1995).

Source: Breurskens 2015

Adapting in height: The current design of the CiTG east façade consists of primary aluminium mullions that are connected to the concrete structure of the building. They are positioned on the inside of the rest of the façade, as presented in detail drawings previously. The façade profiles that frame the window, spandrel and glazing units are connected to the mullions through an intermediate wooden stud. This composition results in the possible independence of the mullion and the framed outer component, which will be referred to as the “panel”.

The mullion could be over dimensioned in height, which would not pose a problem for the CiTG, but in turn allows for a second application in a standard new office building. To cover the remaining gap in the actual thermal envelope, an additional panel of 60cm could be added. For a more widely applicable concept, the existing panel of 3,11m was also divided into sub-components, which can now be independently attached to the mullion. A new set of profiles was chosen, derived from Rebecca Leising´s thesis of 2017. These profiles are part of a hybrid solutions that shares characteristics of both stick-system facades (assembling vertical and horizontal structural parts first, then adding infill units) and unitized systems (where components are completely prefabricated elements that connect directly to each other without a separate primary structure). Transoms are added to form the horizontal structural elements that are needed for this system. Using Leising´s system does not change the order of elements drastically from the initial CiTG retrofit design, while it gives the advantage of independently demountable elements and a universal interface of components to each other.

Summing up, the following changes were made:

- Over dimensioning the mullion in height
- Dividing the CiTG panel into smaller parts, for independent reconfiguration.
- Changing profiles of the panels to Leising´s hybrid solution, therefore adding transoms.
- Adding a panel on top, to reach the desired height of the standardized building with a clear opening height of 3750. The combination of 5 panels (total height of 3556) and their start- and end-profiles fulfil the requirement.

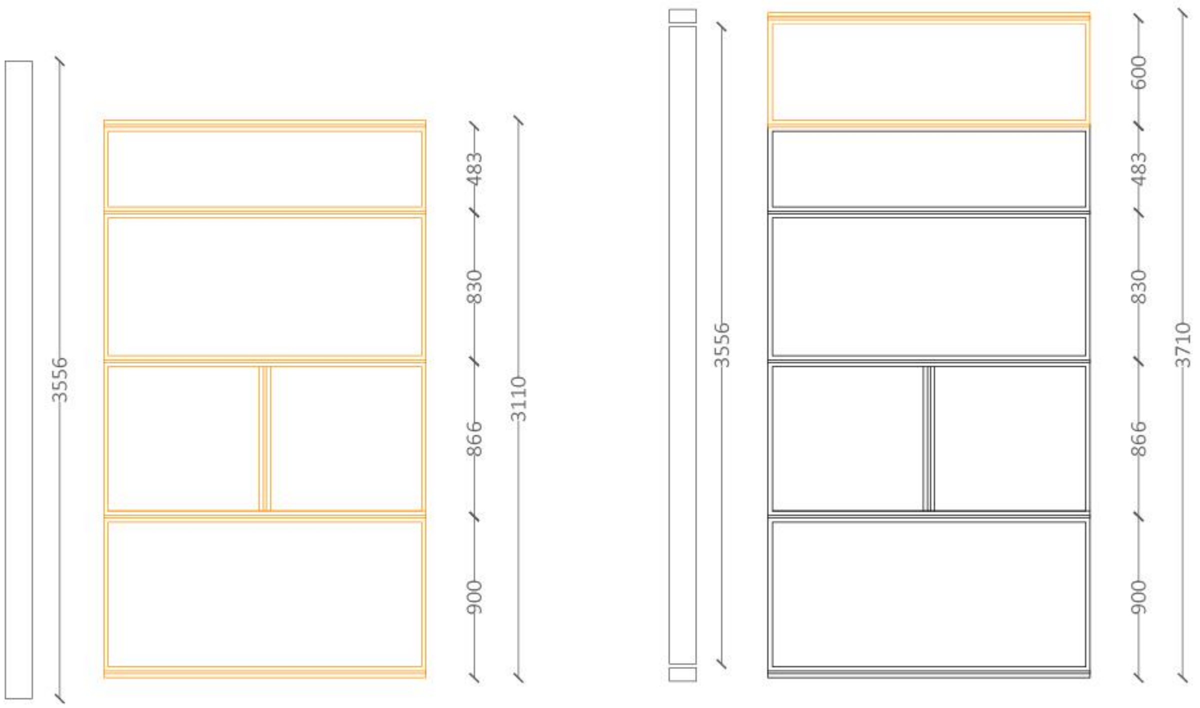


Figure 35: Elevation of CiTG panel (left) and Panel combination for

new standard building without a ring-beam (right). Source: Author´s own.

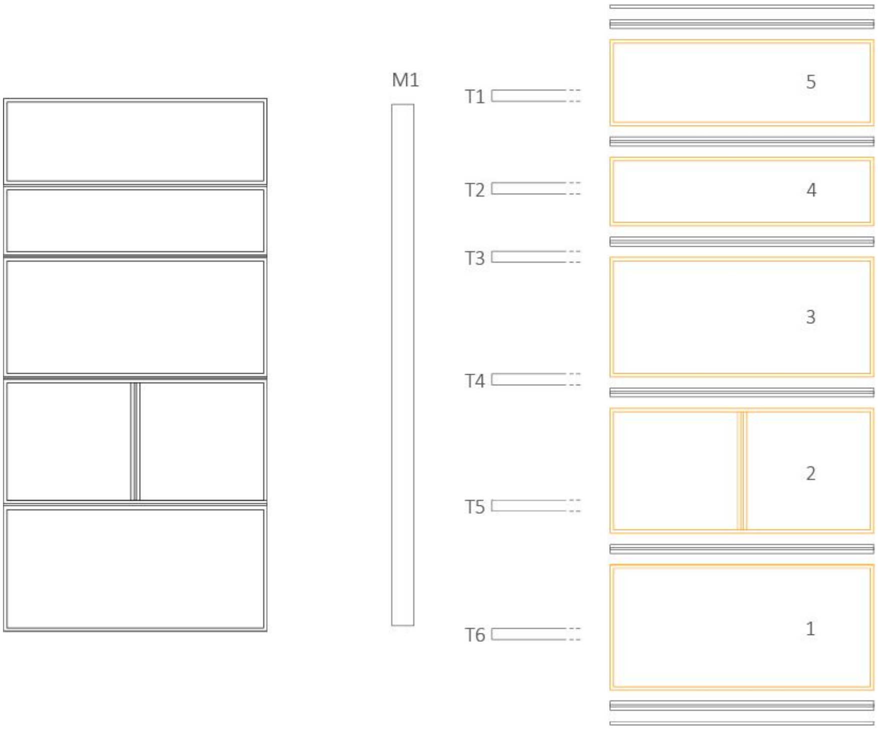


Figure 36: hybrid system of mullions (M1), transoms (T1-6) and unitized panels (1-5) to be reconfigured in reuse, while keeping components intact. Source: Author´s own.

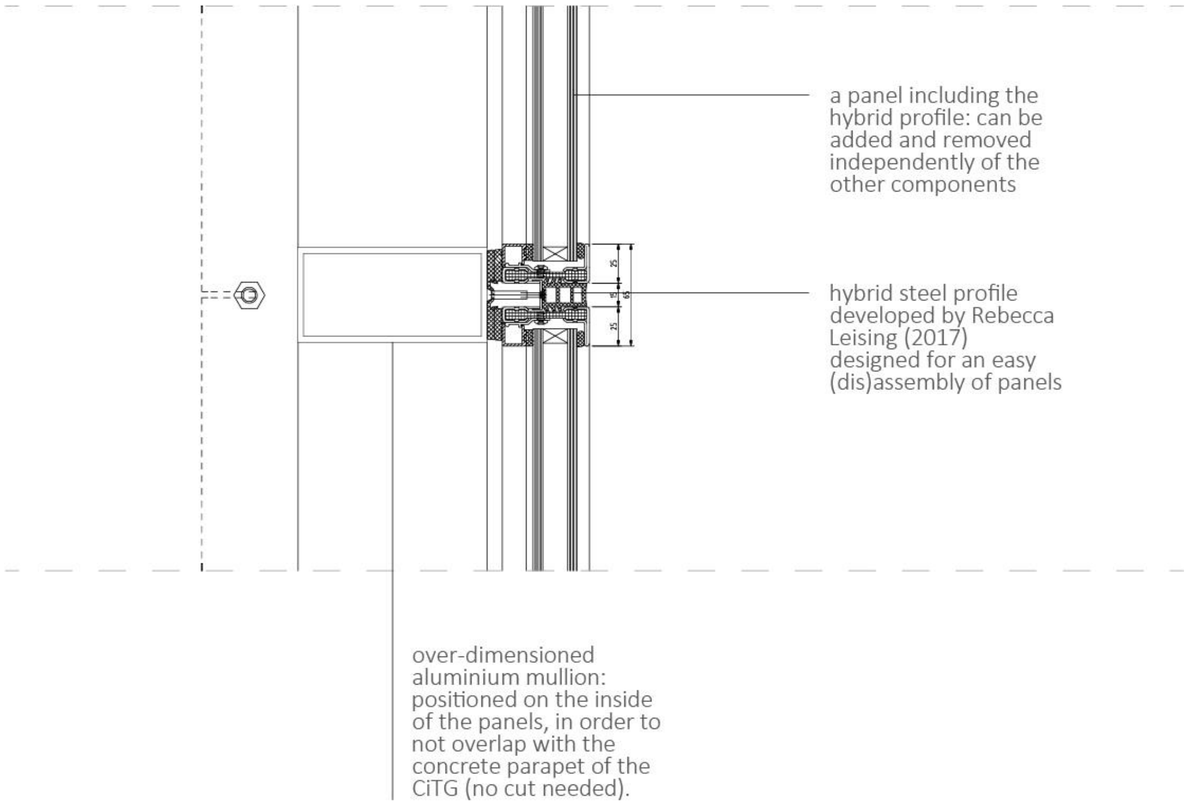


Figure 37: Detail of standard building facade in horizontal section. Source: Author´s own.

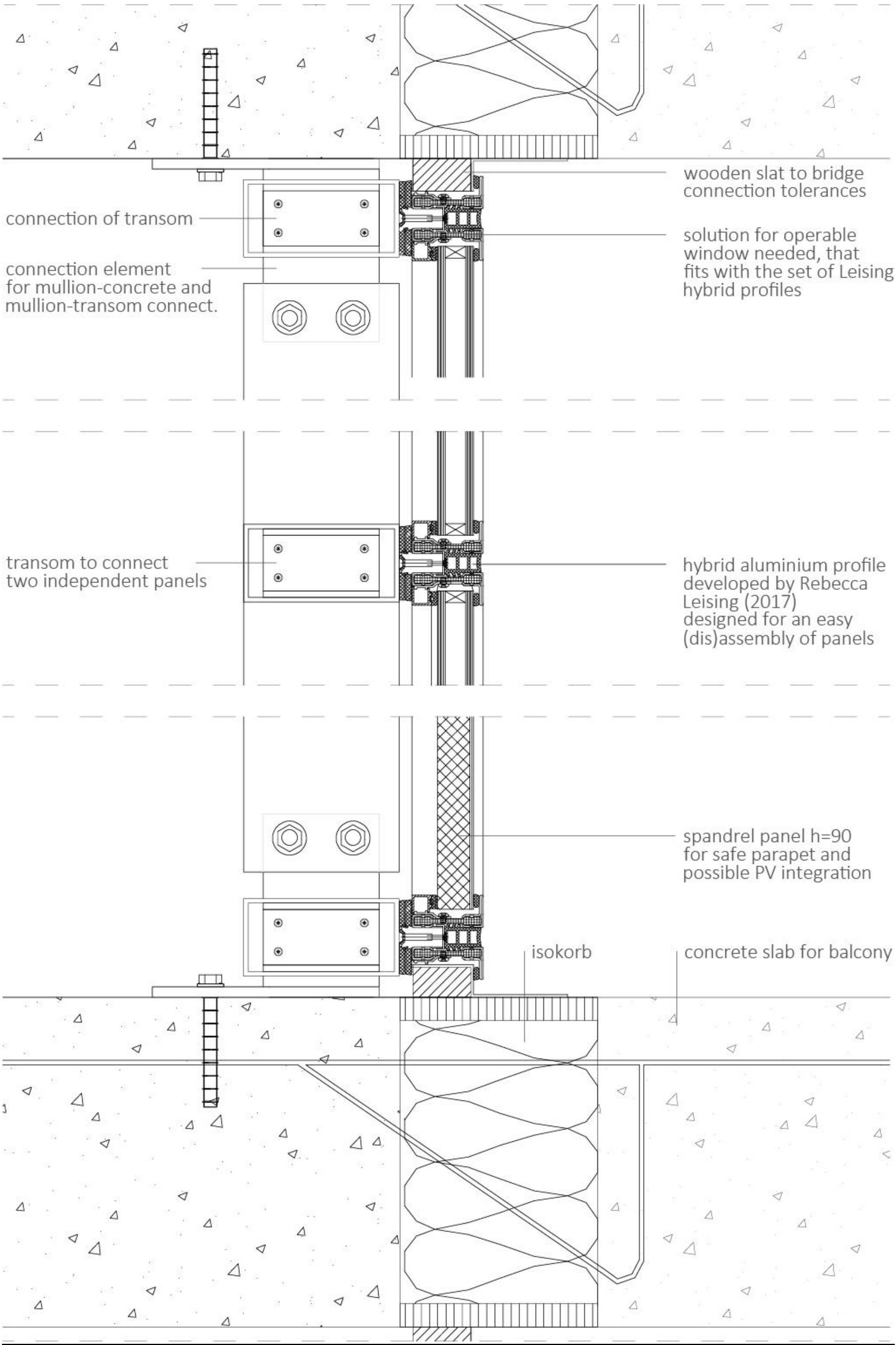


Figure 38: Detail of standard building facade in vertical section.

Source: Author´s own.

Conclusion of research through design process: The Hogekamp UT Enschede is a building with high similarity to the CiTG, and therefore the components of the leased east façade could be reapplied directly, without major adjustments. For this specific purpose, components of a fixed height of 3,11m could work. However, further statistics on office typologies in the Netherlands would be needed, to determine how common this exact typology is.

For a more universal application on a wider range of buildings, the PSS façade would need to be made more adaptable. A stick-system with over dimensioned mullions would provide a slight adaptation of a widely used system, while allowing the façade to scale in height by stacking infill units as needed. In the situation of a new building with a higher clear opening, as presented before, the added sub-component would give the opportunity of aesthetical customization in the second life application.

In this brief exploration, only cases of facades were assessed, that are positioned in between the floor slabs. For facades located on the exterior, for example a hanging unitized system, additional options could be found, to make these constructions reusable.

For façade suppliers and their collaborating architects and engineers it will be essential to get a strategic understanding of the specific solutions that apply to different façade constructions and building typologies. For every first design and application of a façade it can already be planned, which possibilities of reuse might apply. The required reverse-engineering can then be done, to ensure the highest residual value after the component´s first service life.

Literature: For studies on similar topics, interfaces of components as well as disassembly, flexibility and modularity, the following theses serve as relevant further readings:

- Leising (2017): Steel curtain walls for reuse. Implementation of the Circular Economy principles to optimize the steel curtain wall system of ODS NL
- Beurskens and Bakx (2015): Built-to-rebuild. The development of a framework for buildings according to the circular economy concept, which will be specified for the design of circular facades
- Azcarate Aguerre (2014): Façades as a Product-Service System. The potential of new business-to-client relations in the facade industry

Conclusions of design questions

The conclusions of the design related two sub-questions are interdependent and are therefore answered consecutively: Question 2.1: “How does the PSS façade design compare to a standard construction?” highlights the point in which a standard construction does not meet PSS requirements. In response, question 2.2: “What design criteria emerge from supplying facades as PSS?” is answered in form of a list of new design criteria applicable for facades as PSS.

DQ1: How does the PSS façade design compare to a standard construction?

Standard façade constructions are tied to the building they encase. They are designed with a single building in mind, constructed without consideration of a second service life. The overall construction of a standard façade as well as the connection to a building´s structure would typically consist of customized elements that are not flexible to relocation. This includes fixed connections, in-situ sealing for air and water tightness as well as thermal insulation, and interfaces between elements that do not allow for damage free demounting. The overall design of the façade does normally not allow for any other customer´s interest in giving the façade a second life on their building. Additionally, the façade and its materials are tied to the building in terms of its lifecycle. Even if building products were designed for a second service life, there is no management strategy set up for the marketing of the used items.

1. A standard façade is **tied to one building**:
- Constructively
- In the level of customization
- In the material value and life cycle

2. A standard façade has a **low level of flexibility**:
- In both hardware and software during the operational phase

3. A standard façade has a **low feedback level**

DQ2: What design criteria emerge from supplying facades as PSS?

A PSS façade is designed to be independent from any single building project. In a PSS the owners of façade and building are two separate actors. This gives the opportunity to release the façade from its ties to one single building, also in its physical form. Façade products need to be designed for reuse, in order to make use of this opportunity. They should be easily demounted and remounted, in terms of their internal construction and connections to the building. The overall design should provide a high residual value of the product after its first use, by reducing customization and focussing on more widely applicable products. The marketability of products for a second service life is supported by reusability of components, sub-components, elements and materials. In an advanced PSS facade design, all these elements should ideally be independent of the life cycle of any single building.

Flexibility is a key factor of an advanced service, in a PSS façade. The operational phases of the façade should be adaptable processes, where physical parts can be changes and updated along the way. The operational strategy of dynamic features is ideally reviewed and optimized to allow for an efficient use of features.

Receiving feedback about the functionality of the façade and the resulting IEQ and energy performance of the building is a requirement for a successful service agreement. Three physical elements are to be incorporated, to understand and balance out interdependent mechanisms: For an advanced PSS that includes all stages presented in the demarcation scheme of producer responsibilities (chapter 1), measurement devices are used to keep track of the indoor comfort conditions. Monitoring devices allow for a better assessment of how mechanical parts such as windows, ventilation openings and sun shading devices are used, to understand their effect on the measured parameters of temperature, humidity, CO2 and lighting. For a holistic management of both IEQ and energy consumption, the HVAC system should be integrated into the façade. This is important for the successful compliance with goals, set in an advanced service agreement between client and supplier. A building management system can then be used to optimize the interaction of systems and therefore the overall performance.

1. An **independent** PSS façade should be
- demountable and remountable.
- relevant for multiple applications and clients
- enabling an independent life cycle of its building products

2. A **flexible** PSS façade provides that
- the physical components can be updated or added on to
- the way of operating dynamic features can be adapted during the operational phase (software and hardware)

3. A PSS façade helps **collect feedback and balance IEQ with energy efficiency** by
- Setting up mechanical measurement devices
- Setting up mechanical monitoring devices
- Integrating HVAC systems

DQ3: In which way can the design of PSS facades contribute to a more circular facade construction?

In a PSS for facades, a link between the business aspect of a circular economy, and the available technologies to make facades circular is created. Although take-back agreements are easier to implement for smaller building elements, the product service system for the entire façade system gives the unique opportunity of a supplier retaining ownership of all parts and managing their efficient reuse possibilities. **In the assembly of a façade, a certain value is created, that is larger than the sum of its parts.** It includes the cost of designing, engineering and labour to produce the façade as a complete building part. Additionally, losses are made in dividing the component back into individual elements, when they have been altered in a manufacturing process, to serve their purpose in the exact initial arrangement. Reusing an entire façade component seems to be the strategy for maximum residual value: Demounting and remounting components, to serve a function of equal quality on another building. However, this theory is challenging to implement in practice, because no solution for such a reuse has been developed yet.

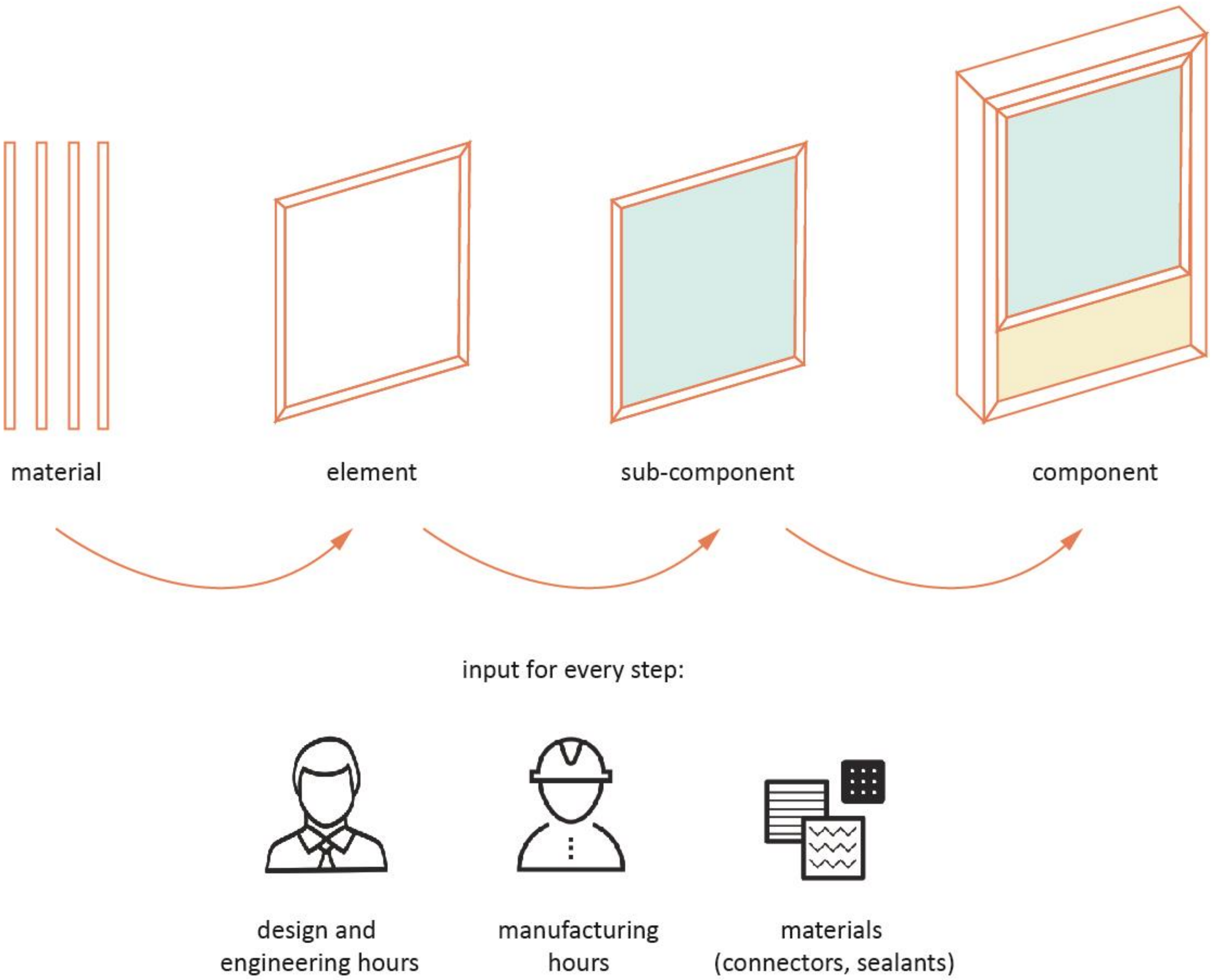


Figure 39: Input required to produce façade components. Source: Author´s own

In this thesis, it has been briefly explored, whether components could be reused directly. The studies point out some major difficulties, especially concerning the size of components. Finding a correct dimension for façade components to fit more than one building consecutively is a difficult process. By the means of some workarounds however, solutions may be found of how to reuse façades without decomposing them entirely into elements. Here, a solution was conceived, that makes use of a primary structural system (mullions and transoms) that can host a set of different individual panels with a compatible interface. It that way, a more customized solution can be configured, while all components stay intact and reusable.

Main DQ: What is the effect of the PSS approach on the design of facades?

When one party is clearly responsible for a façade and it is used as a performance-delivering tool, the related approach to design will change. The supplier invests directly into future years of long-term involvement.

Suppliers of a successful PSS will be:

1. ***thinking in systems*.** An ongoing process will be designed for, rather than a single use façade product. Life cycle management, designing for an easy assembly and disassembly, and ensuring a high residual value of parts after their first application is critical.
2. **designing in a *result-oriented* way, using the façade as a *performance-delivering tool*.** A facade would be designed for high performance, systematic operation and maintenance. The practice becomes result-oriented instead of only fulfilling product-centred requirements. It means that the envelope is made to serve the interior conditions. It is a reminder that we are making buildings for people, and need to ensure with all means, that facades prove to have the desired effect on their environment.

5. Reflection

Relationship between Research and Design

This thesis studies the role and tasks of the supply side in a PSS façade-leasing model, discussing the points of demarcation towards an indoor comfort and façade performance guarantee. The pathway towards product service systems is discussed in collaboration with Alkondor Hengelo. In setting up a graduation plan in early research stages, a design and multiple alternative designs for the CiTG pilot project façade were intended to serve as a larger (or more extensive and detailed) part of the thesis, as well as a tool for research through design. This was planned, because the aspect of circularity was understood as the main unsolved link towards providing a leased façade. However, in the process of further literature research, discussions with my mentors and taking other expert experience into account, a better understanding of the CE and the process of façade construction was obtained. This led to the conclusion, that there are multiple developments within the field of new circular business models, which are equally important and linked to each other: The technical implementation of product service systems in the construction industry and facades as part of a circular economy. To narrow down the scope of this research project, the demarcation of producer responsibilities within product service systems was chosen as the main focus, because once it is ready to be implemented, it is said to give an incentive for circular design and was therefore seen to have higher urgency of problem solving. In other words: to safeguard a sustainable lifecycle of materials in giving one party the responsibility to do so, a system of adding value to undertaking this task first needs definition and development: the PSS. Therefore, extensive literature research and discussion was done before proceeding to answering design questions. Subsequently an exemplary field study was added, to get a better understanding of how the reuse of façade panels on existing buildings might work. Lastly, a reapplication of the CiTG façade panels on a fictional new construction was conceptualized, to assess a scenario where an existing façade would form a preselected building element, defining the early design stages.

Relationship to Master Track Building Technology

The topic touches upon many relevant sub-topics of sustainable design, such as circular façades and performance optimization during the operational phase. The research questions in the field of façade design, product design and climate design are informed by multiple disciplines of the built environment, in the intersection of architectural design and engineering. Integrating these fields with product design and more business-oriented aspects of façade construction is an inherent requirement of answering questions related to façade leasing concept. The thesis explores a detailed scale of façade engineering, as well as the large scale of integration into the built environment, considering the construction industry and its effect on the environment, as well as architectural value and urban development. It is situated in the field of Building Technology, as the topic represents a complex new concept in the future of sustainable design.

Elaboration on Method and Approach

The first stage of basic literature review led to the definition of some preliminary research and design questions. One of the largest challenges in writing this thesis was the definition of a methodology and formulating the correct research questions. This stems from the highly experimental nature of the façade leasing pilot projects and limited experience of all actors: The outlines and goals are known, but details are still blurry. Therefore, some research and design questions that were once seen to be answered have been revised multiple times, because of the abstract nature of the topic. It seems like the questions could only be formulated correctly once a possible answer could be visualized. That said, some other parts of the methodology seemed clearer from the start, such as the use of a simulation to quantify and further define some of the otherwise theoretical answers. During the process of setting up said simulation, a deeper understanding of questions related to the facade construction was obtained, because causal relations became clear.

Relationship between Project and Social Context

Looking at the future of energy consumption in the built environment, newly built constructions will probably not be the biggest problem – The old building stock is our main challenge, as that is where most energy losses occur. Renovation, especially of the building envelope, is the key to cut out these Co2 emissions, but new strategies need to be found, as how to renovate the large mass of underperforming building stock. This involves solutions on the technical basis of new materials, production processes, building products and their application, but the bigger picture is equally important to keep in mind. How can we achieve all these renovations, who will invest in them, and how will we manage the facades upkeeping, so that we are not faced with more problems in some years' time? Both the physical component, and the process of implementation has potential for innovation and needs advancement. The circular business model of façade-leasing could be a valuable approach to solve issues on more than a single project-basis. It could prove to be a beneficial new way of stakeholder interaction, rethinking how facades are designed, managed, operated and set into a circular loop. There is a clear need of finding large scale solutions, that reach beyond singular solutions of renovation. Although governmental legislations are known to be set to prohibit the use of office buildings below label C in a few years, that only predicts the need for renovation, but does not answer the "how?" for every owner and user of an underperforming building. Defining the process of façade leasing in more detail and working towards making it fully feasible on a managerial and technical level, could help solve issues of financing renovations, and securing the quality of the result.

A product service system in which the supplier guarantees a level of indoor comfort and energy performance related to the façade helps bridge the gap between theoretical energy labelling and physical performance indicators that can not only be measured in the building but are also experienced by users daily. In a theoretical future scenario in which non-renewable energy is highly taxed, the performance of facades becomes the most critical factor for thermal indoor comfort.

Ethical Issues and Dilemmas

A product service system with the intent of guaranteeing a certain indoor comfort and energy performance of a façade would need monitoring of comfort conditions and the use of energy data to verify the results of the applied construction. This means that, in a time of heavy discussion about the protection of personal data online, it could translate to ethical dilemmas related to monitoring of occupants´ real life behaviour in a building. For example, the level of occupancy of an office can be seen as an invasion in workers privacy, collecting and possibly sharing information that is usually not discussed. An official agreement from occupants with what is being measured, could be a solution to exclude these issues.

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7. Appendix

1. Literature Review

The following literature review was mainly made for my internal reference, to summarize the most relevant information found in publications used in this thesis. It is placed in this appendix, in case readers and potential future researchers are interested in an overview of different topics related to this thesis. It is not a summary of works, but more of a commented collage of selected pieces of text. Nevertheless, it might be useful to others, who are not yet familiar with façade leasing or what to consider in the adjacent fields of research.

PSS and Façade Leasing

Azcarate, 2014: ***Façades as a Product-Service System: The potential of new business-to-client relations in the facade industry***

Azcarate looks for innovation in business strategies for façade construction. He starts his research by assessing façade value, in form of the performance criteria of common interest to all stakeholders. To specify the field within the built environment, case studies in the Dutch university sector are chosen. Referring to façade value criteria of Den Heijer 2011, university campus buildings are assessed according to their functional, financial, strategic and energy performance value, to analyse recent trends in commercial architecture in the Netherlands.

According to Azcarate, the requirements for a project to be funded seem to have shifted from plain functional parameters to different types of added value. Those can be found in social aspects of user interaction, as well as in memorable building characteristics. Additionally, the life cycle costs of a building have become a more important consideration, especially energy costs and material resources. It is also mentioned, that maintenance is essential to reach high performance of facades, and services have become more expensive with the rising complexity of electronics and mechanics in current construction. Azcarate states that “Breaking down the operation costs of a standard commercial building, we can see that a major part of global expenses can be attributed, fully or partially, to the performance of the building envelope. (…) Overall, I have estimated that over 25% of yearly operation costs could be “outsourced” to a third-party providing facade-leasing and indoor climate services. This by adding a fraction of each expense concept which could be attributed to the operation of a facade and its supporting systems.” (Azcarate-Aguerre, 2014, p. 16; Den Heijer, 2013). This introduces the concept of façade leasing. Using data of the case study projects, a financial benchmark (average financial investment per square meter of façade) is calculated, to assess the acceptable cost of leasing. Before defining benefits of leasing, and therefore a more concrete sense of what the client is willing to invest, the concept of façade leasing and different types of stakeholder relations are addressed.

Azcarate et al, 2017: ***Integrated façades as a Product-Service System – Business process innovation to accelerate integral product implementation.***

Here, product service systems are presented as a promising combination of tangible technical products and intangible services, creating well performing façade systems while limiting the use of finite resources. A “gap between supply-side discoveries and demand-side needs” ((Azcarate Aguerre et al., 2017, p. 2) is seen to be a critical challenge to overcome, for suppliers to commit to a façade’s performance throughout its entire life cycle, and clients to make more innovation-forward choices. Both principles of PSS and Circular Economy (CE) are explored. The paper elaborates on stakeholder conditions and incentives and their relation to the implementation of a PSS business model. It refers to the research project of Azcarate 2014. It is argued that a PSS model for façade construction “could accelerate the rate and depth of building energy renovations” (Azcarate Aguerre et al., 2017, p. 2) and benefit the transition to a CE by redefining “product ownership, service contracting, and performance delivery.” (Azcarate Aguerre et al., 2017, p. 2). It is mentioned that innovative business models are needed, to give incentives for energy renovations, making them financially accessible, and motivating investors with the benefits of long-term product operation. A long-term cooperation of suppliers and clients is seen to be favourable, not only from an economical point of view, but also in an ecological sense. A service-based system would mean moving away from purely short-term interest of product sales, towards a more holistic care for them over an entire operational cycle and beyond. In that way, some important steps towards a Circular Economy could be taken.

The paper discussed the potential benefits of facades as PSS from two main points of view: Building Technologies (technical solutions and energy performance) and Real Estate Management (functional, financial strategic goals). In my master thesis, I am mainly adding to the latter, by addressing technical matters of both construction and energy performance, while the main research question is also related to the strategic side of the proposed system.

The PSS model is described and the following sentence was of great use for me, as it summed up the starting point of my research: “A true PSS-oriented business model will have all stakeholders tied, materially and financially, to the optimum performance of the building throughout its service life, including end-of-service material extraction and reuse.”(Azcarate Aguerre et al., 2017, p. 10) It reminds of the focus points that are to be achieved within the product and service part of the system: reaching an optimal performance and using materials cautiously, within a circular system. It is further stated, that the stakeholder’s assessment of advantages as well as uncertainties and risks is the first step in transitioning to a new business strategy. The combination of these two facts is directly related to the research method of this thesis: Defining the demarcation of stakeholder´s responsibilities taken towards achieving a well performing envelope, and assessing the related uncertainties, translating them to more comprehensible risk factors. Additionally, the crucial financial and environmental factors of the reuse strategies and residual value are integrated added the equation, addressing the circular aspect of façade leasing.

Lastly, it is stated that there are also changes needed in the architectural practice. Irregular forms and highly customized building elements should be rethought for a successful PSS, where a higher level of modularity and standardisation as well as compatibility of parts are directly related to an increased residual value. This is an important factor and a sensitive topic, because the aesthetics of facades might need to change from current practice, following a new set of design criteria related to PSS (concerning the sizes of elements, connections, materials, colours and so on). And as Tillmann Klein states about the architect: ”Frankly said, he also is the lonely defender of his architectural intentions (…) .” (Klein, 2013, p. 74)

Azcarate et al, 2018: *Drivers and barriers to the delivery of integrated Facades-as-a-service.*

The drivers and barriers of the Façade Leasing business model are explored, from the point of view of four stakeholder parties: demand-side, supply-side, financing party and governance. The different actors had been represented in the EWI Façade Leasing Pilot Project 2016, which was means to be both a technical demonstrator and the initiating centre point of stakeholder discussion. Their main drivers and concerns are assessed.

1. Owners: The residual value is seen to play a large decision-making role of increasingly environmentally conscious building owners, looking for solutions with a small footprint in use of materials and energy. It is argued that clients are willing to invest in a complete, worry-free solution for façades that perform well energetically. An important point made is, that owners are aware of the difficulty of defining performance indicators for facades, because of their complexity, acknowledging that it is not easy to know if or what is enhancing the comfort and productivity of a building´s users.
2. System suppliers: This user group is important to my thesis, as they are argued to be the party with the highest responsibility and risk, making their drivers and barriers key elements of the success of facades as PSS. In Azcarate et al, 2018, it is said that tender processes are currently overly focused on technical specifications, rather than the outcome, with a rather small amount of influence of the suppliers. But as the role of contractors is said to decrease in the future, new concepts for circular and leased services with solutions for the end-of-service-life could be offered by a group of cooperating suppliers. One of them will most likely take over the leading task of "system integration". In this thesis, the façade supplier Alkondor is seen to become said actor.
   A two-part statement is made about where the value is held within the properties of the physical façade for the supplier: Firstly, it is argued that the residual value of a façade is minimal, after it has been removed from one building, because costs associated with demounting, logistics and remounting will not be outweighed by the rising material prices. While this might be true for the current situation, I would criticize it as an outlook to the future, because I believe the residual value will play an important role for suppliers, if products and their market can be redesigned. Secondly, it is said that the improvement in energy performance can become a guarantee for the savings to cover loan repayment, if a track-record of successful renovations is built.
3. Governance: According to this paper, it is important to distinguish legal ownership and economic property within the system of facades as PSS. A pilot project with real contractual constraints is anticipated to test the business model, assessing governance related challenges. This year (2019), the ongoing renovation project of the CiTG building represents the product of these plans, and the case study of my thesis.

Tukker 2004: *Eight types of product– service system: Eight ways to sustainability? Experiences from SusProNet.*

In his 2004 paper, Tukker opposes the assumption, that all PSSs are valuable means of achieving goals of sustainability, which lead to a large investment of EU funds into the then called "Sustainability Product Development Network". He states that "At least eight different types of PSS exist, with quite diverging economic and environmental characteristics." , where as "The exception is the PSS type known as functional results, but here liability and risk premium issues, amongst others, need a solution." (Tukker, 2004, p. 1). While it is general and not specifically related to the construction industry, his scheme of "main and subcategories of PSS", amongst others, serves as a basis of defining the different levels of facades as PSS in my thesis. Tukker´s types of product-service systems will be referred to in more depth in the main body of text. One of his main statements is an important consideration in this thesis: He states that with advanced product service system types, finding indicators for quality performance is likely to be difficult. When assessing the value of sustainability of different PSS types, he finds that "Functional result PSSs have, in theory, the highest potential since the provider offers a result closer to a final client need and hence has more degrees of freedom to design a low-impact system. " (Tukker, 2004, p. 13). This makes those holistic models promising while challenging to implement. In more concrete terms, Tukker states that result-oriented models shift risks and uncertainties from the demand-side to the supply-side. These barriers, as also mentioned in Azcarate et al (2017), must be overcome, as they will otherwise prohibit a financial success of the supply company, or result in overly high leasing costs to account for unknown risks, which the client might not be willing to pay. For me, this theory highlighted the need for risk assessment in the case of the energy performance of facades, when guaranteed in a product-service system. Therefore, the report at hand covers the question of "how far does service go?" and it is tried to minimize the current uncertainties of achieving performance results.

Energy Performance and Indoor Comfort

Bluyssen 2009: *The Indoor Environment Handbook: How to Make Buildings Healthy and Comfortable*

In the Indoor Environmental Handbook of Bluyssen 2009, designers of the built environment are consulted on how to successfully handle issued related to the complex matter of the indoor environment. The human reaction to environmental conditions is explained, and an insight in the evolution of environmental management is given. It is mentioned, that strategies have appropriately developed away from component-based assessment, towards result-oriented ("bottom-up") indicators. In a later chapter, it is mentioned that health, comfort and safety of building´s occupants are not only general design goals, but hold an economic return, because user productivity is closely tied to those factors. A company for example would financially benefit from a reduced amount of sick-leaves, and medical costs can be saved.

Bluyssen also describes what "perfomance" of buildings or components means, stating that it refers to the result rather than the mean or way of construction, and that perfomance has a "quantitative base for testing". (Bluyssen, Oostra, & Meertins, 2009, pp. Chapter 5.3.1 Performance Evaluations- of e-book). She also mentions an interesting fact, that no complete method of perfomance evaluation related to indoor comfort conditions is availiable for the entire life-cycle of a building.

Although my thesis will not specifically add to the research needed to provide such a method, the concept of facades as perfomance-delivering tools with a long-term service component will highlight the need for it. While I will focus on quantifying the general risks involved with guaranteeing façade performance, (to form a starting point for stakeholders interested in the developing business strategy), further research is surely needed, to form a framework for perfomance evaluation throughout the life cycle and multiple service lives of a circular façade, supplied as a PSS.

Bluyssen, Oostra, Meertins 2013: *Understanding the Indoor Environment: How To Assess and Improve Indoor Environmental Quality of People?*

Bluyssen et al. (2013) is a call to rethink the methods of achieving favourable indoor environmental quality. They propose looking at “real exposure situations” and a multi-disciplinary approach. A direct relation of building related factors and human health and productivity is highlighted. It is stated, that simply following standards for IEQ can result in a lack in user comfort and health, because of “the fact that buildings, individuals and their activities may differ widely and change continuously; not every person receives, perceives and responds in the same way” (Bluyssen, Oostra, & Meertins, 2013, p. 4). Producing well-performing buildings is seen as a joint task, of user-awareness and a mutual understanding between all stakeholders involved in the design, construction and maintenance process. The approach of System Engineering is proposed, where “subsystems (that) do matter, but the system will only function if all sub-systems (components) are optimised along with the total system, whether this is related to health, comfort or sustainability issues.” (Bluyssen et al., 2013, p. 6). To accompany that system, a bottom-up information flow from users, but also the measured indoor and outdoor environment, as well as the building components is said to be useful, functioning as a database for the entire life-cycle.

These ideas seem valuable for the model of facades as product service systems, because the so-called “performance-gap” needs to be minimized (hence, assessing situations that are as close to reality as possible, taking the joint entity of a building and its variables into account, rather than its static individual components) and a management system has to be found, in which a result-oriented effort of combined stakeholder knowledge is made (forming cohesive supply chains on a wider-than-project basis). Additionally, as discussed with a representative of the façade supplier Alkondor, a bottom-up information flow as described above could prove to be an asset in achieving performance goals.

De Wilde 2014: *The gap between predicted and measured energy performance of buildings: A framework for investigation.*

The paper of De Wilde (2014) describes the performance gap, between actual performance as a measurable result in the building and expected performance in design and analysis. The main conclusion is that predictions need to be improved and current practical approaches within the building industry are to be changed. The importance is signified by stating that the actual energy consumption is often more than twice as high as assumed. He refers to Almeida et al., 2010, p. 157-174, when stating that minimizing the gap is “(…) a key prerequisite to novel modes of building delivery and facility management, enabling concepts such as performance-based building, or performance-contracting (…)” (de Wilde, 2014, p. 1).

He also suggests, that there are three main stages of origins of the performance-gap: the design, construction and operational stage. The point of hand-over between supplier and owner is a critical point. He therefore refers to a UK practice called “Soft Landings”, where the timespan of handing over the responsibility is extended up to multiple years, to reduce unsolved matters of lack of constructive quality. It is mentioned that this does still not provide a satisfying result. This could mean that for facades as PSS some similar issues may be detected, or on the other hand, the continuous line of planning and management of the product and its performance, as well as aligning interests (the supplier aims for a well-functioning construction in his or her first and foremost interest) could provide a better outcome.

Kurvers et al. 2009: *Methode voor binnenklimaatonderzoek* (english: “method for indoor climate research”)

In this paper, Kurvers et al. look for a method of assessing indoor climate performance. It is a report commissioned by TU Delft, as reliable testing is especially important in public private partnership building projects. The problem is stated, that the indoor climate of buildings is an effect of multiple dynamic factors such as user behaviour, the weather, and building related factors such as ventilation and insulation, and that there is no universal protocol for measurement or research.

General inaccuracy in testing and prediction. Some of the parameters of inaccuracy listed by Kurvers et al., 2009, p.26, are the following:

- Measurement tolerances
- Constructive difference
- Occupancy rate / cycles
- Lighting
- Inner heat loads
- Building services for light- and sun-shading
- Air change rate
- Ventilation system´s power
- Weather conditions

The issues of producer risk and consumer risk are described. The latter might occur when the IEQ of a space is tested and quantitatively defined to be below agreed-on standards of comfort conditions, while users do not feel said lack of performance. The producer might invest in fixing problems that are not subjectively detected by the occupant´s, whose opinion should ultimately count. Consumer risk on the other hand, can occur when users feel uncomfortable in the indoor environment, while tests with measurement equipment show theoretically satisfying results. That means that consumers (occupants and building owner) pay for a performance that they do not experience positively.

Kurvers et al. state that the chance of achieving a correct assessment is called the distinctiveness of a test. The goal is to minimize producer risk to max. 5%, and the combined risk of producers and consumers to below 20% (Kurvers et al., 2009). It is also mentioned that this is an especially important requirement for service contracts. This again relates to facades as PSS.

It is stated that in service agreements, a responsible party for IEQ needs to be defined, as well as a protocol of testing that quality of performance in a reliable and verifiable way. (Kurvers et al., 2009) It is mentioned not to forget, that amongst all points of measurement in our buildings, the users themselves are the most valuable, long-term and steady network of data collection. They know best about the indoor climate and its problems. A diagnose-approach means that for example office workers are asked for their extensive input and concerns. That way, users feel taken seriously in the communication with management and researchers. The latter get a better view on the IEQ, because information is gathered for a multitude of locations within the building. The management and users are both more likely to feel that their worries are taken care of. I see user communication as a vital part of a successful PSS model for façade leasing, because of the abovementioned reasons. Additionally, it could potentially be even more useful, in a system of cooperative supply parties, looking to improve the quality of their products, by getting feedback. User´s opinions in a real operational stage might hold great value for system suppliers, who normally would not get this input. When such a system is put in place, both users and producers can benefit from sharing information about problems of IEQ, and solving them, either by optimizing the management and operation of systems, or even replacing malfunctioning components.

Kurvers et al. 2013: ***Robust Climate Design Combines Energy Efficiency with Occupant Health and Comfort.***

Kurvers et al. 2013 open their paper by saying that “It is hypothesised that, in daily practice, certain building typologies are more “robust” in terms of indoor climate design and energy performance.” (Kurvers et al., 2013, p. 1). They conclude that the so-called “climate-oriented typologies” score low on the number of building related health symptoms per year, as well as on energy use deviation (comparing predicted to measured consumption). See page 7 of Kurvers et al. 2013 for explanatory figures of how other design profiles compare. It is said to make climate-oriented designs the most robust. Factors of less robust buildings are listed as a lack of user-control (because it is beneficial to experienced indoor comfort for users to make their own choices and trade-offs) , active design (vs. passive design), high maintenance requirements (because they are prone to budget cuts), as well as combined heating and ventilation systems. (see Kurvers et al., 2013, p. 4).

An important point is made, as “it should be noted that most green building certifications are based on theoretical performance, as predicted during design” and “Long term overall performance – e.g. 5 or 10 years after project completion – is rarely published.” (Kurvers et al., 2013, p. 1). The question arises, how predicted energy performance and IEQ compare to practical results. Different graphical data highlights that the performance gap is not just generally apparent, but critical examples can even be found amongst LEED-certified buildings. This could be the result of different factors, but one interesting concept is stated: With higher standards of building performance, the bandwidth of indoor temperature decreases. In the highest standard category, this can have the effect that relatively more energy for HVAC systems is used to reach the strict goals of indoor comfort. Even though the case study of my thesis, and therefore a representative application of leased facades, is a renovation project with no climate certificate in mind, the above-mentioned issues are a valuable consideration. When defining the performance goals within a product-service contract, a realistic range of indoor comfort should be agreed on, considering the amount of energy needed to achieve them. That means analysing the specific building at hand, including all cold bridges and reasons for overheating that are not being solved in renovation, to find realistic goals of indoor temperature.

Sakellaris et al. 2016: ***Perceived Indoor Environment and Occupants’ Comfort in European “Modern” Office Buildings: The OFFICAIR Study***

The publication is a result of the OFFICAIR study, which addressed questions to “7441 workers in 167 “modern” office buildings in eight European countries (Finland, France, Greece, Hungary, Italy, The Netherlands, Portugal, and Spain).”, about the indoor environmental quality of the buildings they were situated in. It was added to the body of literature used for research in this thesis, to find out about the most prevailing factors resulting in poor indoor comfort. It was concluded that acoustical issues were the highest concern of occupants and more specifically the “noise within the building” was the most important parameter associated with comfort, followed by “noise from the building systems” and “outside noise”. Interior acoustical insulation (between or within offices) can hardly be improved by any façade-related measures, which means that even after a successful energy renovation of the envelope, occupants might remain somewhat unsatisfied. The acoustical insulation of the façade and its openings on the other hand must be taken as a critical design criterium, referring to the study results. However, that parameter is most important in the design stage (providing a well-insulated envelope and smart means of natural ventilation, with integrated sound insulation), because measures that can be taken to improve acoustical insulation during the occupancy period are limited to the maintenance of gaskets. For that reason, the choice made for this thesis, to focus computational analysis of the case study building on the thermal aspects of IEQ, are contrary to the conclusion of the OFFICAIR study.

Circular Economy and Circular (Façade) Construction

Ellen Mac Arthur Foundation 2017: *Achieving Growth Within*

In the publication by the Ellen Mac Arthur Foundation (2017) it is argued that the transition towards a circular economy in the European Union entails not only environmental benefits, but major investment opportunities. Technical innovation is said to play a large role. Three main sectors are discussed: mobility, food and the built environment. Accelerating the rate of investment is seen as a key to success in reaching many of the 17 European Sustainable Development Goals. The challenge is said to be that the EU has not truly returned to the economic growth rate of before the financial crisis. The authors say that "This lack of investment seriously hampers the EU's industrial innovation and renewal, its future competitiveness, and it puts Europe's industrial core at risk of slow erosion." (EllenMacArthurFoundation, 2017, p. 11). Therefore, the Ellen Mac Arthur Foundation introduces "ten attractive circular innovation and investment themes, totalling €320 billion through to 2025, (…)" (EllenMacArthurFoundation, 2017, p. 12). First-mover companies are said to have access to most attractive investment opportunities, while moving away from the linear economy. However, launching a circular business model is anticipated to be more challenging, compared to linear ones. Closing the material loop by remanufacturing or second hand retail in general, requires a predictable inwards flow of used products towards the (re)supplier, and also users that are interested in buying those remanufactured parts. Even though some initial investment is needed to perform the transition, and some additional production costs might arise, the authors state that "designing and producing for prolonging and looping is often profitable, (…) it opens up potential new revenue streams and some emerging customer segments are likely to be willing to pay a premium because the product has a higher value to them". (EllenMacArthurFoundation, 2017, p. 25).

A statement is made, which is very much related to the topic of my thesis: It is said that high costs and a fragmented group of stakeholders hold back the implementation end-of-life solutions for building materials. It is proposed that "This can be mitigated by shifting to performance-based or service-based business models where buildings are rented or leased"(EllenMacArthurFoundation, 2017, p. 33). Key to a successful transition to these new business models is said to be the collaboration of stakeholders.

The system of material or product passports is seen as a promising approach to strengthen the resale market for end-of-service life products. Users could share information about a product that they no longer need and receive buy-back offers from companies who are interested in the residual value. This would also have a positive effect on product design, because an easy disassembly then becomes an important consideration in business strategies. For façade leasing to be a circular model, it is important to build a competitive market for second hand materials and building products, because only then, the theoretical residual value of façade components (after one of multiple service lives) becomes a genuine financial opportunity. This consideration will be discussed later on in this thesis.

Webster et al. 2017: *The Circular Economy. A Wealth of flows*.

Ken Webster (2017) highlights the issue of our "throwaway society", building economical growth and rising living standards on the consumption of raw materials and energy for mass-production. He states that an unrealistic assumption is made, that financial success leaves room to invest in "cleaning up" the ecological and societal problems that come with our linear economy. Webster promotes the transition towards a circular economy.
Our current approach of recycling (some of the) materials after a single use is said to include so-called "leakage" in the cycle. He states that, especially for low-cost single use products, a seemingly high efficiency in recycling still leads to a waste of resources, because of the fast cycle from factory to bin.
Webster presents four shifts that are embedded into the transition towards a CE, (referring to Amory Lovin´s theory of *abundance*), including the switch from goods to services. He states that modern information technology can be used to facilitate systems for temporary use and sharing, while lowering costs. In a Circular Economy, the actors known as "consumers" would become users.

In a CE, "functional service" models are characterized by suppliers retaining product ownership, while providing their use as a service. In this thesis, the concept of offering the use of products as a service is taken one step further, by researching the possibility in façade leasing, of supply-demand transactions that focus only on the performance of said product. Clients do not pay to use the façade, but for a complete service package, that leaves them with a purely performance-based result, without any actual commodity to worry about. Webster (2017) refers to founder of Wired magazine, Kevin Kelly, when saying that the future holds a sharing economy, providing a less rigid environment with on-demand services.
Ken Webster states that product-service-systems promote efficient service life periods, and end-of-service-life management systems, as a result of suitable design practices, higher product durability and properties of disassembly (incentivised by the new business models). He also states that one of the most important change in suppliers´ practice will be to understand and act on the cost and risk of waste within their own business, instead of handing it over.
By introducing practices of reuse and remanufacturing, efficient labour is seen as a renewable resource, promoting a more human-centred economy. He proposes a taxation of only non-renewable resources, thereby benefiting all practices within a circular economy, in primary, secondary and tertiary sectors.
For the use of materials, the "cradle-to-cradle" principle is described. Following the principle successfully is said to hold economic benefits. Materials are categorized according to their end-of-life properties: biological materials are safety biodegradable, while technological materials are not, which means they need to be maintained qualitatively and managed in a different, technological cycle. For technological building materials the amount of embodied energy of raw material extraction is typically much higher than in later manufacturing phases, where however most of the manual labour is needed. In CE, the consumption of raw materials is no longer part of production practices, so the value chain is inverted.

Façade Value and Real Estate

Den Heijer 2013: *Assessing facade value - how clients make business cases in changing real estate markets.*

Den Heijers paper "elaborates on how (a) the trends in real estate markets and (b) changing priorities in decision making affect the quality demand for buildings and their facades." (Den Heijer, 2013, p. 3). She argues that for parties investing in the built environment, there are added values, besides those of a financial nature. She introduces 4 key performance criteria, which can be used to assess façade value: (1) organizational performance, (2) financial performance, (3) user performance (productivity) and (4) energy performance. The first criterium represents an organizations identity and status in the competitive market. Secondly, life cycle costs and market value make up the financial value of facades. Thirdly, user performance is related to the functional value of facades. Lastly, a good energy performance of facades is a combined criterium of indoor climate and the effect on the environment. It is stated that proving a negative productivity is easier than a positive one. She mentions an interesting fact, that:

“Even the traditionally supply-driven market for ‘commercial real estate’ has become demand-driven, paying more attention to future use and users. Investors that have traditionally focussed on ‘financial value’ are now expanding their view to ‘functional value’, ‘energy value’ and ‘strategic value’, because their potential tenants have plenty of alternative choices.” (Den Heijer, 2013, p. 6). Stakeholder´s interest in the model of facades as PSS, as seen in their participation in pilot projects on the campus of TU Delft, surely demonstrates this shift of interest. In my thesis, the aspects of “functional value” and “energy value” are touched upon, in the context of façade leasing. As a development of the last two centuries, Den Heijer says, it can be observed that a good energy performance of buildings leads to an increase in cash-flow, because customers are interested in that characteristic. Therefore, the three values of energy, function and finance are tied. This fact is an important consideration for the work of my thesis. She also mentions that most buildings are not commercial, but either corporate or public, and that the interest of owners of the latter is especially “demand-driven”. For example, a building of an educational function is primarily meant to keep the user’s productivity high, to increase the success of education.

For those building typologies, budget cuts have been seen to lead to lower initial investments, which can result in lowered productivity and increased operational costs, as stated by Den Heijer (2013). However, she noted that in recent decades, “assessing ‘life cycle costs’ and measuring the effect on performance has become more common.” (Den Heijer, 2013, p. 8). Following these developments, it can be concluded that the issues that are being tackled by the model of product-service systems for facades are very relevant.

Further, Den Heijer states that “30 years is considered a standard depreciation period” for buildings, while “components of the building could have a longer or shorter functionality, which could lead to new investments (replacements) after 15 years.” (Den Heijer, 2013, p. 9). She concludes that the decreased operational cost of façades with a longer service-life span would outweigh any higher initial costs, because the latter is typically lower than the former (when compared on an annual scale).

Den Heijer also lists the key performance indicators (here used to assess multiple case study buildings on university campus sites), which range from CO2 emissions per user, to profitability, but interestingly also the competitive advantage which is related to the universities repetition, which has an effect on potential students choosing a university. However, the idea of constructing landmark buildings as means to success is seen as an invalid approach, at least when prioritizing values correctly. As Den Heijer describes as part of her recommendation, it is vital to strive for “health, safety, social and aesthetic needs (in that order). Focussing on aesthetics before focussing on health and safety issues negatively influences user satisfaction and functional value. Even fulfilling social needs – like adding to the sense of community – precedes satisfying aesthetic needs, according to Maslov’s hierarchy of needs. Increasingly, organisations want to be open and transparent, show the production process and enable (social) interaction to encourage innovation – facade design should support this ambition.”(Den Heijer, 2013, p. 14). For the practice of façade construction, those statements are useful guidelines on how to approach some dilemmas that arise in façade design, and discussions in my thesis.

Van Winden 2016: ***Value and cost assessment of an Integrated Facade as a Product Service System.***

Jeroen van Winden´s thesis of 2016 is used as a source of information about previous research on the physical implementation of leased facades at TU Delft, more specifically the demonstrator project at the faculty building of Electrical Engineering, Mathematics and Computer Science (EWI). He introduces his report about integrated facades as product service systems by wanting to research "the added value of different components and integrated services for both sides systems" (Van Winden, 2016, p. 6), meaning supply and demand stakeholders. Talking about PSS-type business models, he finds that challenges of legal and contractual nature need to be overcome, and the demand-side needs to get accustomed to it. In his research, he gathered input from different stakeholders, who expressed their interest in the project. The EWI project was therefore put into place, "to really make all people around the table think about the realization of the concept" (Van Winden, 2016, p. 12). By transcribing and analysing interviews and researching case studies of integrated façade solutions, he designed different options for façade test panels, using a different set of components by assessing the added value, using the scheme of four categories of value, introduced by Den Heijer (2013).

About facades as PSS, he states that the supplier is responsible to safeguard a continuous level of performance throughout the service-life, including the "strategic performance", which is related to the identity of the customers organization and "fashions" in the building industry. He assesses not only the performance requirements at the beginning of a building´s life span, but the changing needs over time. In a set of graphs, he visualizes the need for a system of façade upgrades. Designing future-proof envelopes therefore means, as stated by Van Winden, that provisions need to be made in both the contractual setup (investment will be needed for the upgrades) and the physical façade design (must be flexible to changes). While this consideration is kept in mind during the work on my thesis, more research is definitely needed, to convert some first general results into a successful business model that proves in the test of time.

Façade Renovation

Ebbert 2010: *Refurbishment strategies for the technical improvement of office facades*.

Thiemo Ebbert (2010) introduces his thesis by reminding of the urgency to renovate the existing stock of underperforming buildings, to reduce energy consumption in climatizing them, and also to save their functionally sound internal structure, as well as architectural identity from demolishment. He sees the lack of innovation in the current building practice as a barrier, and states that "The planning team is often lacking the necessary overview of the challenges of office façade refurbishment. This research helps reduce the number of possible alternative planning solutions before the project actually commences." (Ebbert, 2010, p. 10).

He focusses on analysing Western-European post-war offices in need of refurbishment. He starts off by making clear, why refurbishment should be chosen over other options, stating that currently the majority of energy and resources flow into the construction and operation of buildings. Therefore, he says that the goals of reducing CO2 emissions by 2050 for a sustainable development can only be met by reducing the demand of buildings, especially by refurbishing the building envelopes of old, underperforming stock, (he states that "In operation, refurbished building can then save up to 75% of energy.") (Ebbert, 2010, p. 18) and reducing the construction of new stock, by keeping what we already have.

As Thiemo Ebbert phrases: “Buildings are stored capital. Money is bound in dead materials.” (Ebbert, 2010, p. 19)

Next to material and energy related factors, the importance of IEQ is proven to be a defining factor for successful buildings and their renovations, as Ebbert (2010) takes from a field study of the University of Berkley, showing that in a comfortable environment, people are up to 15% more productive, in terms of their work and the days of presence. Additionally, he states that “the profitability of a building rises” (Ebbert, 2010, p. 20). Next to these quantifiable benefits of refurbishment, Ebbert mentions the architectural and urban value of facades, defining spaces of our cities, in need of thoughtful renovations that maintain historical values of identity, while critically reviewing past design decisions that do not support a society´s needs.

In a later chapter, Ebbert discusses different façade components, including “Service integrated facades” which here refers to facades with integrated, decentralized building services such as HVAC units. For those heating and cooling functions, he argues in favour of their façade integration, because the handling of air does not include leasing it through long distances of ducts, which would be less energy efficient. The large amount of maintenance points however is said to require a well-managed system. It could therefore be concluded, that a service integrated façade would run most smoothly when implemented as part of a PSS, where maintenance should be an indispensable part of the service contract, and the knowledge about the technical build-up as well as operational requirements is directly available. A clear service contract of leased facades can help solve the issue that Ebbert addresses as the following: “The major problem for the marketing of service-integrated façade systems still lies in the unclear responsibility of different parties.” (Ebbert, 2010, p. 45). These challenges, combined with the benefits of placing all climate-control systems on the façade (hence making it easier for the façade supplier to control and therefore guarantee performance of energy and IEQ) form promising arguments for the integration of building systems into the façade. This idea is already picked up by some other works of research, including the thesis of Van Winden (2016). It is an interesting addition to the general concept of facades as PSS. In my thesis, I am not doing further research on it, because the renovation of the CiTG case study building is performed without altering the setup of existing climate-control systems. However, the current building does not have a mechanical cooling system and tends to overheat in summer. In case the project is taken further than the expected leasing period of 15 years, it might be a valid consideration to upgrade the (leased) east façade with integrated systems, especially because the structural layout somewhat prohibits a free layout of ducts towards a centralized HVAC system.

But the most concrete use of information found in Ebbert´s thesis is found in chapter 5.1, where the CiTG building is used as one of the case study projects, applying multiple design variations, and assessing the economic, architectural, material and comfort aspects that characterize each solution. Extended reference to his thesis can be found later, in the main body of the text.

Façade Design and Construction Concepts

Hövels 2007: *Open modular facade concept.*

The thesis of Joep Hövels (2007) addresses the topic of the modular design of system integrated facades. He states the fact that facades have become more complex with an increased amount of integrated functions, resulting in a more difficult construction process which is said to be problematic during the assembly on site. His goal is to brainstorm different options for modular, system integrated facades, and then rate them to find which one is most promising and worth defining in more detail. Besides integrating different functions, Hövels also aims for a functionally and geometrically flexible solution, which can also be upgraded over time. To achieve these goals, he discusses the meaning of modularity, the interface between components, and different reasons for components to be demounted from their position.

The definition of modularity and what comes with it was interesting to me, as I had used the word "modularity" when referring to individual components of a system, that are easily connected to form or become part of a whole, shaped in sub-divisions of a certain "master-grid". All of these things can be achieved but are not automatically part of the definition. I was mostly thinking about unitized façade constructions, with a so-called "sectional interface", where all panels connect directly to each other along their edges, and simultaneously characterized by a "decoupled interface", meaning that individual elements are functionally independent so that they could be replaced without having to adapt the entire system. Reading Hovels´ thesis, it became clear that a modular façade design includes a multitude of choices to be made.

Hövels´ design result, the "Smart Post", fulfils the requirements he set up for his work, but they are specifically focussed on system integrated facades, while I will not focus on those in my thesis. I believe that a modular concept for the CiTG building and similar retrofit projects would face some entirely different challenges. Therefore, mostly the introduction of the general topic of modularity in Hövels´ thesis is used as a source of information, while any further design related discussion does not apply.

The questions I am asking, revolving around modularity, are related to standardization and ease of disassembly. A circular, leased façade should ideally move away from complete customization on a single-project basis, and towards a certain level of standardization in terms of sizes and interfaces. This will be discussed later in the main body of text.

Klein 2013: Integral Facade Construction: *Towards a new product architecture for curtain walls.*

In his publication of 2013, Tillmann Klein gives an overview of historical and current processes in façade construction. Further, he argues that "With continuously rising requirements in terms of energy savings the constructional principle has reached its limits and strategies for improvement are needed."(Klein, 2013, p. 7), and therefore he assesses future challenges, sees how case studies respond to them, and concludes the designs´ advantages and disadvantages. He states, that an integral approach in stakeholder interaction is needed, and a diverse product architecture approach is key to future success.

Klein mentions about the building process of facades, that "the entire building process is divided into separate crafts" (Klein, 2013, p. 24), while the architects task is to act as a link between them, choosing either standard solutions or defining customized aspects. He further explains that

"However, problems in combining the traditionally separated crafts of façade building and services are far from being solved. It will need new building processes and physical interface structures to address these issues. And we need to answer the question who will take the lead in engineering the details and how the responsibilities will be distributed. These are problems that are rather new and challenge the traditionally separated building disciplines." (Klein, 2013, p. 27)

These questions are far from being answered completely, because different approaches are possible. In a PSS scenario, the main façade supplier clearly takes a leading role in detailing and taking responsibility, not only for products but their performance. In this case, the relation between architects (currently forming the intermediate bond between stakeholders) and suppliers will change, because shifting responsibilities also requires a shift in decision making about the physical building products. Klein (2013) is used as a source of information about the current practices in the industry, including tender processes, which be the initial definition of actor´s roles in a project. To understand stakeholder relations and their effects, Tillmann Klein includes interviews and their evaluation into his research. The information will be referred to in related discussions of my thesis.

Venancio et al. 2011: *Understanding envelope design: Survey about architectural practice and building performance.*

The paper of Venancio et al. (2014) shows research used as a step towards developing simulation methods for architectural design. The authors argue that there is a lack of concrete informational support behind most design decisions, because they are taken by architects upon qualitative intuition and reference projects, leading to reoccurring errors. While that approach can present generally useful, the authors see quality enhancing opportunities in adding simulation tools to the process. To understand how decisions are currently taken, the papers research is based on the findings of an online questionnaire, addressed to groups from different professions.

Venancio et al. (2011) conclude that

“The results of the survey indicate that the use of building performance simulation (BPS) by designers and researchers is still limited (…).”(Venancio, Pedrini, Van der Linden, CVan den Ham, & Stouffs, 2011, p. 7) And discuss which party would be most likely to add information by taking the task of using a simulation method: “Although consultants have the technical expertise to carry out computer simulations (…) Consultants have limited autonomy to take design decisions and rarely have access to all subjective criteria used by designers.”(Venancio et al., 2011, p. 7). Most important to me was the conclusion that “Each category has features that can be merged and benefit the development of concepts to use simulation within the design process.”. This would present a solution as how to combine the knowledge of different professions involved with the design process of facades. Of course, a simulation tool alone would not exclude the need for interdisciplinary communication. Additionally, the questions in facades as PSS go beyond the pooling of knowledge, as discussed in my thesis: Defining the demarcation of responsibilities related to the IEQ and energy performance of facades is equally important as the question of who makes design choices and how.

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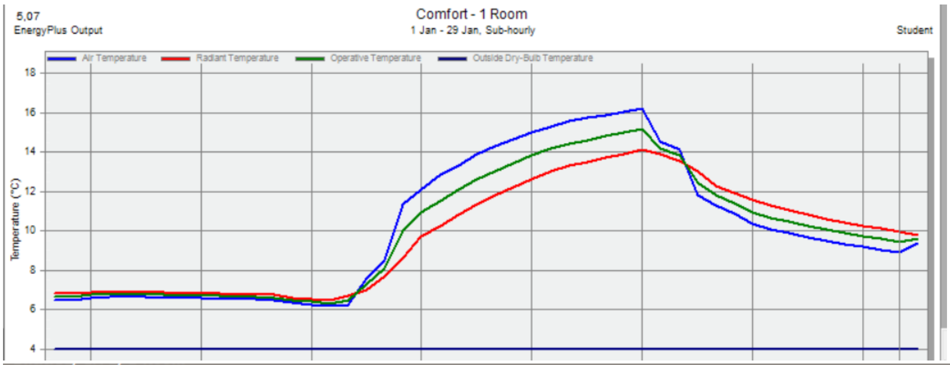
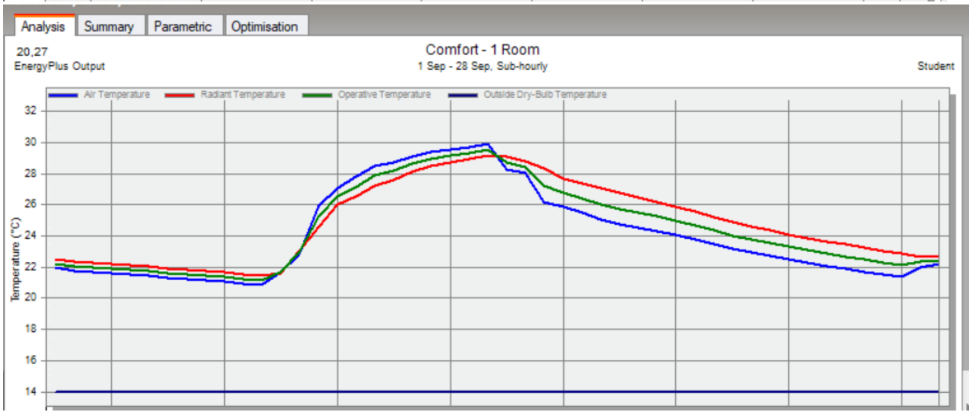
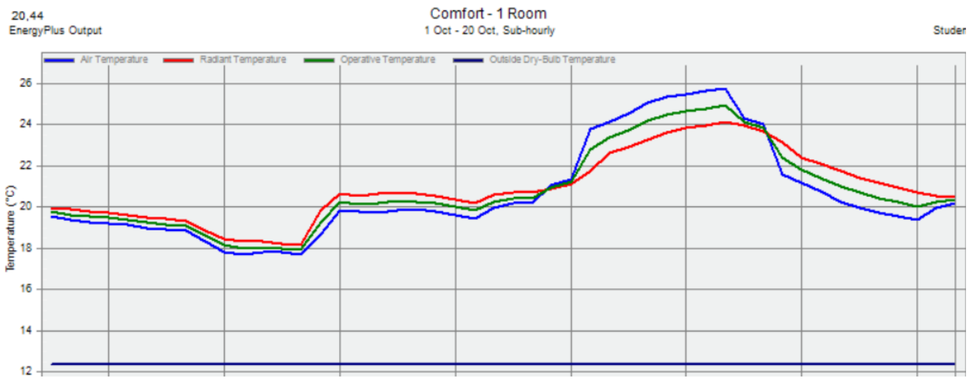
2. Design builder results

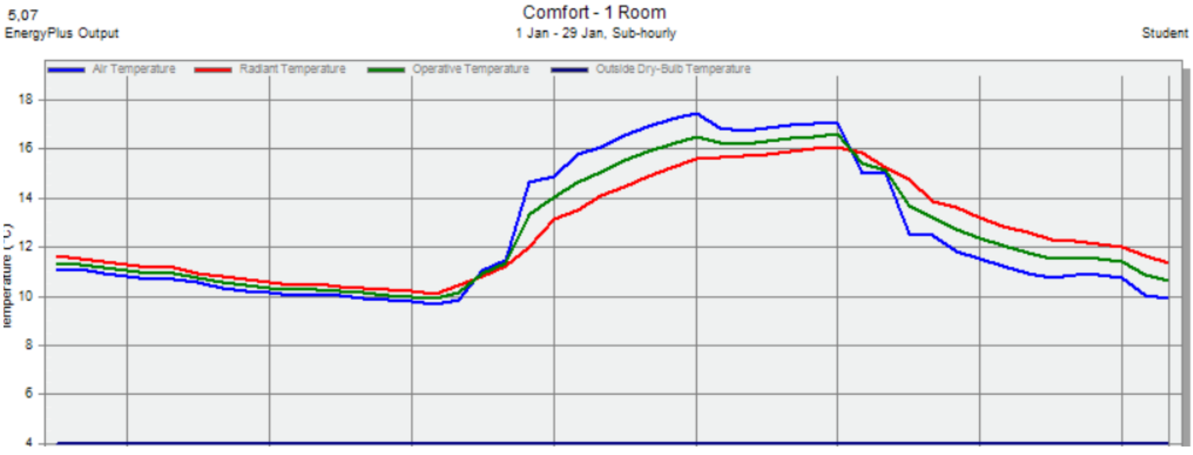
Results A= before tuning:

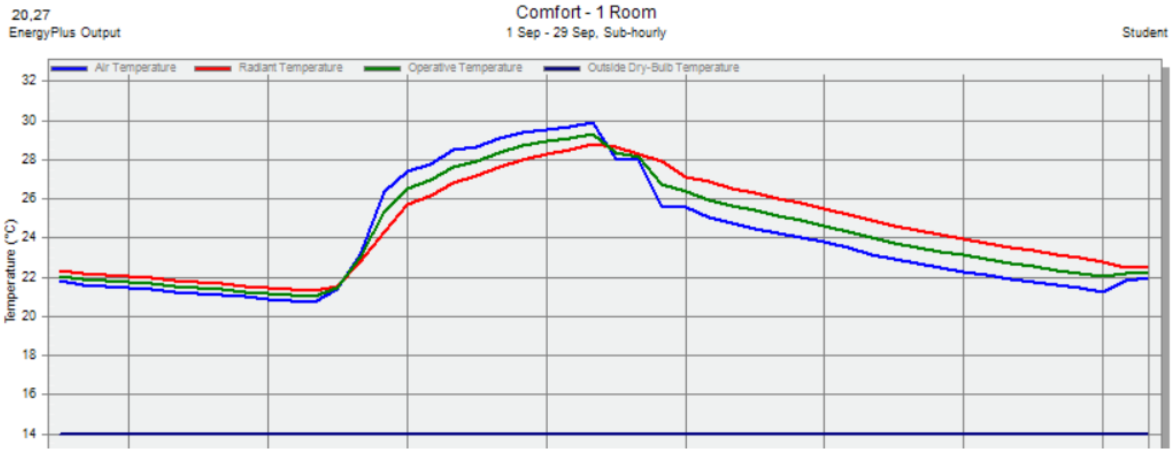


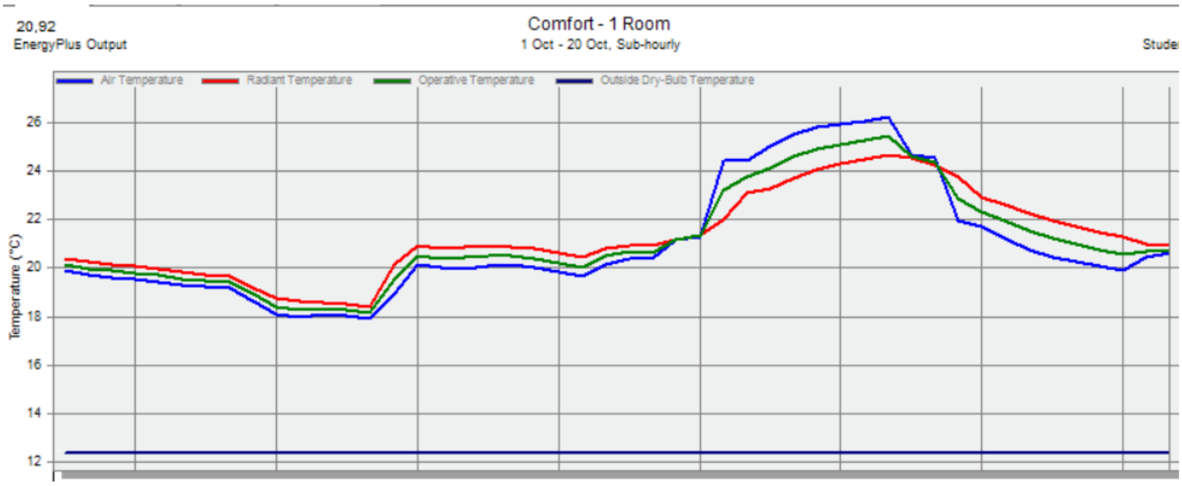




Results B=After tuning shading, ventilation rate and internal heat gains. (same weather data)







Results of the other simulations are given in chapter 3.

3. Heat balance equation

Steady state hand calculation to verify stage 1 of design builder simulation.

Heat gains = heat losses

Qppl.+ Qappl.+ Qsun = Qv + Qtr.

Qappl. = 240W

Qappl. =500W

Qsun (28. Jan., average) = 11 W

Qsun (27.Sep., average) = 67,6 W

Qsun (18.Oct., average) = 0 W

Te (28. Jan., average) = 4 °C

Te (27.Sep., average) = 14 °C

Te (18.Oct., average) = 12,4 °C

Qv = 0,35 * n * V * ΔT ; n=0,7 ; V=95,9m^3 ; ΔT=Ti-Te

Qv = 0,35 * 0,7 * 95,9 * ΔT

Qv=23,5 ΔT

Qtr. = (U concrete * A concrete * ΔT) + (U window * A window * ΔT) + (U spandrel * A spandrel * ΔT)

Qtr. = 2,7 ΔT + 48 ΔT + 3,5 ΔT = 54,32 ΔT

28. January, 10:00:

240 + 500 + 11	=	23,5 ΔT + 54,32 ΔT
751	=	77,82 * (Ti – 4)
9,65	=	Ti – 4
Ti (Jan.)	**=**	**13,65 °C**

27.September, 10:00:

240 + 500 + 67,6	=	23,5 ΔT + 54,32 ΔT
807,6	=	77,82 * (Ti – 5,7)
10,3	=	Ti – 14
Ti (Sep.)	**=**	**24,37 °C**

18.October, 10:00:

240 + 500 + 0	=	23,5 ΔT + 54,32 ΔT
740	=	77,82 * (Ti – 15,2)
9,5	=	Ti – 12,4
Ti (Oct.)	**=**	**21,9 °C**

4. Campus buildings assessment:


Faculty of Technology, Policy and Management


Faculty of Industrial Engineering

The following notes were taken while assessing some campus buildings for a theoretical refurbishment reusing the CiTG panels:

The faculty of Technology, Policy and Management has different facades on different sides of a larger building. Neither one of them shares a similar type of façade: the east façade (left image) has smaller windows that are positioned in between closed parts. Large glazed panels as in the CiTG could not be integrated without making major changes. The opposite case can be seen on other side of the building: There, the entire façade is positioned outside of the structure, in relation to both vertical and horizontal load bearing elements. The façade grid does not align with the dimensions of the CiTG.

The façade of the faculty of industrial design has a generally similar division of glazed and opaque parts, however the dimensions of glazed areas is too small to be replaced by the CiTG leasing panels.


Faculty of Mechanical, Maritime and Materials Engineering


Faculty of Applied Sciences (Lorentzweg 1)

The faculty of MME has glazed areas of around 3,2 m x 3,2 m (excluding separation by small dividers). In the vertical direction, this would align quite well with the CiTG panels, but the horizontal direction seems to be confined by columns. It would have to be defined, whether these are primary structural elements or are made for a different purpose. In order to mount the CiTG panels, the only solution would be to position them outside of the existing facade plane. With that, some additional insulation elements would need to be added. Overall, it is not seen as a promising application (unless the vertical dividers could somehow be repositioned).

The faculty of applied sciences has a very defined facade grid, with narrow glazed openings. Dimensions were not taken, but assumed to be in-between a 1,80 and 3,60 width, which does not allow for an application of the CiTG system.



Education Building 35

The Dream Hall

The "Education building 35" shares the same façade typology as the faculty of MME. The same conclusions can be made.

The "Dream Hall", positioned only a few meters away from the CiTG, has quite large glazed areas, and closed parts of brick finishing. Although this building is not very large, its façade dimensions do not inhibit a reuse of the proposed panels. Exact dimensions would need to be assessed, as well as the structure used to mount the panels.




Faculty of Mathematics and Computer Science

Bouwcampus

The Faculty of Mathematics and Computer Science has very small windows, in between closed parts made from aluminium cladding. It is not seen as an option.

A series of buildings in close distance from another is known as the "Bouwcampus". The northern most one (building b), can be seen on the right-hand picture. In comparison to the other buildings of the complex, it has quite large windows, where an array of 4 glazed panes is enclosed by vertical concrete columns and the edges of floor slabs, as well as a closed surface area finished in white brick texture. If the sizes of the glazed panels are around 1,80 wide each, and the closed spandrel element could be removed, possibly the remaining opening would be fit for the CiTG façade elements.

Faculty of Applied Sciences (Van der Maasweg 9)

The Faculty of Applied Sciences at the north end of the campus is a rather new building. It has a large grid of openings, in between a concrete structure of 60cm wide columns and beams. The openings have dimensions of around 3 m x 3 m. The problem here is mostly the width of openings (which is neither fi fore one 1,8 panel, nor two of them). Unfortunately, that is a problem that is not easy to overcome. Additionally, this building will probably not need a retrofit in the coming years.

Faculty of Aerospace Engineering

The high-rise part of the Faculty of Aerospace Engineering has a similar layout of glazed and non-glazed façade areas. The exact dimensions could not yet be assessed. Therefore, no conclusion was made about this building.

The Fellowship

"The Fellowship" is located next to the Aerospace building, and can clearly be asessed as not suitable for the reuse of CiTG panels, because the façade consists of fully glazed areas, which do not have a suitable structure behind them, to mount the reused panels. The strutural typology forms a barrier.