GRADUATION LAB | ARCHITECTURAL ENGINEERING

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GRADUATION THESIS | ARCHITECTURE OF CHANGE

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PART 1 CONTEXT

The first part of this thesis covers the context of the design project. The design brief is evaluated and all relevant aspects that form an inherent part of the design assignment are evaluated.
1.1 design brief

In the graduation studio of the Architectural Engineering track the theme mobility stood central. The relevance of this lies in the fact that mobility plays a central role in the economy of the Netherlands. This concerns mobility on international scale, on the scale of the country, on the scale of the economic heart ‘Randstad’ and even on the scale of the individual highway. No wonder that a major highway junction, the Prins Clausplein near The Hague, is set as the site for this study.

The exact design question was defined as:

Develop a program for the left over spaces of the Prins Clausplein in relation to the perspectives of 2040, based on the assumption that nowadays problems will be solved by the automotive industry.

The 2040 in this refers to a recent policy document by the Dutch government called ‘Randstad Holland towards 2040’. This document gives an analysis of the current state of the economic centre of the Netherlands and a vision on what should be done to improve and develop this area. Some interesting relevant quotes from this document are given in the following.

The urban structure consists of a network of large urban and economic centres, which serve as junctions in international connections (road, water, air, rail, internet), with Amsterdam as international gateway. This network is unlimited and geographically linked rather than contiguous. This spatial functional structure will be scaled up, land use will be intensified, the internal and external accessibility will be improved (increased substance) and the urban quality and intensity will be reinforced. The focus will shift towards the power of the cities.

All of the urban areas are under constant pressure in terms of growth. More central urban living environments are needed in part, which forms a good basis for intensification around transport junctions, for example, and for switching to new urban functions such as housing on former industrial and port sites, railway yards and the like. The utilization of existing urban areas will at any rate be continued through, for instance, the transformation of an old port terrain into a living or living-working area. The aim is to meet at least 40% of the new housing demand in existing built-up areas.

If a serious and intensive investigation of the inner-city opportunities indicates that new locations are needed, these will primarily be sought in direct connection with the cities, partly using the possible shift of extensive ground utilization functions on locations situated relatively higher and linking up with the traffic and transport infrastructure.

Translating what the issues summed up here could mean for to the local scale of the Prins Claus Plein was the start of the development of the design. Especially the potential of the site as building ground for new urban expansion seemed very interesting from the start.
1.2 location

The site of the Prins Claus Plein offers the opportunity to examine a new built typology which is based on multidimensionality and four-dimensional expression. The fact that the area has not been defined yet with other building gives a high degree of freedom on what is conceivable.

Technology more and more takes away the limitations concerning safety and health-issues in the direct surroundings of the highway. This offers the opportunity to fill the location up with functions like living and working.

The Prins Clausplein takes up about 1 square kilometer of space. Looking on the map the site it is not near The Hague, but essentially in The Hague since the city has expanded to the east side of the A4 highway.

An aspect that also can be seen on a map, but even more on aerial photos, is the fact that the site has a very ‘green’ character. Until now it has been hard to develop urban developments near the highway, so the rest space is given to ‘nature’. When the possibilities for using this site are investigated, this should not be overlooked. It should be regarded as a quality of the site.

Finally the Prins Clausplein should not be regarded as just a junction of highways. The railway connection The Hague – Utrecht is another important traffic flow on this location, although it is hardly noticeable from the cars point of view. For the access to the site the secondary road to the south of the junction is quite important. The site is hardly accessible as a destination, but if this was to be tried, this secondary road is the nearest possibility.
1.3 boundary conditions

The Prins Clausplein is a four level stack interchange. The two major roads A4 and A12 cross eachother on a bridge, with connector roads crossing on two further levels. For a good understanding of the site, it is crucial to have a good understanding of the dimensions involved. Since the terrain between the highways is unbuilt-on, one can only relate to the measurements of infrastructure and vehicles. For the main crossing trajectories, the size of these profiles are about 50 x 10 meter. The ramps connecting these highways measure 20 x 10 meter in profile.

These profiles concern the existing situation. A study must be done into the need for widening these profiles for the matter of possible widening of the highways. If this should be necessary, this space will be secludeed from the available space on ground level.

The traffic in the current situation is equivalent to extreme noise and problems concerning pollution. If a living- and working environment is created on the location of the PCP, these factors will have to be taken into account. For comparison, for living environments a maximum sound pressure of 50dB(A) is required whilst the average sound level is higher than 75 dB. At the same time future improvements on this behalf will have to be recognized. Therefore contemporary protection should be achieved in such a way that it is adaptable in the future.

Aspects like pollution, small particles and traffic hazard should be taken into consideration too. The simple fact is that either one of these aspects is such a potential danger that it stops all potential for developments on this site. In this case too it is necessary to trust in future improvements.
In this part the process of developing ideas is being dealt with. The theories, research and thinking that preceded the actual design process explains the choices that stood at the basis of the design. Furthermore a brief description of similar projects gives a clue of what has been done before and what has been of influence on my design.
2.1 genius loci

Dealing with architecture near a high density of traffic infrastructure, needs a radical new approach towards the typology of buildings. One can build along a highway, or even over it, but in the end it will always result in two different entities that happen to stand next to each other. For this project my aim was to interweave the world of the highway and the world of architecture.

The traditional view on architecture will not suffice for this, for it is relates to the present and historic built environment and is therefore by definition not up to date with the latest developments in practice. Therefore that what is possible does not correspond to the general view of what a building is; an autonomous cumbersome object.

The term 'genius loci' refers to a location's distinctive atmosphere, or a 'spirit of place'. The thinking in terms of what the location is or represents offers a way of thinking in new typologies in architecture. Hence the unorthodox location is the immediate cause for unorthodox architecture.

Thinking of the distinctive atmosphere of the location, the idea of a hotspot of mobility is rather obvious. This can then be interpreted in different ways. For starters the site is constantly changing, because traffic is constantly changing. The site is only experienced in movement and therefore never regarded as a static environment. Moreover, infrastructure in the long term is always subject to change, because mobility now is not the same as it was twenty years ago and in 20 years it will be changed again. Images of what this change in mobility may lead to are known from as long as the twentieth century. Utopia's (or dystopia's) of what could be our foreland are shown on the left. Rather than assessing these pictures in a formalistic manner, they give a good insight in the way mobility and our thinking of the future are related.

In all of these interpretations, the aspect of change plays a central role. Change as a concept in itself, or as part of aspects like dynamic, modern, advanced and movement. The site thus, one could conclude, breaths an atmosphere of 'change'. This is what architecture on a place like this could and maybe should embrace; a notion of change. Maybe the Prins Clausplein is not a place for monumental architecture that it is here to stay. Maybe the element of change could be regarded as a quality and translated into aspects such as flexibility and adaptability. This way the architecture could relate to what the site is actually al about...
2.2 theoretical framework

“Now there is an ever-increasing need for these functions (complex human activities, red.) to be more flexible and adaptable, in both application and location, than they have ever been in the past.”
Kronenburg, 1996

Although the terms flexibility and adaptability might speak for themselves it proved useful to further specify these and other relevant terms. In this way differences in definitions and interpretations that are available are made insightful. This gives a starting point from which it is possible to determine the way the terms will be interpreted in the design.

An objective, non-specific definition of the various terms can be found in the dictionary, in this case the Oxford English Dictionary:

- **flexible** adj.
  1. Capable of being bent or flexed; pliable.
  2. Capable of being bent repeatedly without injury or damage.
  3. Responsive to change; adaptable

- **adaptable** adj.
  Capable of adapting or of being adapted.

A somewhat cynical assertion by Periáñez (1999) on the other hand lists synonyms which describe one and the same building type: adaptable, enlargeable, à la carte, convertible, dynamic, elastic, extensible, flexible, mobile, module-friendly, customizable, versatile, transformable, and variable.

Naïve as it may seem, this statement does give a good insight in the problem at hand, since the definitions of the listed terms and the differences between them can be rather vague. This again appeals to the need of defining what is meant exactly with the words. For this a scan through the available literature is made.

Kronenburg has written extensively on this subject. In the following he speaks quite generally about certain aspects of flexibility:

“Where functional problems have necessitated a responsive, built environment, flexible architecture has formed at least a part of the solution.”

“Flexible buildings are intended to respond to changing situations in their use, operation or location. This is architecture that adapts, rather than stagnates; transforms, rather than restricts; is motive, rather than static; interacts with its users, rather than inhibits.”

Adaptive buildings can be defined as ‘performance-based’ buildings. This is the way at least, as the word is put to use by the ‘Adaptive Building Initiative’, an institute that has the mission to bring designers and engineers together to create adaptive systems for architectural projects. The following is a statement by Chuck Hobcrman, a member of ABI and a president of Hoberman Associates which is a multidisciplinary practice that specializes in transformable design.
"We call these adaptive buildings because they can adapt their shape and function in real time to environmental changes. This field remains far less developed than other areas of practice, but the logic of adaptive performance — which is time-based, responsive, and dynamic — is compelling. Buildings that continuously attune their configurations in accordance with changing environmental conditions use less energy, offer more occupant comfort, and feature better overall space efficiency than static buildings."

"The logic for performance-based strategies is straightforward: Buildings that maintain optimized configurations to environmental conditions function more effectively."

Kronenburg speaks of adaptability mainly in the context of the relationship between people and building. To him, adaptable architecture implies the absence of a single design process, which is to be replaced by the interaction of all kinds of participants during the lifetime of a building. The influence on the design decisions by the users of a building is therefore one of the most significant attributes of adaptable architecture according to Kronenburg.

Adaptation to Zuk and Clark is a response to pressures that act upon a structure. Architecture is defined as a 'three-dimensional form-response to a set of pressures'. This implies that a change in pressure (this can be a change in any outside element like climatic changes or differing needs of people) needs to be reacted upon by the architecture of a structure. This is what adaptation truly is. The ability of a structures adaptation is thus determined by the way the differentiation of pressures is provided for by the designer.

According to Duffy, there is no such thing as a building. "A building properly conceived is several layers of longevity of built components". Having distinguished four different, more or less independent layers, later researchers extended the list to seven different layers. These layers are:

- Site: geographical setting, eternal
- Structure: foundation and load bearing elements, 30-300 years
- Skin: façade and roof, 20ish years
- Services: installations, ducts etc, 7-15 years
- Space plan: interior layout, from 3 (commercial) to 30 (domestic) years.
- Stuff: furniture and belongings, from 1 day to several years

This is relevant in that way, that it seems impossible now to speak of the transformation of a building. One can only speak of the transformation of an independent layer of a building. Thus, whenever adjustment is needed to cope with a changing need in flexibility, the right layer of a building is to be addressed instead of adjusting the whole building.

This theory of organizing adjustment through a system of independent levels of decision-making was first recognized by Habraken in the 1960's. He understood that there is a hierarchy in the different layers and that a transformation of one layer does not automatically imply a change in another layer.
Habakken treats transformation as a system, composed of interdependent sub-systems. The three interdependent subsystems that form a transformational system are:

1. Spatial transformation (implies change in usage and functional obsolescence)
2. Structural transformation (implies technical obsolescence)
3. Material/element transformation (implies physical obsolescence)

The strategy of spatial transformation ensures that a space adapts in such a way that it remains relevant to its users. This strategy is the common way of speaking about adaptability, since the space remains intact in contrast with the other two strategies. Whereas ‘common’ buildings are typically designed to remain unchanged and static for a period of about sixty years, this attitude ensures that structures are designed to be (many) different buildings through time. To be able to implement this strategy, an understanding of a range of changes that might occur during the lifetime of the building will be necessary. Spatial transformation can potentially happen during the whole of the lifetime of a building and can be defined as:

- Extendibility (enlargement of the space),
- partitioning (rearrangement of space units),
- multi-functionality (rearrangement within space units),
- functional mutation (mutation from one function to another).

Structural transformation provides continuity through the disassembly of a building (and obvious replacement), combined with the recovery of parts of the building. The structure as a whole can be left intact for example, whereas the rest of the building is dismantled. Technical flexibility is related to the ability of building components and systems to be easily replaced, displaced, reconfigured, reused, and recycled. The indicators of technical flexibility are:

- Accessibility,
- replace ability,
- reconfiguring,
- separation.

There is natural interdependency between technical flexibility and spatial flexibility and they cannot be isolated from each other. Every change within the space has consequences for the technical systems of the building, and vice versa. Rearrangement of spatial systems for instance is difficult to achieve if the components brought together to create a particular spatial system, are not designed for exchangeability.
Having searched for the right way to use terms like flexible and transformable, it is time to take a stand in the offers that theory gives.

Relating transformability to only a certain layer of a building can be useful in a conceptual way, but it is somewhat challenged by the notion that there is a strong interdependency between technical and spatial flexibility. This implies that every change will somehow affect other parts, probably including other layers of the building.

The different kinds of transformation should be monitored closely, since it might be too easy to automatically only have an eye for spatial transformation, neglecting the other two ways of transformation.

Lastly, literature on adaptive and transformable structures usually mentions a lot of warnings in between the benefits this type of architecture has. In order to be able to design with the aspect of transformable spaces, it might be wise to take the following comments to heart.

The key obstacles for successful transformation of buildings are often related to:
- spatial inability to mutate from one use concept to another,
- inflexible load-bearing structure,
- inflexible installation systems that cannot easily adapt to different spatial typologies,
- fixed integration between load-bearing and non load-bearing parts of the building.

Kronenburg, 2007

A valid criticism of adaptable architecture is that it cannot provide a close fit to the functions that it must support. It is a solution that must, by necessity, be able to accommodate other uses and these may be compromised.

A strategy that deals with this issue is the idea of fluctuating space. In essence this approach to design is to incorporate in a building dedicated, functional spaces, that address specific functions that need to be carried out there (...)

Kronenburg, 2007

Transformation is not an easy characteristic to introduce into building. Problems occur in three main areas: movement mechanisms, joining of internal and external partitions; and operation of services under the different conditions.

Kronenburg, 2007

Simplistic attempts to increase flexibility often result in a loss of flexibility. Flexibility is achieved not just by keeping your options open, but by making decisions. It is thus important to define the parameters of the ‘design world’ within which flexibility is required to be achieved.

Rosa, 2003
2.3 precedents

Cedric Price | United Kingdom

"Price redefined the role of the architect as 'an agent of change', whose main responsibility was to anticipate that, and offer new possibilities for society as a whole."

By engaging with existing economic, political and structural networks, Price explored architecture's potential to nurture change, intellectual growth and social development. To Cedric Price architecture was not about the finished building but more about an ability to enable and facilitate change in a changing world.

Fun Palace

Price's 1960-61 project, The Fun Palace, established him as one of the UK's most innovative and thought-provoking architects. The idea was to build a 'laboratory of fun' with facilities for dancing, music, drama and fireworks. Central to Price's practice was the belief that through the correct use of new technology the public could have unprecedented control over their environment, resulting in a building which could be responsive to visitors' needs and the many activities intended to take place there.

Using an unenclosed steel structure, fully serviced by travelling gantry cranes the building comprised a 'kit of parts': pre-fabricated walls, platforms, floors, stairs, and ceiling modules that could be moved and assembled by the cranes. Virtually every part of the structure was variable. "Its form and structure, resembling a large shipyard in which enclosures such as theatres, cinemas, restaurants, workshops, rally areas, can be assembled, moved, re-arranged and scrapped continuously," promised Price.

Inter-Action centre

Price could put his ideas into actual practice at the 1971 Inter-Action Centre in the Kentish Town area of north London. This building constitutes an open framework into which modular, pre-fabricated elements can be inserted and removed as required according to need. Central to his thesis that a building should only last as long as it was useful, the centre was designed on condition that it had a twenty year life span and was accompanied by a manual detailing how it should be dismantled.
Archigram United Kingdom

Committed to a ‘high tech’, light weight, infra-structural approach that was focused towards survival technology, the group experimented with modular technology, mobility through the environment, space capsules and mass consumer imagery.

Plug-in-City

Plug-in-City is a mega-structure with no buildings, just a massive framework into which dwellings in the form of cells or standardized components could be slotted.

Aware of an increasingly throw-away culture, Archigram decided to work with this “disposable aesthetic”, and propose buildings and cities which could be replaced section by section. Working amidst a maelstrom of cultural change - yet seeing “the crap going up in London”, as Peter Cook put it - they were increasingly aware that buildings wouldn't last. Their Plug-In City proposes that change could and should be built-in.
Metabolists Japan

The word ‘Metabolism’ stresses the basic idea of an endless change that occurs inside an organism and in its nearby environment. The Japanese architects that joined this movement promoted a flexible architecture and dynamic cities that could develop and grow through the elimination of their exhausted parts and the regeneration of new components in accordance with the necessity of the socio-economical environment.

The Metabolist movement emerged in Japan in the 1970s through the works of Kisho Kurokawa, Kenzo Tange and Kiyonari Kikutake. The philosophy of metabolism was based on the biological processes of growth, transformation, re-configuration of ‘cells’.

The key to the work of Metabolists groups in Japan was a philosophy that allows for the replacement and change of components in such a way that the remainder of the structure is not disturbed. Many of the projects by Metabolists presented high-rise mega-structures of prefabricated apartment capsules which were modified and replaced according to their life cycles and fashion.

The Osaka Expo ’70

Built for Expo’70 in Osaka, the Takara Beautillion synthesizes the philosophy of metabolism, by virtue of being quickly assembled and disassembled from prefabricated components.

High technology capsules were inserted into the frame, displays were inserted into the frame, while the building was left visually and physically frayed and open ended at the edges, symbolic of endless growth.

Follow-up

The preceding movements left a great deal of theoretical background, that was put to use by individual architects. For instance, both the Fun Palace by Price and the different projects of Archigram are said to have inspired Richard Rogers and Renzo Piano’s early 1970s project, Centre Georges Pompidou in Paris.
2.4 strategy

A sustainable building is an outcome of a design which focuses on increasing the efficiency of resource use — energy, water and materials — while reducing the building impacts on human health and the environment during the building’s lifecycle, through better siting, design, construction, operation, maintenance, and removal.

Sustainability nowadays is usually involved with smart, energy generating systems and all kinds of additions to a building. Although these developments are very valuable, most of the time they do not go as deep as they could be. As Michael Braungart would say ‘doing less bad is not doing good’.

Sustainability is a key driver in this study, but not in the form in which it is presented to us most of the time. It is not dealing with sustainable elements in a building but with a strategy of building a new type of architecture, using a new strategy on being sustainable. It focuses more on the use of architecture and the flexibility then on the generating of energy and such.

Sustainability in architecture stands or falls with the use of buildings. If a building is not used, it can perform as energy efficient as can be, but it still is not sustainable. In the Netherlands, buildings of 100, 200 or up to 500 years old are still being inhabited or used by people. That is, the envelope of the building is still as it originally was. Presumably 50% up to 90% of the material in the building is not original.

From this some critical assumptions and questions can be raised.
- Why resign on a buildings envelope (overall shape and geometry) to be permanent?
- Why build structures that can last for 200 year, when the average building only stands for 50 year?
- Why build something that is only able to be demolished and not demountable?
- Why integrate installations (as promoted with arguments on sustainability) when you know for sure that during the life of the building better, more efficient installations will come?

Architecture has traditionally been perceived as enduring, permanent structures. Even today, there is little consideration given by architects or clients to the life of any building other than to assume that it will always stand. It is only poorly being considered that any building might at some future time be altered, expanded, contracted, moved or terminated. Such changes are only conceivable at great additional expense, if possible at all. Present construction technology is mostly the same. Everything within a building is fixed and in place. Mechanical systems for instance are usually integrated in wall construction and structure. Changing anything means demolition of that which exists, followed by replacement with new materials and equipment.

One could argue that the longer a building is in use, the more sustainable it is. Let’s assume for the moment that this is valid. Now look at the strategy that was (maybe unconsciously) used to build buildings that have been in use for more than a century.
Why old buildings are sustainable
- redundancy
- over dimensioning
- capacity to change
- mass (durable & thermal management)

In the case of inner-city buildings there is also a matter of push-factors for renovation:
- monumental value
- usually the site of monuments makes it harder to replace then to modify

Then again, this strategy has its limitations
- limited possibilities in adaptation (healthy building physics demands are hard to reach)
- buildings envelope sets harsh boundaries
- although modifications are possible, they take up a lot of energy / resources
- integrated services / installations are hard to replace
- in modern building industry it is hard to maintain this strategy since building materials are more efficient and economical and have a shorter write-off period.

The strategy for building has not been changed much in current architecture. When completing a building we still see the object as a finished product, instead of an evolving structure. We still use materials that have a longer lifespan than the building and we still make use of rigid connections between building materials that cannot be demounted. There must be a better strategy, because we must acknowledge the fact that buildings keep changing.

Buildings keep changing: people either have to or want to keep reworking them to seek the unfolding patterns of their lives. Reality makes the new building necessarily unfinished and imperfect (but perhaps perfectible in time). Buildings need to learn the same way we do. Give them time.

Stewart Brand, 1997

A strategy of allowing, or better, assuring change could bring forward new insights in to deal with architecture. It is not about being as flexible as possible in a certain building envelope, but about having a flexible envelope to start with. The goal is to provide an architecture that is flexible enough to be a long-lived tool: a structure which has the ability to become whatever it needs to be by use of addition, subtraction and substitution.

Incremental architecture as a system may be opened to accept new, outside elements at any given point in time. The design decision necessary to meet future changes does therefore not have to been made prior to erection of the original form. The new forms may not have existed at the time of the original form inception. For this reason, incremental architecture can respond to a very wide range of pressure changes.

The flexibility infers a major, qualitative shift in the process of design. First the process cannot be based upon a fixed set of criteria which describes what the building must be, thereby specifying optimal solutions. Rather, design will have to be based upon the range of potential, encounterable pressures. The major problem of design now moves to a higher level, i.e. to the design of building systems which can meet anticipated needs for flexibility.
The major change in the process will have to be accompanied by a new 'hardware'. Naturally inherent in the development of IA will be industrialized mass production techniques. Furthermore material properties, such as weight, cost and potential useful life will result in the development and acceptance of new materials.

In any architecture in which changes may be made by addition, subtraction and substitution of parts, joints present a special and critical problem. Besides the apparent problems of structural integrity, weatherproofing and aesthetics, the potential for interchangeability and compatibility of parts raises questions of establishing standards in jointing techniques. The primary concern is with the design of the interface, where the two parts meet. This does not mean that there will be substantial loss of freedom in the overall design of the module. With a standardized interface a wider range of options and choices will come to live. As in other industries these standards would permit replacement of outdated parts. On a broader scale, this would recognize a potential for the building to adapt to changes within the pressures that act upon form, thereby reducing a building's obsolescence.

One direction which may be necessary in incremental architecture is the separation of the various functioning systems within a building. It is recognized that not all parts of any system become obsolete at one time. Thus the problem becomes one of identifying the probable patterns of change and recognizing the varying rates of obsolescence of the parts. This might suggest for example that structure should be separated from special enclosure, and that mechanical spaces should be separated from use spaces. At the least it does imply that any part within the whole should be separable in order to facilitate removal, renewal or replacement. Louis Kahn’s concept of served and servant spaces is a realization of such a separation between equipment space and use space.

It will not be needed any longer to build a building larger than is required to create future space for growth. Such space must obviously be a part of the initial investment. With additive architecture, future growth space is paid for as needed; the building can be bought in parts. On a small scale, young people with no children do not have to buy a house with three bedrooms. Rather, additional spaces could be added as the family grows and its finances improve.
2.5 idea & scheme

Flexible buildings are intended to respond to changing situations in their use, operation or location. This is architecture that adapts, rather than stagnates; transforms, rather than restricts; is motive, rather than static; interacts with its users, rather than inhibits. Flexibility allows architecture to meet future changes. One could think of climatic changes or changes in the use of a building, but likewise changes in the aesthetical perception of what people like or dislike.

Adaptive buildings can be defined as ‘performance-based’ buildings. This is the way at least, as the word is put to use by the Adaptive Building Initiative (ABI). Chuck Hoberman, member of ABI emphasizes the logic of adaptive architecture. Buildings that continuously attune their configurations in accordance with changing environmental conditions use less energy, offer more occupant comfort, and feature better overall space efficiency than static buildings, he claims.

If boxes are stacked, they are dependent on each other for their place in space. Take on out and all that rests on top of it will shift. When pattern or shape of the elements is changed, this dependency is decreased because now single boxes can be removed without consequences. Nonetheless a system based on stacking is to limited to start with. In order to freely shape building blocks and patterns, a division is needed into two different types of space.

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<thead>
<tr>
<th>Service space</th>
<th>Servant space</th>
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<tr>
<td>Construction</td>
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<td>Circulation / Accesses</td>
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<td>Technical Infrastructure</td>
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The service space is the spine of the building which makes it stand up an which makes it usable. The servant spaces are all the spaces that are dependent on the service space and thereby not on each other. Now the question is how these space relate to each other. Some possibilities:

It is the last scheme that offers the full possibilities of disconnecting Service and Servant spaces. Consequences are:

- units need to be lightweight in order to make it structurally possible
- plug-and-play interface for connecting technical services
- placement rules need to be set to prevent keeling over in one direction
- a grid for placement of elements needs to be defined and possibly combined with floors and/or main structure
There are different possibilities for how separate spaces can be placed and can relate to each other, as can be seen in the schemes on the left. If the spaces are completely separate, the highest degree of freedom is maintained, since the change of one space will not affect another space. If the spaces are combined in one envelope, this freedom is reduced. If the envelope is constant, the spaces are very dependent of each other, whilst a flexible envelope offers more flexibility.

The last scheme is a combination of the first and the third option. The spaces are connected by a constant element, whilst the spaces themselves are freely formable and the spaces can be freely placed and deleted. It is this scheme that forms the basis for this design project. The starting principles that can be derived out of this are:

Change should not only be a functional feature, but just as well a feature that can be experienced from the appearance and configuration of the building.

A synergy between permanent and temporary elements guarantees continuity in the process of change.

In principle all temporary building elements should coexist in an independent fashion.

The goal is to provide an architecture that is flexible enough to be a long-lived tool: a structure which has the ability to become whatever it needs to be by use of addition, subtraction and substitution.
This part of the report covers the translation of ideas and schemes into an actual form and design. As the causes for going into a certain direction are explained in the previous parts, now it is time to take a more formalistic point of view. This, in the end, leads to assessing how function and operation perform within the form they are designed in.
3.1 form

The site of the Prins Clausplein is for about 40% covered with infrastructure. This could lead to the conclusion that more than enough ‘in-between-space’ is left to build on. To my opinion though, it is not preferable to start with only the unbuit-on spaces. First of all these spaces are all separated from each other. This makes it hard to connect the building with each other and with the main infrastructure, without adding a complete new infrastructural hub. Apart from this the potential of the site is to my opinion not fully made use of if buildings are merely built alongside the highway. To me building at the heart of the node occurs as far more interesting.

A vertical ground plan is tilted, in a way that a vertical plane runs over (and through) the junction. Obviously the parts where this plane is penetrated by roads cannot be used, but everything else is. This way the ‘left over space’ is not regarded as the two-dimensional ground level, but as a three-dimensional space all that runs through the site. This plane was to be the permanent element of the scheme that was discussed in part 2. To this ‘served spaces’ are to be attached in such a way that the shape in the end is mostly defined by the cantilevering objects.

An image of a random ‘cloud’ of single modules like in the images on the left combines this idea of a three dimensional buildingsite with ideas of how the building should relate to each other an to the passing traffic. The fact that the modules form a random pattern strengthens the idea of the independency of the single elements. Nonetheless the overall shape is obtained by the full combination of elements.
In the giving shape to the basic outline different aspects played a role; connecting to all traffic flows;

The building should be accessible from the motorways, but also from the railway and the secondary roads. A scheme of the points that need to be connected for doing so can be found in paragraph 1.1 relating to the overall shape and scale of the infrastructural spaghetti;

The rounded forms of the plan of the Prins Clausplein are peculiar. If one could somehow relate to this shape, the building could get a stronger attachment to the location.

optimizing the shape for a stiff construction;

The shape of the plane can add to the stiffness of the building. A straight plane is as a rule less stiff than a plane that is i.e. curved or folded.

defining a shape that is experienced ‘four dimensionally’.

It takes about 15 seconds to cross the Prins Clausplein driving at 80 km/h. Ideally the building is experienced as a changing or ‘flowing’ object, rather than a static object that is understood at first glance.

These aspects combined has led to the developing of the general outline of the vertical plane that serves as the core of the building. The height of this plane was first left open for further defining. At a certain point during the engineering it became clear that certain limitations on the height were necessary in order to keep the slab quite slender. In the end the height was limited to 60 meter above ground level. This way the highest ramps were penetrating the plane at half-height, which gave the best results in a study of the volume.
3.2 function

In principle, the structure can house all kinds of functions. Apart from looking at how specific functions should be integrated, it is very interesting to see how these functions relate to each other in the structure. Nonetheless it is good to analyze what specific functions could be integrated in the design.

housing

In the municipality of The Hague a growth of 17,000 households is expected until 2025. Of those, 11,000 households are either single people or couples without kids. This makes the housing market a plausible option for the usage of the building.

A consideration linked to the choice for housing is the fact that it comes with the highest restrictions and demands ‘livable’ standards. The demands on the ‘skin’ concerning the protection against pollution and sound are high either way, but when housing is involved they will be highest.

Two categories of housing types can be distinguished. On the one hand one could think of detached houses that offer the most freedom and have the possibility of daylight coming in from the side. On the other hand stacked houses with sharing walls or floors could be constructed cheaper. This could involve student housing, hotels etcetera.

offices

Another potential group of functions are formed by offices. Especially the potential of starting with a single unit office, while being able to grow to twenty units when needed could be very interesting. Offices could be designed as units for starting entrepreneurs, as conference-centers, as ateliers, as large scale multinationals offices or simply as any other type of office. Whereas housing units would typically benefit from an orientation towards the sun, offices and ateliers would be more suited on the north side because the glare of the bright sun is usually regarded as hindrance in a working environment. Other aspects like the view and the distance to the main accesses are the determinants of which function is most suited for which location.
To the commercial spaces, functions like retail, restaurants and fitness could be considered. The building might in the end become a complete shopping mall or it could just support a few commercial functions that people use in the time they would otherwise spend in traffic jam. Especially in the market for commercial functions the presence of one space attracts more similar functions. This way certain areas of the building will probably become almost completely commercial, while in other parts of the building no commercial activities will take place at all.

This is what makes the building the most interesting: the dynamics of changing functions through time. This also is what poses the greatest challenge for the building as a whole, because the quality of the basic preconditions determine the success of this formula. The services and installations must be designed in a way that new outlets can easily be added. The capacity of the installations should be sufficient for the situation when all places are occupied, but not that high that 90% of the time the system is working on overcapacity. More on these issues in part 4.
The main structure is the backbone of the building. Its primary function is to keep the building upright in the air. Apart from this the space of this structure performs as the organizing element of the structure, like streets in an urban plan.

The fifteen floors that make up the building allow people entrance to the living spaces. Every third floor is a full floor, but the floors in between leave space for atria, vides and stairways. This way the hallways become dynamic open spaces instead of hundred meter long plain halls. Central shafts are added to the building, in which central staircases and lifts are housed to connect all floors. The placing of these shafts is approximately every hundred meters. Although they are placed on the outside of the main structure, they blend in with the pattern of units that hang on the outside of the structure.

Apart from circulation space for people, the horizontal and vertical lines of this organizing structure is also used for technical infrastructure. Ducts and shafts are placed underneath the ceilings and in the core of the vertical shafts to house all ducts and wires. Water, sewage, electra and data are all provided to the units this way. As for the heating and cooling another mechanism is used, which is described in principle in part 4.
From an architectural point of view it is particularly interesting to think about the appearance of the different types of units. On the one hand it might be preferable to somehow have control on the appearance of the building at any time during its lifetime. On the other hand this would discard the idea of freedom in use and space.

The principle of the way Borneo Sporenburg is built might give a solution for a way to deal with this. In the urban plan of this neighborhood in Amsterdam, shown in the picture on the left, the façade of all houses are different. The main volume of every house is not constant, but it is based on a standard system of measurements. Thus the blocks are not the same in size nor the same in appearance, but they are regarded as pieces of a larger entity, rather than single units. What connects them is something that could be described as ‘unity by diversity’. As long as the diversity stays between certain limits, this principle seems to work. The question therefore rises what these boundaries are.

If a new block was added to this series, measuring the width of 4 standard blocks, this would disrupt the image. Too large a difference in size is clearly not good for the harmony. Too much of difference in shape is neither. If a block was to be remodeled into a ‘blob’, it would no longer be part of the ensemble.

Looking at the houses on the picture, most blocks are dominated by one material. This can be the glass of the windows, or a dominant cladding material like a certain color of brick. The more materials are added in one block, the more of a single unit it tends to become. If a block was added with for example ten different cladding materials, it would attract all attention, discarding the unity of the ensemble. Clearly a limited amount of coloration or material will help keeping control over the unity of the whole.

Two other aspects of interest should be mentioned regarding the distribution of units. One of them is the large difference between units that are flanked by other units and units that are horizontally detached. The second type of units offer panoramic views. For the first type, enough opportunities are open for a comfortable lay-out. If only the front is free for windows, still more than enough day-light can enter the space. For one this has to do with the fact that the spaces are very high: up to approximately 3.5 meter. This way high windows can be placed that let the light shine deep into the unit. Furthermore, also the wall towards the inside should not be forgotten. The hallways are very transparent and therefore windows facing this side still allow light from outside to come in.

As mentioned in the part on commercial spaces, it could be expected that at a certain time during the lifecycle of the building in certain parts clusters of similar functions start to occur. Particularly commercial spaces tend to attract each other. This way ‘shopping streets’ or eating areas could emerge. And when these run out of business, the units are replaced and the street houses only dwellings again. That is the beauty of the dynamic spread of units. In principle every unit and every function should be possible at any vacant spot.
3.3 materialization

The units that cantilever from the main structure combined form the main appearance of the building. As mentioned in the previous paragraph, this synthesis relies on the concept of unity through diversity. For the materialization this means that a very diverse pattern of diverse materials. In fact the materialization of each unit is left free for the choice of the user, as long as simple rules are regarded.

Each unit should consist of a maximum of three materials, including the glass of windows. This will ensure that each unit will be ‘read’ as one entity in the whole.

When units are combined, it should be averted that the expression of the facade is repeated endlessly. Preferably each unit differs in appearance, regardless the possible links inside.

The weight of the unit is a rather important factor. This can easily be understood if one knows that the elements can cantilever up to 12 meter outwards. In the part on engineering, this is elaborated upon. For now it is enough to understand that the skin of the units is built up modularly with lightweight elements. Facades of concrete or brick are out of the question, rather materials like aluminum, polycarbonates and foamlike materials could be regarded.

In the end, the materialization of the units open for all that people can think of. With trends in building industry going toward lightweight materials, even options that not yet exist are possible. This is the beauty of the system; the design decision does not have to be made beforehand.
As the structural analysis will show, the factor weight is of great importance in this design. This goes for the materialization of the unit, but also for the main structure itself. Because of this a pure glass cladding was considered not plausible, although a very transparent structure was preferred. Another material was to be found that should meet the following criteria:

- lightweight
- transparent
- good thermal insulation
- spans of at least 4 meter (storey height)

The material that combined all these criteria was found in ETFE cushions, as known from architectural projects like the Allianz Arena in Germany by Herzog & De Meuron. Apart from meeting the criteria, the material furthermore provided a lot of new opportunities for the functioning of the structure.

The material ETFE (ethyleneretetrafluoroethylene) is a relative new building material. Introduced in the ‘50s in some prototype projects, it has become more and more custom in modern building industry. The strength of the material lies foremost in the fact that it uses the air inside to perform. The pressure of the air gives enough shape to the cushion to resist the force of the wind. Furthermore the air insulates the inside from the cold outside. The material itself acts only to hold the performative air.

Façade panels will have to be placed and removed on a regular basis, because they have to make place for units. For this, the cushion system is quite a good solution too, because the cushions can easily be individually deflated. What remains is three layers of foil, which can easily be removed and stored, taking up hardly any space.

A nice feature of this type of façade is the adaptability one can achieve with them. This is partly due to the adaptive transparency that can be obtained by the variable layer in the middle. As shown in the drawing on the left, this layer can make the difference between translucency and almost fully opaque. Especially for the south façade, this feature might perform excellent as sun shading to keep the buildup of heat inside under control. Another way of obtaining an adaptable façade is variable lighting. Changing the color of the light that shines on the cushion from the back gives the possibility to make the façade perform as a media façade. Constantly changing light patterns or even pixels building up a pattern of light are possible.

In detailing the façade, the aim lies on transparency during the day and lighting patterns during the night. A minimum of framework holds the cushion of 9 x 4 meter on its place. In the middle, the width of the cushion is approximately 1,5 meter, but this obviously does not take any transparency away. Because of the angle, the reflection of a ‘normal’ glass façade is even reduced, which makes the transparency even stronger. Hidden in the middle zone of the floor, LED lighting is fitted. This lights up the façade during the night, with the possibility to light and color each façade panel individually.
In the last part of this thesis the engineering aspects of this project are being covered. The major component of this part of this thesis is a study of the basic mechanical behavior of the building. When relevant, other disciplines, like acoustical engineering and material sciences are involved. Moreover, relationships with aspects from the discipline of architecture are constantly sought, in order to vouch for a synthesis between the 'image' and the 'calculation'. In the end the basic outline of the climate design is covered. In an unorthodox building like this aspect too is designed and engineered very specifically.
4.1 introdution structural analysis

The design of the building is extraordinary because of its dynamic nature. The design is not a matter of optimizing for a static situation, but a search for the best way to deal with varying situations. The structural design is therefore the main subject of the engineering study.

The structural design focuses on a representative part of the building. The same principle of equilibrium between dynamic loadings is present everywhere in the building. If the workings of this principle are uncovered, it can be applied everywhere in the building.

The start for the design is shown in the schemes on the left. The design is based on the idea that the site to build on is flipped upwards to a vertical position. This imaginary vertical plane has no thickness and it can be ‘covered’ with buildings on both sides. Moreover the plane is penetrated by the highway intersection.

Obviously several problems directly come to mind. For starters the plane cannot have a thickness of zero. The plane will have to become a slab with a certain thickness in order to be possible at all. Next the issue of placing elements on both sides of the slab is at hand. As long as elements are placed in perfect symmetry this poses no threat, but asymmetry might harm the structural integrity. For the structure as a whole the clear span over the highways is obviously something to consider and what about wind directly on the slab? On a smaller scale the demountable fixing of elements on the slab is an issue to study. Finally the materialization needs serious consideration because aspects like weight, durability and sound insulation are vital for the success of the design.
Basically the building is composed out of two unities. The permanent structure and the temporary units attached to this. For the structural design of the building a constant switch between these levels is needed because the one cannot be designed without the other.

For this structural design the object of study is reduced to a characteristic part of the building as showed on the left. The main structure, a slab with a maximum height of 60 meter, determines the main shape. The principle of the mechanical behavior of the slab is best seen in section, as schematized on the left. To stay upright the structure needs to be strong enough to bring its own weight and the load caused by the units fixed to it to the foundation. Furthermore the structure needs to be able to resist the force of the wind. In order to bring this load to the foundation a certain width is needed. Finally the structure needs stability to resist the moment caused by the asymmetrical placing of units. The working of these aspects are described in principle first.
For the design of the slab several materials are available. Given the profile of the section really only concrete or steel were serious options. In an early stage a choice was made to use steel for reasons of relatively slender structures (compared to concrete) and the fact that a demountable structure would be possible. A post and beam structure was to form the main structure that is further referred to as the slab.

In a structure as shown as shown on the left the principle of two columns functioning together is of the utmost importance. In this case trusses are drawn, but other ways to combine them are possible too. Because of this linkage the two columns have a combined stiffness, or moment of inertia. This moment of inertia can be found with this formula:

\[ I = \sum (A \cdot e^2) \]

From this formula it can be derived that increasing the distance between two columns has a quadratic larger result on the stiffness of the section then increasing the sectional area A of the column. It makes perfect sense to give the slab several meters of width in order to make it stiff enough.

On the other hand the sectional area of the columns cannot be lowered infinitely, because the forces need to be able to go through the material. If it where only the forces caused by the loading of the own weight this would not be as significant as it is now. Because of the moment caused by the asymmetric loading, one side of the structure is compressed far more. All these forces need more material to go through, given that each material can only take a certain maximum stress per square millimeter.

The last aspect to keep in mind is that the widening of the section increases the dead load and, if the floors grow with it, the variable load.

In order to find an acceptable starting point for designing the structure, first a calculation by hand is done. Using basic equations for strength, stiffness and stability, the interrelation between the abovementioned aspects are found. Based on these interrelations a sound estimation for dimensioning the slab can be found. In the following the study for finding this estimation is described.
The figure on the left shows two mechanical schemes of the section of the slab. In this, the following variables and parameters are most important.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>l</td>
<td>Height structure</td>
<td>m</td>
</tr>
<tr>
<td>a</td>
<td>Width structure</td>
<td>m</td>
</tr>
<tr>
<td>b</td>
<td>Width bay</td>
<td>m</td>
</tr>
<tr>
<td>v</td>
<td>Number of floors (\lfloor \frac{n}{4} \rfloor)</td>
<td>-</td>
</tr>
<tr>
<td>g</td>
<td>Weight standard unit</td>
<td>kg</td>
</tr>
<tr>
<td>E</td>
<td>Modulus of elasticity</td>
<td>kN/m²</td>
</tr>
<tr>
<td>p</td>
<td>Wind load on façade</td>
<td>kN/m²</td>
</tr>
<tr>
<td>A</td>
<td>Sectional area column</td>
<td>mm²</td>
</tr>
<tr>
<td>ZF</td>
<td>Combined loading of fixed units</td>
<td>kN</td>
</tr>
<tr>
<td>q</td>
<td>Dead load of structure</td>
<td>kN/m²</td>
</tr>
<tr>
<td>M</td>
<td>Moment caused by eccentric loading</td>
<td>kNm</td>
</tr>
<tr>
<td>I</td>
<td>Moment of Inertia</td>
<td>m²</td>
</tr>
<tr>
<td>u</td>
<td>Displacement</td>
<td>m</td>
</tr>
<tr>
<td>φ</td>
<td>Angle of deflection</td>
<td>rad</td>
</tr>
</tbody>
</table>

The interrelation between these entities can be captured in formulas. Since these calculations are merely the start of this study, this is not elaborated upon here. Nonetheless a full model of interrelations is made using Excel software. By doing so I was able to study the effect of increasing and decreasing certain values in the model.

The aim was to find sound estimations for the most basic dimensions;

- width of the structure
- distance between single-bay-frames
- sectional area per column

When all but these variables are set static, the interrelation between these three variables were very helpful to get an idea of dimensions. The table on the left for example shows the relation between the width of the construction horizontally and the sectional area of a single column vertically. Without the knowing of all other parameters the values obviously do not mean anything, but the relations stay more or less the same.

Simultaneous with this mechanical approach, the design was developing in ideas on functionality. If the slab was going to have a thickness, the space should be used functionally. The more concrete these ideas were becoming, all the more t was needed to start modeling in a precise way. This was when modeling in GSA software began.
First of all a fresh start was made to find the main dimensions of the slab. The relationship between the width of the section, the width of the bay and the sectional area was studied by analyzing the deflection of the top. Again the structure is fully stiffened with the help of trusses.

At first only the dead load and the wind load were taken into consideration. The model as shown in figure 4.8 was built using these parameters:

<table>
<thead>
<tr>
<th>abbreviation</th>
<th>description</th>
<th>value</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>l</td>
<td>Height structure</td>
<td>60</td>
<td>m</td>
</tr>
<tr>
<td>v</td>
<td>Number of floors ([l/4])</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Modulus of elasticity</td>
<td>2.1E+08</td>
<td>kN/m²</td>
</tr>
<tr>
<td>p</td>
<td>Wind load on façade</td>
<td>0.5 – 1.5</td>
<td>kN/m²</td>
</tr>
<tr>
<td>Q</td>
<td>Dead load floors</td>
<td>125</td>
<td>Kg/m²</td>
</tr>
</tbody>
</table>

By checking the deflection $U_x$ and $U_z$ of the top of the structure it became clear what the effect of dimensioning was. For a fixed sectional area and a fixed distance between single-bay-frames the results of widening the section are shown in figure 4.9. Increasing the width from 1 to 5 meter results in a decrease of $U_x$ by a factor 21. Further increasing the width to 10 meter reduces $U_x$ by a factor of 3, compared to the 5 meter section. Widening the section is obviously not directly proportional to its resulting deflection.

The effect of widening the distance between single-bay-frames on the displacement $U_x$ is shown in figure 4.10. In this case the steps from 5 to 10 and from 10 to 15 meter both result in an increase of the displacement by a factor of about 1.4. More important thought is the vertical displacement. As shown in the scheme the connecting beams start to sag. In order to be able to increase the width, the section of the beams will have to be enlarged. This example shows the interconnection between arguments of engineering and those of architecture. When aspects of functionality are added to this, the real complexity of engineering this structure became obvious.
4.2 structural analysis: modeling and refining

principle

The problem of giving strength and stiffness to the structure became clear. It was obvious that the slab would have to consist of elements working together by adding stabilizing connections. For this several principles were modeled and tested, using GSA software. The principle solutions are described and commented upon in the following.

Firstly a model was made in which all bays are fitted with a crossed trusses. The trusses lead to a perfect synthesis between the two columns on both sides of each bay. By doing so the columns can be modeled rather slender and buckling becomes the normative factor. The problem with this system is the fact that the slab is to be used for horizontal circulation space. For this the crosses will cause to much of hindrance, even when they would be constructed as single construction members.

The second model anticipates on the horizontal circulation by eliminating 80% of the trusses. Now the floor slabs become more important in structural sense, because the wind load is carried through the floors to the trusses bays. This does not necessarily mean that the floors will have to be made of concrete slabs, because horizontal trusses work just as well. The problem with this model lies in the fact that architectonically the hallways in this case do not comply with the proposed design. Vertical relations between the floors are preferred to make the long hallways playful and interesting. If these relations are only visual, horizontal trusses would not impede with this, but if elements like atria and stairways are added, this model does not suffice anymore.

In the third model two of every three floors are eliminated in structural sense. Now both horizontal and vertical connections are possible, albeit that the connections stop at every three floors. This model meets with all the demands, although the vertical trusses that are left would have to be carried out as pressure members. A way to even eliminate these last obstacles is to search for the solution outside of the outline of the slab. This is exactly what is done in the fourth model: extensions are made outwards to make place for stiffening vertical elements. Because from a functional point of view it was preferable to place the vertical infrastructure and circulation space outside of the building, this possibility appeared to make perfect use of the situation. Therefore this last model would be the basis for the rest of the structural design.

Along with the working on the design principles came the basic outline for the dimensioning. If the slab was only going to be used for horizontal circulation space, the width could not be more than a couple of meters. Projecting the cantilevering inwards on the other hand, would mean that the space inside was going to be functionally used. Because of this a width of 7 meter distance between centre lines was quite acceptable. This started as a arbitral dimension, but turned out to work out fine. The bay-to-bay distance was founded on the idea that a functional space with a cantilevering distance of up to ten meter should be possible in this distance. Several distances were tried and tested for their structural implications. A distance of nine meters was chosen to allow for spacious 90m² single unit apartments.
Criteria

A structure cannot be modeled without knowing the criteria it has to meet. Some of these criteria rest on material properties such as the maximum of stress that is physically possible to pass through a certain sectional area. Apart from criteria like these, normative regulations are available. In the Netherlands the relevant regulations are combined in the standard NEN6702 by the Netherlands Standardization Institute. Especially the criteria in which the relation between the geometry of the structure and the maxima of deflection are useful in the design stage.

NEN 6702| 10.3 criteria for horizontal deflection

- The total horizontal deflection for a multiple storey buildings does not supersede \( h/300 \)
- The total horizontal deflection for a multiple storey buildings does not supersede \( h/200 \) per storey

NEN6702| 10.4 norms for vertical displacement

- The vertical displacement of floors may not supersede \( 0.004 \times l_{rep} \)
  \( l_{rep} \) is the length of the span and in the case of cantilevering structures twice the length of the extension.

Furthermore this norm gives the maximal occurring wind load, which can be used in modeling the situation.

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Acoustical protection

It may seem curious to involve the issue of sound at this stage, but the relevance of this will become clear soon enough. The schemes in the previous paragraphs showed the way the cantilevering elements affect the deflection of the structure. From this follows the logical consequence that it makes sense to limit the weight of each unit. In principle this works fine, but it becomes problematic when the acoustical behavior of the skin is added to the equation.

Given the location of the building, it is necessary to have a good look at the way acoustical insulation can be achieved. Already in the first part of this thesis a ‘sound map’ was shown, from which a peak sound load of over 75 dB(A) could be derived. To put this into perspective, for living comfortably, a maximum sound level of 35 dB(A) is required.

Usually a good solution for sound insulation is the adding of shear mass. As can be seen in the diagram on the left, there is a linear relationship between the amount of mass and the sound insulation. The mass makes it harder for sound to make the wall vibrate.

In this case, adding mass will not suffice, because of the structural effect mentioned earlier. A better solution can be found by the use of a cavity construction. Constructing a wall in two parts with air in between can achieve a large degree of sound insulation for a relatively low mass because of the lack of direct transmission of vibration from one leaf of a cavity wall to the other.

The problem with cavity structures is the leaves can due to resonance. At the points where this occurs the sound insulation drops dramatically. On the plus side, this aspect reveals a way to easily determine the properties for good insulation. By ensuring that the first resonance point lies as low as possible, the overall insulation is guaranteed. The first resonance point \( f_0 \) can be calculated with the following formula:

\[
f_0 = \frac{60 \sqrt{\frac{2m}{m^2 \cdot b}}}{b}
\]

where:
- \( m \) = mass of a single cavity leaf
- \( b \) = width of the cavity

By reversing this formula, the relation between the mass and the width can be calculated for a given resonance point. Given the curve of the isophones of the human ear, the sound level at 1000 Hz is normative. If the first resonance point is given a value lower than 100 Hz, the curve as shown on the left will be at a sufficient level by the time it reaches 2000 Hz. In the graph the relation between the mass and the width are shown for the case \( f_0 = 50 \) Hz and \( f_0 = 80 \) Hz. From this follows that for a width of 10 cm a mass of 20 kg/m² per cavity leaf is needed. The 10 cm is based on the assumption that the construction can be places in between the leaves. Should the construction become larger, a thinner leaf can be chosen.
Now that the skin of the unit is known, the rest of the unit can be dimensioned as well.

The floor and the roof are modeled as steelframe floors with a weight of 125 kg/m² and the facades are modeled as a cavity construction with leaves of 20 kg/m². It is assumed that the units are constructed in such a way that neighboring units share the same walls or floors. This way no double layers are created, which save a lot of weight. The units as given in the table on the left formed the input for modeling the structure digitally.

Even though the structure is not super lightweight, it is still that light that the live load is higher than the deadload. This raises the question if no restrictions should be made on the usage of the units in order to lower the maximum live load. For practical reasons this has been left out of this model, in order to maintain the greatest amount of freedom in the use of the units.

| buildingpart | component | weight | load | dimensions | area | gross load | load factor | rep. load | |
|--------------|-----------|--------|------|------------|------|------------|-------------|-----------|
|              |           | kg/m²  | kN/m²| length (m) | width (m) | | | kN | kN |
| Floor        | deadload  | 125    | 1,2  | 7          | 9     | 53         | 77,3       | 1,2       | 92,7 |
|              | liveload   | 2,0    | 7    | 9          | 53    | 124,0      | 3,5        | 189,0     |
| Roof         | deadload  | 125    | 1,2  | 7          | 9     | 53         | 77,3       | 1,2       | 92,7 |
|              | liveload   | 0,8    | 7    | 9          | 53    | 59,4       | 3,5        | 75,6      |
| Façade side 1| deadload  | 1,0    | 7    | 9          | 53    | 21,0       | 1,2        | 32,2      |
| Façade side 2| deadload  | 1,0    | 7    | 9          | 53    | 21,0       | 1,2        | 32,2      |
| Façade front| deadload  | 1,0    | 7    | 9          | 53    | 21,0       | 1,2        | 32,2      |
|              |           |        |       |            |       |            |            |           |
| total deadload|          |        |       |            |       | 228,7      |            |           |
| total live load|         |        |       |            |       | 264,6      |            |           |
| total        |           |        |       |            |       | 493,3      |            |           |
At first, the full design of the main structure was assumed to be of steel. During the modeling it appeared that this would result in very large profiles for the columns in each bay. Because of this, and because of fire-safety issues (see later on in this study), the choice has been made to design the columns as steel-concrete hybrid profiles.

In GSA software an ‘element’ can be assigned material and sectional properties. The possibilities for input are very broad, but limited to homogeneous materials. In order to calculate on a steel-concrete element it is necessary to translate the material properties of these two components into one virtual material. This virtual material can then be used as input for GSA. A description of this process is given in the following.

The section of the element is assumed to consist of a standard rectangular tube, filled with concrete. Some of the standard dimensions for this tube are given in the table underneath.

As for the material properties, the Young’s modulus for concrete and steel are most interesting; these are:

<table>
<thead>
<tr>
<th>E-modulus</th>
<th>steel: 210.000 N/mm² (E₁)</th>
<th>concrete: 26.000 N/mm² (E₂)</th>
</tr>
</thead>
</table>

With these properties three primary structural properties of the columns can be calculated:

\[
E_{Iy} = E_2 \left( \frac{1}{12} b' h'^3 \right) + E_1 \left( \frac{1}{12} b h^3 - \left( \frac{1}{12} b' h'^3 \right) \right)
\]

\[
E_{Iz} = E_2 \left( \frac{1}{12} h' b'^3 \right) + E_1 \left( \frac{1}{12} h b^3 - \left( \frac{1}{12} h' b'^3 \right) \right)
\]

\[
E_4 = 4 \left( E_1 + E_2 \right)
\]

If the red-colored dimensions are used, these formulas give the following results:

\[
E_{Iy} = 26.000 \cdot \left( \frac{1}{12} \cdot 114 \cdot 244^3 \right) + 210.000 \cdot \left( \frac{1}{12} \cdot 146 \cdot 260^3 - \left( \frac{1}{12} \cdot 114 \cdot 244^3 \right) \right) = 1.54E+13
\]

\[
E_{Iz} = 26.000 \cdot \left( \frac{1}{12} \cdot 146 \cdot 260^3 \right) + 210.000 \cdot \left( \frac{1}{12} \cdot 146 \cdot 260^3 - \left( \frac{1}{12} \cdot 146 \cdot 260^3 \right) \right) = 5.35E+12
\]

\[
E_4 = 7675 \cdot 210.000 + 15456 \cdot 26.000 = 3.20E+9
\]
It is actually the outcome of these formulas that is used in GSA software. So although usually the properties I, E and A are inputted independently, for the model it makes no difference what the individual quantities are, as long as the outcome is the same. This enables the possibility to generate a virtual material and a virtual section with properties that are not valid by themselves, but if combined result in sectional properties as given above.

In GSA a user defined material can be entered in a table like this:

In this case especially the Young's modulus is of importance. A new (virtual) material can be added with a virtual Young's modulus. In this case the new material is called 'steel/concrete' and the virtual Young's modulus is given the value of 100.000.

The density is a 'real' value and is based on an average section of 88% steel and 82% concrete.

Now the sectional properties must be quantified. The GSA wizard for this is found under 'explicit':

In order to come to the results of the example, the value for Iyy can be found with the formula:

\[ I_{yy} = \frac{b h^3}{12} \]

in which \( b \) is the outside perimeter.

The same applies for the values of the area and Ixx.

The property J is representative for the factor of torsion. Given the shape of the section it is assumed that the perimeter of the section (the steel tube) is almost fully responsible for this value. Because of this the concrete core is neglected and the value is derived by this formula (Bredt):

\[ J = \frac{4 \pi \cdot \text{area}^2}{P} \]

in which \( P \) is the outside perimeter.

The properties Kx and Ky are used for shear stress and therefore in this usage not particularly relevant. They are given the value of a hollow tube.

The graphical view looks quite odd because the sectional area of the columns is that of a virtual material whilst it now is represented as a real property. This is part of this way of working, so that is not really of any importance.
modeling in GSA

For the structural analysis, a model has been made using GSA software. Not the whole building, but only the west wing has been modeled, because it concerns a analysis of the mechanical behavior in principle, which is the same at every bay.

The primary study goes to the effect of the eccentric loading of the structure, when unequal amounts of units are placed at both sides of the structure. Before going into this though, the preconditions have to be modeled right, gravity and wind loading being the primary of these conditions. This has resulted in a model as shown on the left. This model is based on the principle as described in the beginning of this chapter. It consists of the following elements:

bay
- column: concrete filled steel hollow beam
  - centre to centre 7000 mm
  - square 400/200/16 mm
- girder: steel hollow beam
  - square 300/200/16 mm

bay to bay
- façade beam: steel hollow beam
  - centre to centre 9000 mm
  - 2 degree rotation at each bay
  - square 200/100/10 mm
- floor: lightweight steel frame floor
  - every third floor is full and trussed
  - 125 kg/m²

outrigger
- at the first and eleventh bay an extra bay is placed outwards

In the model the elements at the bay most eastwards (right) are pinned, since the triangle is supposed to perform as a stiff element, countering all forces and moments on this bay.

The field between bay 12 and thirteen proved to show the greatest deflection under wind pressure. Because of this, this field represents the ‘worst case’ for even more deflection by the placing of units. Thus the study for the effect of eccentric loading is performed on this zone.
Using the described model, the mechanical behavior of the section of the structure is analyzed.

Firstly the behavior of the structure is analyzed in the situation that all units are hung from one side, without units counterbalancing. In the graph on the left the horizontal displacement (vertical) is plotted against the increasing amount of units. The blue line represents the displacement of the reference point at the top of the main structure, in the situation that the weight of each unit (G) is as described before. The red and green line represent the same displacement, but now for the situation that each unit is twice or triple the weight.

The shape of the curve of the graph is curious. One could expect that the deflection would relate linearly with the increasing load. The first part of the graph corresponds with this expectation quite well, but at about a third of the sequence, this trend is disrupted. From that point onwards, the deflection increases less and less as than was expected. This can be explained by the geometry of the structure. When units are added, the structure as a whole becomes stiffer, because each unit is directly connected to its neighbor. This increase in stiffness makes it harder for the structure as a whole to deform, hence the lower results.

Secondly the structure is loaded on both sides, but still in an uneven way. The left is loaded with double the amount of units compared to the right. Furthermore the sequence of the adding of units on both sides starts on the top of the structure and goes down. The graph again represents the situations for single, double and triple the weight.

The graph shows that the deflection of the structure decreases quite a lot, when a counterbalance is provided. The increase in stiffness is this time that high, that the maximum deflection is not occurring at the maximum loading. By that time, the structure is already that stiffened that much that its deflection at a lower normative load is even higher.

Lastly, the structure is again loaded with a counterbalance of 50%, but this time the vertical distribution of the units is opposite. At the one side the sequence starts from the top, at the other it starts from the bottom.

This time the fact that the peak of displacement is not at the end of the sequence appears more natural when the schemes of the sequence are considered. It seems obvious that the deformation of the structure is highest before the units start to appear at the same level. The fact that the overall displacement is higher than the situation as modeled in the previous example also appears natural, since the vertical length between the entities is much larger.
When the three situations are plotted in one graph (based on the standard weight), the graph on the left is the result. Added to this graph is the 100% counterbalance situation. The fact that the line for this situation shows a value of approximately 12mm seems peculiar, since the units are presumed to nullify each other's effect on the displacement. The fact that this is not the case is the effect of the geometry of the plan. Since the bays rotate 2 degrees inwards, the plan has a tapered geometry. The unit on the one side therefore is slightly larger than the unit on the other side, hence the small (constant) deformation.

Based on this graph, a choice can be made on what freedom is given to the placing of the units. This will result in a value for the displacement caused by the eccentricity of the loading. When this value is reduced from the total acceptable displacement, the allowed deformation caused by the wind can be found. This in the end determines the overall structural design.

The 100% counterbalance is the benchmark for the minimum of displacement caused by the units. Obviously this strategy is not sufficient, even only for the fact that the units will probably not be placed exactly at the same time. On the other hand, 0% counterbalance will probably be excessive, since the design is based on the fact that units will always be placed at both sides of the structure. Not making use of this counterbalancing effect at all does seem a pity. A good middle course appears to take the 50% counterbalance, but then in such a way that the vertical distribution is fully free. The peak of the 50% counterbalance with opposite vertical placements can then be taken as the maximum value of this displacement. This way units can still be placed relatively free on the structure, only limited by the need for a certain counterbalance at a given point during the lifetime of the building. A physical boundary like this could increase the dynamics of the operation of the building though.
testing the main structure

The GSA model is refined in such a way that the zone with the highest displacement caused by the wind is now loaded with a distribution of units that represents the ‘worst case’ for the horizontal displacement caused by eccentricity. Combining this loadcase with the loadcase of the maximum occurring frontal wind, gives the situation in which the maximal deformation may occur.

From the tests it appeared that a minor adjustment of the model was needed, in order to fulfill for this test. The final model consisted of the following elements:

- bay column: concrete filled steel hollow beam square 450/250/16 mm
- girder: steel hollow beam square 300/200/16 mm
- bay to bay façade beam: steel hollow beam square 200/100/10 mm
- floor: lightweight steel frame floor every third floor is full and trussed 125kg/m²
- outriggers at the first and eleventh bay an extra bay is placed outwards
Two more tests were done to check whether the structure indeed met with the standards. Firstly the axial stress was checked to see if this did not supersede the yield stress of steel. This proved to be sufficient. Furthermore, the graphical output on the left shows that the stress is exactly where it is supposed to be: in the trusses. Secondly the situation of crosswind was modeled in order to see if the square columns could resist this too. This proved to be fine too, so the model was accepted and the sections of the structure were used in the design.

The structural engineering has caused some major design decisions. The foremost being:

- the width of the structure is rather wide, with the reservation that units would penetrate inwards to be able to use this space functionally;
- the factor weight proved to be that high that the super lightweight material of ETFE cushions was chosen for the façade of the structure;
- continuing on the factor weight, the units were left to be designed as light as possible, as described before.
design of the unit

In the previous paragraph the relationship between the main structure and the units proved to be rather strict. The one is in the end fully dependent on the other. Not surprisingly this shows up again when engineering a unit.

One of the major concerns in the structural design of the unit is the vertical displacement. Since each unit is cantilevering outwards, the psychological effect of a unit tilting down is enormous. This will be the starting point of the design of the unit.

In this case, the vertical displacement of a unit is based on three factors, as shown in the schemes on the left:
- tilting of the main structure under wind loading;
- bending of the columns in each bay;
- tilting of the unit under its own weight.

As mentioned in the paragraph on criteria, the limit for the vertical displacement is directly related to the length of the cantilever. The maximum value for this is given in the following table.

<table>
<thead>
<tr>
<th>Length cantilever (mm)</th>
<th>Norm (mm)</th>
<th>Angle 0.45°</th>
</tr>
</thead>
<tbody>
<tr>
<td>4000</td>
<td>32</td>
<td>64</td>
</tr>
<tr>
<td>6000</td>
<td>48</td>
<td>80</td>
</tr>
<tr>
<td>8000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As for the effect of the tilting of the main structure, the values for the horizontal displacement of a column are used to calculate the angle. This angle is then used to calculate the vertical displacement it causes on a unit, if the assumption is made that the unit itself is infinite stiff. As shown in the table on the left, this effect differs at every height. The effect of this factor is much larger on the lower levels than on the higher levels.
As for the factor of the bending of the column, again the GSA model of the main structure is used to assess the effect. Each time one unit is placed at a certain level and then the difference between the horizontal displacement of the node on top and the node underneath this level is taken. This difference is used to calculate the angle the piece of column makes, which again can be translated into a vertical displacement of an infinite stiff unit. This time it appears that the effect at the top is much higher than the effect on the lower levels.

As for the tilting of the unit caused by its own weight, now a limit can be found. In the graph on the left the results of the previous two factors are plotted in red and blue. What remains is the amount of displacement that is allowed to be caused in the unit itself. It shows that 36% of the displacement is caused by the mechanical behavior of the main structure. This leaves 64% for the tilting of the unit itself. The values that are shown in the table underneath the graph form the benchmark for designing the unit.
The unit is engineered, again using GSA software. This was done in a number of steps, as illustrated by the graphical outputs of GSA on the left.

1. The frame of the unit was based on the idea of a storey-high outrigger at each column, joined by two beams at the ends. As the picture shows, the maximum vertical displacement did not appear at the end, but at two-third of the unit. This would mean that the length of two-third of the unit would be normative for the vertical displacement.

2. A division of two parts of the outrigger was made. This way the maximum vertical displacement was brought to the end of the unit, where it should be.

3. The model was assessed for horizontal displacement. It appeared that the two outriggers were tilting towards each other in the middle.

4. This problem was fixed by adding an extra beam between the outriggers in the ceiling, in the middle of the outriggers. This proves sufficient for the internal stability of the unit.

5. In step 5 a loadcase of crosswind is added to the equation. As the graphical output shows, under influence of this load a major deformation occurs.

6. To compensate for the wind a double truss is introduced, both in the floor and in the ceiling. This stiffens the unit as a whole, but in the end is not enough to keep the horizontal deformation under control.

7. In the final model, the single cross is replaced by a double cross of tension bars. This in the end makes the unit stiff enough to meet the criteria for both vertical and horizontal displacement.
The engineering of the structure was followed by the actual design. For this the elements were modeled in 3d CAD software. The model, as shown on the left, consists of the following elements:

- **Beams**: hollow steel tube square 200/100/10
- **Columns**: hollow steel tube square 100/100/10
- **Vertical truss**: steel rod circle 35 mm
- **Horizontal truss**: steel L-profile L shape 80/80/7.5

The choice for this shape of sections is based on the original assumption that the space between the layers of the cavity structure would be 100 mm. This assumption proved to be enough, because the profiles do fit in between.

The structure of the unit was assumed to be constructed of steel. This choice was merely based on the idea that this would probably be the lightest option, although no in-dept analysis was performed to confirm this. In GSA, the possibility to try other materials is very easy, so the choice for steel could be reconsidered.

Apart from steel, other types of construction material are becoming more and more common in the building industry where the factor weight is of importance. In the group of metals, aluminium is the most prominent concurrent, because it weighs far less than steel while it is widely available. In the non-metal materials a relative new material, glass-fibre composite, is a serious concurrent for steel. It is not that common yet and it is quite expensive when compared to steel, but its characteristics are promising.
In the table on the left, the three materials are compared on some basic characteristics. For material properties the Young’s modulus is a good indicator for the stiffness of a material, regardless of its sectional property. Furthermore the thermal conductivity of each material is listed, for reasons that will be elaborated upon later.

For a comparison on sectional properties, an I-beam is considered as an arbitrary example. For all materials an exact shape of the section is chosen, based on commercial availability and in such a way that they are comparable on outside dimensions. From this it appears that steel is far heavier than the other two options and, that its section has a far smaller moment of Inertia. This value represents the stiffness of the material with a given geometry. The combination of the Young’s modulus and the moment of inertia in the end determines the stiffness of the element.

To see what the effect is of applying different materials to the section of the elements in the model, an mechanical analysis is performed using GSA software. In this the mechanical behaviour of the unit is assessed by looking at the displacement of a reference point at the tip of the unit. As indicated in the scheme on the left, both the vertical and the horizontal displacement are analysed. The values for the displacement of the unit with beams of the same sectional geometry, but with differing materials are listed in the table below.

<table>
<thead>
<tr>
<th></th>
<th>∆Ux</th>
<th>relative increase</th>
<th>∆Uz</th>
<th>relative increase</th>
<th>density</th>
<th>relative weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>steel</td>
<td>14,5</td>
<td>%</td>
<td>26,5</td>
<td>%</td>
<td>7850</td>
<td>%</td>
</tr>
<tr>
<td>aluminium</td>
<td>105</td>
<td>%</td>
<td>26,5</td>
<td>%</td>
<td>2700</td>
<td>%</td>
</tr>
<tr>
<td>glass fiber (Pultex®)</td>
<td>77</td>
<td>%</td>
<td>23,8</td>
<td>%</td>
<td>2600</td>
<td>%</td>
</tr>
</tbody>
</table>

This comparison shows that steel beams are stiffer than those of aluminum or glass fiber. This was to be expected because of the higher Young’s modulus value. The effect is that the horizontal displacement increases with up to double the displacement for steel. On the other hand, the weight of steel is about triple that of both aluminum and glass-fiber. This could lead to the conclusion that if the wall-thickness of the beam is doubled, the element is still lighter than steel while performing structurally the same way. The relation is actually not that linear, but the principle does proof to be right: with aluminum and glass fiber lighter beams can be constructed that perform just as well as steel. This can be achieved within the same outside dimensions of the section.

On the downside, the concurring materials are more expensive than steel. On the plus side though, the glass fiber beams have a characteristic that in the end makes them the most favorable. This characteristic is the low thermal conductivity that was mentioned before. As the drawing on the left shows, the beams form a thermal bridge between the two leaves of the cavity structure. Although the inner layer is provided with an isolative layer, the points of contact between the elements will result in energy leaks. For this, using glass fiber beams could be a rather good solution. This is where aspects of construction, architecture and building physics meet in a solution that’s fit for all aspects.
4.3 Climate design

The most common way of engineering a climate design results typically in a cluster of central installations on the roof, from where ducts distribute heated or cooled water through the building. The advantage of this is the efficiency of the heating source. If this concept was to be used in this building, the scheme would look something like the drawing on the left. The vertical shafts could be used to distribute air and water to each floor, from where horizontal ducts would bring it to the units.

Because this is not particularly an ordinary building, this common design will not suffice. The reasons for this are listed in the following.

The amount and distribution of units is not constant. Because of this a central system would probably not be efficient because the capacity would be calculated on the maximum occupation, while it might well be that only 50% occupation is the average.

Presuming that extra or less capacity can be added and taken from the installations, by means of adding installation units for example, the system still would not hold. The technical infrastructure of ducts and shafts would still have to be engineered on maximum capacity. For example if only half capacity is needed, the needed airspeed in the ducts cannot be reached when the air ducts are far too large.

Given the size of the building, the losses in transport are very high. This factor is always present, but in this case it will be probably be that high that the efficiency of the system is reduced very strongly.

All of this is enough reason to come up with a better system. Nonetheless some elements can be taken from common practice. This is especially true for engineering the climate of the main structure. This space will need to be ventilated and heated to a comfortable level, because this space will be used for circulation space.

Given the location, filtering air for all kinds of pollution will be necessary. Given the central position and the availability for placing installations, the floor underneath the central park promises to be the best place to take in the air. The air is let in from the top, where air is most protected from traffic. From here air is centrally purified an preheated, before it is blown into the hallways. Because this system is working on overpressure and the floors are vertically connected behind the facade, the air is distributed through the building automatically. Locally heaters warm up the air to maintain a balanced temperature.
Each unit is self-sufficient in its needs for heating and cooling. For this, each unit is occupied with its own heat pump which uses air as its source. Electric air-source heat pumps, often used in moderate climates, use the difference between outdoor air temperatures and indoor air temperatures to cool and heat your home. A compressor, condenser and refrigerant system is used to absorb heat at one place and release it at another. Outside air, no matter if it is 20°C or -20°C, is a heat container. An air-source heat pump moves, or ‘pumps’ some of this heat to provide hot water and another part for household heating. This can be done in either direction, to cool or to heat.

For the source of this system the air from inside the main structure is needed. This has the advantage that the air is already purified, so only a small CO₂ filter will suffice. Furthermore, the inside air is preheated, which makes the system function more efficient.

From the technical space (orange in the plan on the left) heated air and water is distributed through the unit. The drain points for water are located in the part of the unit that is situated in the main structure. This way the length of ducting is limited. The ceiling is lowered in this part of the unit, to give space for the ducts.

The heating of the unit is obtained by the use of heating ceilings that function on 30°C and can perform for cooling as well. The hot air is redistributed to the heat pump to make use of the heat again. The same goes for the heated air. After gaining the heat out of this, the air is exhausted via the cavity of the unit towards exhaust vents in the front of the unit.
In the end, images say far more than words. Hence, in the final part of this thesis the image plays a central role. The design is showed from different angles, different scales and different perspectives. Only short comments are added to indicate the main characteristics of the design to summarize that what has been described extensively in this thesis.
At the centre of the Prins Clausplein, the building is interwoven in the dynamic infrastructural landscape. The pictures show the way urbanity and mobility meet in a new kind of architecture.
From the perspective of the driver the building is experienced as a random distribution of units that together form a huge complex shape. Meanwhile the people inside the main structure are only separated from the highway by a few layers of foil. The difference in experience could not be larger.
In the centre of the building a green heart lies hidden from its surroundings. This ‘oasis’ in the centre of the Prins Clausplein is the most constant element in a constantly changing environment.
The building is constantly changing. Units are attached, removed and replaced by which the dynamic character of the site is extended in this new type of architecture.