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Performance Assessment Strategies

A computational framework for conceptual design of large roofs

Michela Turrin

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Michela Turrin
Delft University of Technology, Faculty of Architecture and The Built Environment,
Architectural Engineering + Technology department

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Prof.dr.ir. I.S. Sariyildiz
Dr.ir. R.M.F. Stouffs

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To my parents, Fausta and Alfredo

Contents (concise)

Abstract

Using engineering performance evaluations to explore design alternatives during the conceptual phase of architectural design helps to understand the relationships between form and performance; and is crucial for developing well-performing final designs. Computer aided conceptual design has the potential to aid the design team in discovering and highlighting these relationships; especially by means of procedural and parametric geometry to support the generation of geometric design, and building performance simulation tools to support performance assessments. However, current tools and methods for computer aided conceptual design in architecture do not explicitly reveal nor allow for backtracking the relationships between performance and geometry of the design. They currently support post-engineering, rather than the early design decisions and the design exploration process.

Focusing on large roofs, this research aims at developing a computational design approach to support designers in performance driven explorations. The approach is meant to facilitate the multidisciplinary integration and the learning process of the designer; and not to constrain the process in precompiled procedures or in hard engineering formulations, nor to automatize it by delegating the design creativity to computational procedures.

PAS (Performance Assessment Strategies) as a method is the main output of the research. It consists of a framework including guidelines and an extensible library of procedures for parametric modelling. It is structured on three parts. Pre-PAS provides guidelines for a design strategy-definition, toward the parameterization process. Model-PAS provides guidelines, procedures and scripts for building the parametric models. Explore-PAS supports the solutions-assessment based on numeric evaluations and performance simulations, until the identification of a suitable design solution.

PAS has been developed based on action research. Several case studies have focused on each step of PAS and on their interrelationships. The relations between the knowledge available in pre-PAS and the challenges of the solution space exploration in explore-PAS have been highlighted. In order to facilitate the explore-PAS phase in case of large solution spaces, the support of genetic algorithms has been investigated and the exiting method ParaGen has been further implemented. Final case studies have focused on the potentials of ParaGen to identify well performing solutions; to extract knowledge during explore-PAS; and to allow interventions of the designer as an alternative to generations driven solely by coded criteria.

Both the use of PAS and its recommended future developments are addressed in the thesis.

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Summary

This thesis focuses on the integration of engineering performance evaluations during the conceptual phase of architectural design for large roofs. It targets the development of a computational design approach able to support designers in performance driven explorations.

The design decisions taken during the conceptual phase have great impact on the performances of the final design. Considering the relevance of the choices made in the early phase, explicitly understanding the relations between form and performance during the conceptual phase is essential to reduce the investment in poor performing solutions. The importance of exploring different design alternatives is a major characteristic of the conceptual design phase, during which different design configurations can be considered. This process is a combination of generating alternative design solutions and selecting them: steps of divergence generate design alternatives; and steps of convergence select the most promising solutions. In order to perform the selection properly, considering a large range of performance assessments in the conceptual phase, and supporting the assessment with numeric evaluations is also crucial. However, when looking at traditional architectural design processes, diverging steps of explorations are limited; designers typically explore only narrow groups of alternatives and consider small subsets of possible design candidates. Moreover, traditional architectural processes rely the most on shallow exploration across alternative concepts, based on imprecise design information, in which the assessment is subject to interpretation based on the knowledge and expertise of the designer alone. This research aims at developing a design approach for integrating engineering aspects into the conceptual phase of architectural design, to overcome the limitations described above, by empowering the potentials of computer aided conceptual design.

Computer aided conceptual design has great potentials to facilitate discovering and/or highlighting the relations between form and performance. Procedural and parametric geometry can support the generation of geometric design alternatives. Building performance simulation tools can support design explorations proceeding depth-wise, where the pre-selected concepts are investigated based on additional variations of their geometry and performance assessments. However, despite the fact that the potential is evident, current tools and methods lack support for the whole process. They do not focus on the relations between performance and geometry (shape) of the design; they rarely allow for backtracking during the process; and most of the existing design methods in computer aided conceptual design have been developed for design disciplines other than architectural design, and cannot be applied in architectural design as they are. In this light, both the use of procedural geometry and the use of information from numeric evaluations and performance simulations need to be

addressed. The meaningfulness of the geometric procedures and the interdisciplinarity of the process must be guaranteed and structured in order to support the search for well performing solutions.

When dealing with the above described challenges, this research does not aim at constraining the conceptual design process in precompiled procedures or in hard engineering formulations. It is also not the goal of this research to automatize the process by delegating the design creativity to digital and computational procedures. Instead, this research aims at enhancing the design creativity of the architect, by means of digital processes that support multidisciplinary integration. The conception of the design during the creative process is left to the team of designers. Digital and computational procedures are intended to strengthen this process by supporting the integration of engineering disciplines into the creative process. Design creativity and the learning process of the designer are intended to be facilitated.

While the ideas explained above are generalizable for any field of architectural design, large roofs have been chosen as specific application field for this research. Large roofs are structures covering wide areas (such as urban public spaces, squares, entrance halls, courtyards and galleries, transport hubs, sport and leisure facilities), which can be completely or partially enclosed. The reason for which this topic has been chosen is twofold. First of all, large roofs are a challenging topic not only for architectural design, but also for engineering disciplines. It is a topic for which engineering studies developed specific knowledge and for which engineering challenges are faced during the design process. Secondly, it is a topic of growing relevance in everyday practice. Large roofs are increasingly being developed in relation to their iconic potentials as well as for the functional advantages of sheltered areas. In order to bound the research into feasible and meaningful ground, a limited number of relevant aspects have been selected. Besides the traditional attention on structural performance, the control of environmental factors is an important focus, since it greatly impacts climatic comfort. The climatic comfort under large roofs is actually a crucial aspect to consider in the design process, at the various scales of the design. It is important in relation to the need of achieving good comfort; and of limiting the energy consumption required to do so. In light of the relevance of large roofs, this research aims at developing a digital design approach for integrating engineering aspects into the conceptual design of large roofs. Specific focus is given to climatic control, in addition to attention for structural challenges.

Focusing on large roofs, a parametric design approach for integrating engineering aspects into the conceptual phase of design has been developed. It is named PAS (Performance Assessment Strategies). It consists of a framework including guidelines and recommendations in combination with an extensible library of procedures and scripts for parametric modelling. Its goal is to support designers in performance-based explorations during the conceptual phase, also by means of computational tools and techniques.

PAS is structured on three parts: pre-PAS; model-PAS; explore-PAS. Pre-PAS provides guidelines for a strategy-definition phase. It is organized in four sub-phases, during which analytical investigations make explicit the geometric properties that affect the satisfactions of certain design requirements. This phase aims at outputting a list of meaningful geometric properties and their attributes. Based on these attributes, models based on parametric geometry can be built. Model-PAS provides guidelines, procedures and scripts for building parametric models. Subsequently, explore-PAS supports the solution-assessment phase, which concerns the evaluation of different design solutions in search for well performing options (desired solution space) among the ones embedded in the parametric model (actual solution space). This exploration can involve different methods, mainly according to the breath and meaningfulness of the solution space, both of which depend on the strategy-definition phase.

In order to ground the research into practice-oriented processes, methodologies related to action research are used, in conjunction with case studies. A first case study is from practice, and deals with the whole process and focuses on each step of PAS. It regards the work developed by an interdisciplinary team, including the author, for the design of a long span roof, the Vela Roof in Bologna, Italy. During this design process, parametric models have been built to investigate different scales of the project, aiming at identifying geometric configurations that would contribute to the passive reduction of summer overheating of the covered spaces. The obtained instances have been evaluated based on their performance, with a combination of manual and software simulated calculations. The case study developed in this way, supports and grounds the formulation of the guidelines for pre-PAS, in a reciprocal, iterative process of both definition and encapsulation.

Other case studies are from teaching, and deal with the relations between different parts of PAS; and specifically between the knowledge available to the designer in the pre-PAS phase of the process and the challenges of the solution space exploration in explore-PAS. The second case study deals with a process in which only a few relationships between geometry and performances have been formulated during pre-PAS. As a consequence, the parameterization broadened the number and range of parameters, enlarging the solution space of the model. The third case study deals with a process in which the knowledge available during strategy-definition has also been initially limited, but different ways to increase the knowledge in this phase have been explored. Specifically, analytical numeric calculations have been joined with physical measurements and testing in order to gain knowledge and extract the meaningful geometric parameters, and therefore narrow the solutions space, to be explored during explore-PAS. The fourth case study further developed this process, until it has allowed the definition of a deterministic, possibly bijective, relation between performance and geometry. This has led to a correspondence between the desired solution space and the actual solution space, by limiting, sometime annulling, efforts in explore-PAS.

When focusing on cases such as the second case study, the challenge of exploring large solution spaces are experienced. In case of large solution spaces, an exhaustive, systematic exploration is not possible in explore-PAS, due to the breadth of the solution space. In order to face this challenge, this research investigates additional computational supports. Among various search techniques and precedent tools searching for suitable solutions in large design solution spaces, genetic algorithms have been selected and two additional case studies include the use of ParaGen. ParaGen is a method originally developed at the University of Michigan and further implemented as part of this thesis. It couples parametric modelling, performance simulations, genetic algorithms and an on-line database. This method is also suggested for extracting knowledge to be re-used in the pre-PAS phase of further processes. Moreover, its use is also proposed for cases in which fully automated generations driven solely by the coded criteria of the genetic algorithm are not wished by the designer.

The utilizable output of this research is PAS: intended as overall design approach and method, as defined in each of its three single phases.

Samenvatting

Dit proefschrift richt zich op de integratie van technische prestatie-evaluaties in de conceptfase van bouwkundige ontwerpen van grote daken. Het gaat daarbij specifiek om de ontwikkeling van een computationele ontwerpbenadering die ontwerpers kan ondersteunen bij prestatiegestuurde verkenningen.

De ontwerpbeslissingen die in de conceptfase worden genomen hebben een grote invloed op de prestaties van het eindontwerp. Omdat de keuzes die in de beginfase worden gemaakt zo belangrijk zijn, is het essentieel om expliciet inzicht te hebben in de relaties tussen vorm en prestatie tijdens de conceptfase zodat er minder wordt geïnvesteerd in slecht presterende oplossingen. Een wezenlijk kenmerk van de conceptontwerpfase is het verkennen van verschillende ontwerpalternatieven, waarin diverse ontwerpconfiguraties kunnen worden overwogen. Dit proces omvat het genereren van alternatieve ontwerpoplossingen in combinatie met het maken van een selectie uit deze oplossingen: divergerende stappen genereren ontwerpalternatieven, terwijl convergerende stappen leiden tot een selectie van de meestbelovende oplossingen. Een zorgvuldige selectie staat of valt met het overwegen van een groot aantal prestatiebeoordelingen in de conceptfase waarbij men die beoordeling ondersteunt met cijfers. Als we kijken naar de traditionele bouwkundige ontwerpprocessen blijkt echter dat het aantal divergerende stappen beperkt is. Meestal verkennen ontwerpers alleen een beperkte groep alternatieven en maken ze een keuze uit kleine subsets van mogelijke ontwerpkandidaten. Bovendien berusten traditionele bouwkundige processen in hoofdzaak op een oppervlakkige verkenning van een reeks alternatieve concepten met onnauwkeurige ontwerpinformatie, waarbij het beoordelingsproces afhankelijk is van de kennis en expertise van alleen de ontwerper. Om bovengenoemde beperkingen te kunnen ondervangen richt dit onderzoek zich op het ontwikkelen van een ontwerpbenadering die technische aspecten in de conceptfase van het bouwkundig ontwerp integreert en optimaal gebruik maakt van de mogelijkheden van computergeassisteerde conceptontwerpmethoden.

Een computergeassisteerd conceptontwerp biedt uitstekende mogelijkheden om gemakkelijker de relaties tussen vorm en prestaties te ontdekken of deze te accentueren. Procedurele en parametergestuurde geometrie kan het genereren van geometrische ontwerpalternatieven ondersteunen. Het ontwikkelen van prestatiesimulatiehulpmiddelen kan als ondersteuning dienen voor ontwerpgerichte diepteverkenningen, waarbij de vooraf geselecteerde concepten worden onderzocht op basis van aanvullende variaties van hun geometrie en prestatiebeoordelingen. Ondanks de onmiskenbare voordelen van deze aanpak bieden de huidige hulpmiddelen en methoden niettemin geen procesbrede ondersteuning. Ze zijn niet afgestemd op de relaties tussen prestatie en geometrie (vorm) van het ontwerp en bieden zelden de

mogelijkheid van reverse engineering tijdens het proces. Bovendien zijn de meeste huidige methoden voor computergeassisteerde conceptuele ontwerpen ontwikkeld voor andere ontwerpdisciplines dan de architectuur. Ze zijn dus niet gelijk geschikt voor bouwkundige ontwerptoepassingen. Vanuit dit perspectief moet er daarom aandacht worden besteed aan het gebruik van procedurele geometrie en gebruik van informatie afkomstig uit cijfermatige evaluaties en prestatiesimulaties. Om het zoekproces naar effectieve oplossingen te kunnen ondersteunen moet deze zo worden gestructureerd dat het garandeert dat de geometrische procedures zinvol zijn en het proces een interdisciplinair karakter heeft.

Bij het aangaan van de hierboven genoemde uitdagingen wil dit onderzoek zich niet richten zijn op vernauwing van het conceptontwerpproces binnen vooraf gecompileerde procedures of onwrikbare technische formuleringen. Evenmin heeft dit onderzoek tot doel het proces te automatiseren en de ontwerpcreativiteit over te laten aan digitale en computationele procedures. Dit onderzoek wil de ontwerpcreativiteit van de architect juist versterken door digitale processen toe te passen die multidisciplinaire integratie ondersteunen. Tijdens het creatieve proces bepaalt het ontwerpteam hoe het ontwerp precies vorm krijgt. Digitale en computationele procedures zijn bedoeld om dit creatieve proces te versterken door ondersteuning van de integratie van technische disciplines in het proces. Het is de bedoeling dat de ontwerpcreativiteit en het leerproces van de ontwerper daarbij worden gefaciliteerd.

Hoewel de hierboven beschreven ideeën algemeen toepasbaar zijn voor ieder aspect van bouwkundig ontwerpen zijn voor dit onderzoek grote daken als specifiek toepassingsgebied gekozen. Grote daken zijn structuren die grote ruimten volledig of gedeeltelijk overkappen (bijvoorbeeld openbare ruimten in de stad, pleinen, foyers, binnenplaatsen en galerijen, vervoersknooppunten, sport- en vrijetijdscentra). Er is om twee redenen voor dit specifieke ontwerpaspect gekozen. Ten eerste vormen grote daken een uitdaging, niet alleen bij bouwkundige ontwerpen, maar ook voor technische disciplines. Het is een onderwerp waarvoor specifieke kennis is ontwikkeld in technische studies en waarbij technische uitdagingen een rol spelen tijdens het ontwerpproces. Ten tweede is sprake van een toenemende relevantie voor de dagelijkse praktijk. Steeds vaker worden grote daken ontwikkeld vanwege hun iconisch potentieel, maar ook omdat overdekte ruimten functionele voordelen bieden. Om het onderzoek in een haalbaar en betekenisvol kader te kunnen plaatsen, hebben we een beperkt aantal relevante aspecten geselecteerd. Naast de aandacht die van oudsher aan de constructieve prestaties wordt gesteld ligt het accent in belangrijke mate op milieufactoren, aangezien deze van grote invloed zijn op het klimaatcomfort. Het klimaatcomfort onder grote daken dient als een zeer wezenlijk aspect te worden betrokken in het ontwerpproces, op de diverse schalen van het ontwerp. Dit is belangrijk omdat het dak een comfortabel klimaat moet kunnen garanderen, waarbij het energieverbruik dat nodig is om dat niveau te bereiken beperkt blijft. Vanwege de relevantie van grote daken richt dit onderzoek zich op het ontwikkelen van een digitale ontwerpbenadering die technische aspecten integreert in de conceptontwerpfase van grote daken. Specifieke aandacht wordt besteed aan klimaatregeling, naast het oplossen van structurele uitdagingen.

Er is een parametrische ontwerpbenadering ontwikkeld voor integratie van technische aspecten in de conceptfase van het ontwerp, waarbij grote daken centraal staan. Deze benadering, die wordt aangeduid als PAS (Performance Assessment Strategies), bestaat uit een kader met richtlijnen en aanbevelingen in combinatie met een uitbreidbare bibliotheek van procedures en scripts voor parametrische modelontwikkeling. Het doel is om ontwerpers te ondersteunen bij prestatiegeoriënteerde verkenningen in de conceptfase, met inzet van computationele hulpmiddelen en technieken.

De structuur van PAS bestaat uit drie delen: pre-PAS, model-PAS en explore-PAS (verken-PAS). Pre-PAS biedt richtlijnen voor een fase waarin strategische definities worden vastgelegd. Deze fase is onderverdeeld in vier subfasen, waarin analytisch onderzoek expliciete informatie oplevert over de geometrische eigenschappen die van invloed zijn of er aan bepaalde ontwerpeisen wordt voldaan. Deze fase is gericht op het produceren van een lijst met betekenisvolle geometrische eigenschappen en de bijbehorende kenmerken. Uitgaande van deze kenmerken kunnen modellen op basis van parametrische geometrie worden ontwikkeld. Model-PAS biedt richtlijnen, procedures en scripts voor het ontwikkelen van parametrische modellen. Als volgende stap levert explore-PAS ondersteuning voor de oplossingsbeoordelingsfase. Daarbij worden verschillende ontwerpoplossingen geëvalueerd om zo de best presterende opties te kunnen selecteren (gewenste oplossingsruimte) binnen de opties die in het parametrische model zijn ingebed (feitelijke oplossingsruimte). Deze verkenning kan meerdere methoden omvatten, waarbij de armslag en het betekenisaspect van de oplossingsruimte leidend zijn. Beide zijn afhankelijk van de fase waarin de definities worden vastgelegd.

Om te zorgen dat het onderzoek verankerd is in praktijkgerichte processen wordt gebruik gemaakt van methodieken die betrekking hebben op actieonderzoek, in combinatie met casestudy's. Een eerste casestudy is afgeleid van de praktijk en behandelt het volledige proces, met de nadruk op iedere PAS-stap. Het betreft hier het werk van een interdisciplinair team, waartoe ook de auteur behoort, voor het ontwerp van het Vela-dak in Bologna (Italië), een dak met grote overspanning. Tijdens dit ontwerpproces zijn parametrische modellen ontwikkeld om onderzoek te doen naar de verschillende schalen van het project. Daarbij werd gezocht naar geometrische configuraties die kunnen bijdragen aan de passieve vermindering van oververhitting van overdekte ruimten in de zomer. De verkregen voorbeelden zijn geëvalueerd op basis van hun prestaties door middel van een combinatie van handmatige en door software gesimuleerde berekeningen. De aldus ontwikkelde casestudy ondersteunt en onderbouwt de formuleringen van de richtlijnen voor pre-PAS in een wederkerig, iteratief proces van zowel definitie als inkapseling.

Andere casestudy's zijn ontleend aan de onderwijswereld en betreffen de relaties tussen verschillende delen van PAS. Het gaat daarbij specifiek om de relaties tussen de kennis waarover de ontwerper in de pre-PAS-fase beschikt en de uitdagingen van het verkennen van de oplossingsruimte in explore-PAS. De tweede casestudy betreft een proces waarin slechts enkele relaties tussen geometrie en prestaties tijdens pre-PAS zijn geformuleerd. De parameterisatie leidt vervolgens tot een verbreding van het aantal parameters en het spectrum aan parameters en dus ook tot vergroting van de oplossingsruimte van het model. De derde casestudy behandelt een proces waarin de beschikbare kennis tijdens het definiëren van de strategieën ook aanvankelijk beperkt is, maar waarbij verschillende manieren zijn verkend om de kennis in deze fase te vergroten. Analytische numerieke berekeningen zijn daarbij samengevoegd met fysieke metingen en tests om zo kennis te vergaren en de betekenisvolle geometrische parameters te extraheren. Dat resulteert dus in een inkrimping van de oplossingsruimte die tijdens explore-PAS wordt verkend. De vierde casestudy bouwt voort op dit proces totdat het mogelijk is om een deterministische, mogelijk bijectieve relatie te definiëren tussen prestaties en geometrie. Zo is er overeenkomst gecreëerd tussen de gewenste oplossingsruimte en de feitelijke oplossingsruimte door activiteiten in explore-PAS te beperken en soms zelfs te elimineren.

Wanneer we ons richten op casussen als de tweede casestudy gaat de uitdaging van het verkennen van grote oplossingsruimten een rol spelen. Bij grote oplossingsruimten is een diepgaande, stelselmatige verkenning in explore-PAS niet mogelijk door de breedte van de oplossingsruimte. Om deze uitdaging toch te kunnen aangaan wordt in dit onderzoek gekeken naar aanvullende computationele vormen van ondersteuning. Uit diverse zoektechnieken en reeds toegepaste hulpmiddelen voor het zoeken naar geschikte oplossingen voor het ontwerpen van grootschalige oplossingsruimten hebben we genetische algoritmen geselecteerd, evenals twee aanvullende casestudy's die gebruik maken van ParaGen. ParaGen is een methode die oorspronkelijk is ontwikkeld door de universiteit van Michigan en die verder is geïmplementeerd in het kader van dit proefschrift. Deze methode brengt een koppeling tot stand tussen parametrische modelontwikkeling, prestatiesimulaties, genetische algoritmen en een onlinedatabase. De methode wordt ook aanbevolen voor het extraheren van kennis die bestemd is voor hergebruik in de pre-PAS-fase van latere processen. Bovendien wordt het gebruik van deze methode ook aanbevolen voor gevallen waarin de ontwerper niet volledig automatisch oplossingen wil genereren op basis van alleen de gecodeerde criteria van het genetisch algoritme.

De bruikbare uitkomst van dit onderzoek is PAS, dat is bedoeld als allesomvattende ontwerpbenadering en methode, zoals het in elke van de drie afzonderlijke fasen is gedefinieerd.

Contents (extensive)

1 Introduction

The process of designing is a complex and multidisciplinary system of analysis, formulations, considerations, evaluations, intuitive as well as rational decisions. It regards the conception and the realization of something new (Cross, 1982); it is constituted by all the events leading to the completion of a project (Broadbent, 1969); it generates a description of a design object which satisfies a given set of requirements and objectives (Van Langen and Brazier, 2006). Any design process is characterized by these attributes, regardless the nature of the project; from product design to urban design. When focusing on architecture, interdisciplinarity is crucial. Architectural requirements include a large number of intended objectives; the purpose of architecture confronts a variety of human needs, from basic to higher levels. As a consequence, an architectural design process is not an individual experience, but is based on the integration of a number of individual expertise from different disciplines. This process is highly dynamic and each aspect of it is subject to possible changes. Inputs and elaborations from each discipline address continuous modifications. As such, the partial description of the design artefact as well as the design requirements and process objectives can change during the process (Van Langen and Brazier, 2006). This characteristic of the process is especially high when the design process includes or targets innovation. Going behind well-known standards and looking for innovative solutions rely also on real time learning processes, which occur in each discipline and across different disciplines; and which is an integral part of the exploratory design activity and leads to an evolving design path.

Within the whole design process, there is an early phase during which the main goal is generating promising concepts that meet the design requirements and that are to be developed in the following phases. During this early design phase, the requirements and design objectives are synthesized into a number of conceptual alternatives (Pahl, 2007). This early phase is actually the part of the process in which the design is conceived; when geometry is explored into possible alternative shapes for architectural ideas. This phase is called conceptual design phase. It is a crucial part of the process, since the design conception includes decisions highly influencing all architectural requirements.

Despite this, there is a discrepancy between the breadth of architectural requirements and the limited number of disciplines truly involved in the conceptual phase. Engineering requirements are mostly considered in late stages of the design process only. This often results in post-engineering processes, in which the design variations eventually necessary to satisfy the technical requirements of the project are tailored upon preconceived and constraining architectural designs.

This research questions the suitability and acceptability of this tendency. In contrast with this attitude, this thesis aims at enlarging the range of design requirements considered during the early phase. It addresses the integration of engineering disciplines in the conceptual phase of architectural design. This research advocates the use of technical requirements in order to drive creative and innovative design solutions. Their use is encouraged in order to trigger the design creativity. Engineering feedback is not intended as an assessment only. It aims also at inspiring (or even driving) improvements of the design concept, and eventually the generation of new design alternatives. This kind of attitude leads to performance-based design, which searches for design solutions based on their multidisciplinary performances.

In this research, a parametric design approach for integrating engineering aspects into the conceptual phase of design has been developed. It consists of a framework including guidelines and recommendations in combination with an extensible library of procedures and scripts for parametric modelling. Its goal is to support designers in performance-based explorations during the conceptual phase, also by means of ICT (information and communications technology) tools and techniques. The approach is specifically targeted for the topic of large roofs, with focus on passive climatic comfort.

This research has been developed at the chair of Design Informatics, as part of the Computation and Performance research program at Delft University of Technology, under the supervision of Prof. dr. ir. Sevil Sariyildiz and dr. ir. Rudi Stouffs. It is mainly addressed to designers, especially architects and engineers. This includes both practitioners and academicians. The outputs produced in this research are grounded in real processes; and the major relevance of this research for practice relay on its applicability. The research clearly indicates also future direction of possible development, which can be relevant for further academic research, in architectural design, engineering disciplines and computer science. This research is also addressed to teachers and students of architecture and building technology, who may find relevant both the theory and the proposed approach, with the case studies.

§ 1.1 Research motivation and goal

In recent years, computer aided conceptual design (CACD) has shown very powerful potentials. Numerous CACD approaches have been developed, consisting of ICT technologies and computational methods and tools. When looking at the wide spectrum of design disciplines, such methods include decision matrices, knowledge representation models, argumentative process models, tools for concept selection, concurrent methods, and others. These methods have the common goal of structuring the process into a transparent externalization of the design thinking. Intentionally, augmenting the transparency of the process aims at opening the process to multiple contributions; going behind the individuality of internalized thinking. In other words, the transparency aims at favouring the integration of contributions rather than the designer's own knowledge and experience (Jones, 1992).

So formulated, the intention of these methods seems to meet very well the idea of enlarging the interdisciplinary nature of conceptual design; and specifically integrating engineering disciplines in the early conceptual phase. However:

- most of these methods do not focus on the relations between performance and geometry (shape) of the design; while exploring and understanding how different design configurations affect the performances is crucial for conceptual design.
- these methods rarely allow for backtracking during the process; while retrospection is a crucial need when engineering feedback are intended to inspire the design; even more when engineering feedback are intended to be integral part of the exploratory design activity toward the generation of innovative alternative concepts.
- most of these methods have been developed for design disciplines other than architectural design; and cannot be applied in architectural design as they are, due to the specificities of the field. Particularly, architectural design differs from other design activities based on the prominence of its un-structured and un-predictable nature. These are due to its complexity and high variety of requirements. Therefore, focused attention on the specificities of architectural design is needed.

This research aimed at developing a design approach for integrating engineering aspects into the conceptual phase of architectural design, by empowering the potentials of computer aided conceptual design and overcoming the limitations described above.

Nevertheless, this research did not aim at constraining the conceptual design process in precompiled procedures or in hard engineering formulations. It is also not the goal of this research to automatize the process by delegating the design creativity to digital and computational procedures. Instead, this research aimed at enhancing the design creativity of the architect, by means of digital processes that support multidisciplinary integration. The conception of the design during the creative process is left to the team of designers. Digital and computational procedures are intended to strengthen this process by supporting the integration of engineering disciplines into the creative process.

A number of more specific goals to be fulfilled by the design approach can be summarized with the following list. The design approach should:

- allow the designer to explore alternative shapes; and therefore high priority should be given to geometric manipulations of design concepts.
- support the integration of architectural and engineering aspects (rather than superimpose one to the other), toward their mutual empowerment.
- respect the complexity of the architectural design process; it should allow for explicit formulations, but it should avoid flattering the richness of the creative process.
- allow taking advantage of the measurability of most engineering aspects. It should enhance the design process by introducing information from numeric evaluations.
- respect the visual language of the early design phase and should enrich the visualization by favouring an explicit link between form and numeric evaluations.
- support the extraction, or even the generation, of knowledge and the enhancement of design understanding during the process.
- respect the ill-defined nature of the conceptual phase.

§ 1.2 Research focus: an application field

While the ideas explained in the previous section are generalizable for any field of architectural design, large roofs have been chosen as specific application field for this research.

Large roofs are structures covering wide areas (such as urban public spaces, squares, entrance halls, courtyards and galleries, transport hubs, sport and leisure facilities), which can be completely or partially enclosed. In order to help clarifying the definition, one could think of well-known examples, such as the Great Court at the British Museum and the Millennium Dome in London. The reason for which this topic has been chosen is twofold. First of all, large roofs are a challenging topic not only for architectural design, but also for engineering disciplines. It is a topic for which engineering studies developed specific knowledge and for which engineering challenges are faced during the design process. Secondly, it is a topic of growing relevance in everyday practice. Large roofs are increasingly being developed in relation to their iconic potentials as well as for the functional advantages of sheltered areas.

In order to bound the research into feasible and meaningful ground, a limited number of relevant aspects have been selected. Besides the traditional attention on structural performance, the control of environmental factors is an important focus, since it greatly impacts climatic comfort. The climatic comfort under large roofs is actually a crucial aspect to consider in the design process, at the various scales of the design. It is important in relation to the need of achieving good comfort; and of limiting the energy consumption required to do so. This regards both new developments and the chance to improve the conditions of existent building and urban settlements.

In light of the relevance of large roofs, this research aimed at developing a digital design approach for integrating engineering aspects into the conceptual design of large roofs. Specific focus is given to climatic control, in addition to attention for structural challenges.

§ 1.3 Research questions

Considering the discussion in the previous sections, this research addressed the following research question:

How can designers be facilitated in integrating engineering aspects during architectural design conception by means of computational tools, methods and techniques? How can this be achieved in the specific domain of large roofs?

In order to answer this main question, a number of sub-questions have been addressed, which are listed here following.

How can computer aided conceptual design:

- support the generation of geometric design alternatives?
- support the mutual empowerment of architectural design creativity and engineering principles?
- support explicit formulations of aspects involved in the design, without compromising the richness embedded in their complexity?
- support the use of numeric assessments? Therefore, how can conceptual abstract definitions be converted into measurable criteria?
- respect the visual language, which is dominant in the elaboration of design concepts?
- support the learning process of the designer?
- allow the coexistence of hard engineering principles with the ill-defined nature of architectural conception?
- specifically support the design of large roofs?

§ 1.4 Research methodology

Archer (1995) defines research as systematic enquiry the goal of which is communicable knowledge. In his view, research is an enquiry because it is an investigation to answer a question; it is systematic because such investigation follows a proper plan, defined based on the objectives (for which research is a goal-oriented activity); and it generates knowledge (and not mere information), which should be made understandable to the appropriate audience.

Specifically, this doctoral research belongs to the field of design research, which is concerned with the development, articulation and communication of the so-called design knowledge (Cross, 1999). Since it regards manufactured artefacts, design research belongs to the domain of the sciences of artificial, which are concerned with the knowledge about artificial objects and phenomena (Simon, 1969). This knowledge has three sources: people, processes and products. In design research, the first aspect leads to the need of understanding how people (especially professionals, but not exclusively) design. The second aspects leads to the need of understanding the strategies applied during the process of designing; and developing design methodologies that support the process. The third aspect leads to the need of understanding precedents, since previous design products embody design attributes in their form, materials and finishing and therefore knowledge of how the product can be (Cross, 1999).

Ultimately, this doctoral research aimed at favouring better design solutions. However, it aimed at this goal by integrating architectural and engineering knowledge during the design process. Therefore, specifically, this research aimed at improving the design process. In doing so, research must necessarily make a dual contribution to academia and practice (Cole et al., 2005). This means that generating new knowledge in extension or alternative to the existent theories is not enough. The research is also expected to provide an explicit support to practitioners in solving practical problems (Cole et al., 2005); and should lead to solutions relevant for practitioners in similar situations. This research embraced this double perspective. In order to benefit from and relate to previous knowledge and theories, literature review constituted a decisive method. In order to ground the research into practice-oriented processes, methodologies related to action research have been used.

According to Archer (1995), action research is a systematic investigation through practical action planned and performed to devise or test new information, ideas, forms or procedures and to produce communicable knowledge. Action research has a cyclical nature. Kemmis and McTaggart (2000) propose a spiral model to describe the process of action research. The spiral loops cycles, each of which is comprised of three steps: first planning, secondly acting and observing at the same time, thirdly reflecting. This tripartite sequence loops to the following three steps, the first of which is revising the plan. As the authors point out, this structure might not be as rigid as it looks; and the steps of the research process may be in reality much more blurred and sometime even overlapping. However, this is the general structure of the process. In the case of this doctoral research, action research methodology has been used in conjunction with case studies, defined here following.

According to Yin (2003), a case study can be defined as an empirical inquiry that investigates a contemporary phenomenon, within its real-life context. Case studies can be applied both in case of qualitative and quantitative research. In the specific case of this doctoral research, case studies have been used for qualitative research; they regarded the design process; and they have been used as part of the action research method itself. In addition to the phases of the action research cycle, basing the research on case studies allowed benefitting from the exploratory nature of case study methods. In light of this, the design approach developed in this research has been formulated based on case studies and cyclically not only tested and re-formulated, but also extended.

The research process can be summarized in two phases, the first one focusing on literature review; the second one on action research and case studies. These phases included a number of sub-phases, which can be described as following:

- Literature review:
  - The first phase included a literature review regarding CACD methods and tools. It lead to the identification of potentials and limits of current CACD.
  - The second phase included a literature review of adaptive architecture. The thesis focuses both on static and on adaptive design solutions. While static solutions in architecture are the most common output of the design process, adaptive solutions are a possible alternative based on adaptivity. Due to its novelty, this alternative required a clear definition, which has been the goal of this phase.
  - The third phase included the selection of a specific filed of work in architecture; and the analysis of this field. It leads to the selection of large roofs as research focus; and identified in their structural and climatic performances the specific areas in which the research operated.
- Action research and case studies:
  - During this phase, PAS was developed. Its development was based on the knowledge gained from literature review as well as on iterative work on case studies, based on action research. This allowed cyclic loops of development, action, observation and refinement. Six case studies have been particularly crucial: one from practice, one theoretically set for research propose, and four from teaching. During the process of development/refinement of PAS, the exploration of large solution spaces emerged as relevant challenge. For this, PAS was connected with ParaGen. Among the six case studies, two of them specifically focused on this aspect.

The phases are illustrated in figure 1

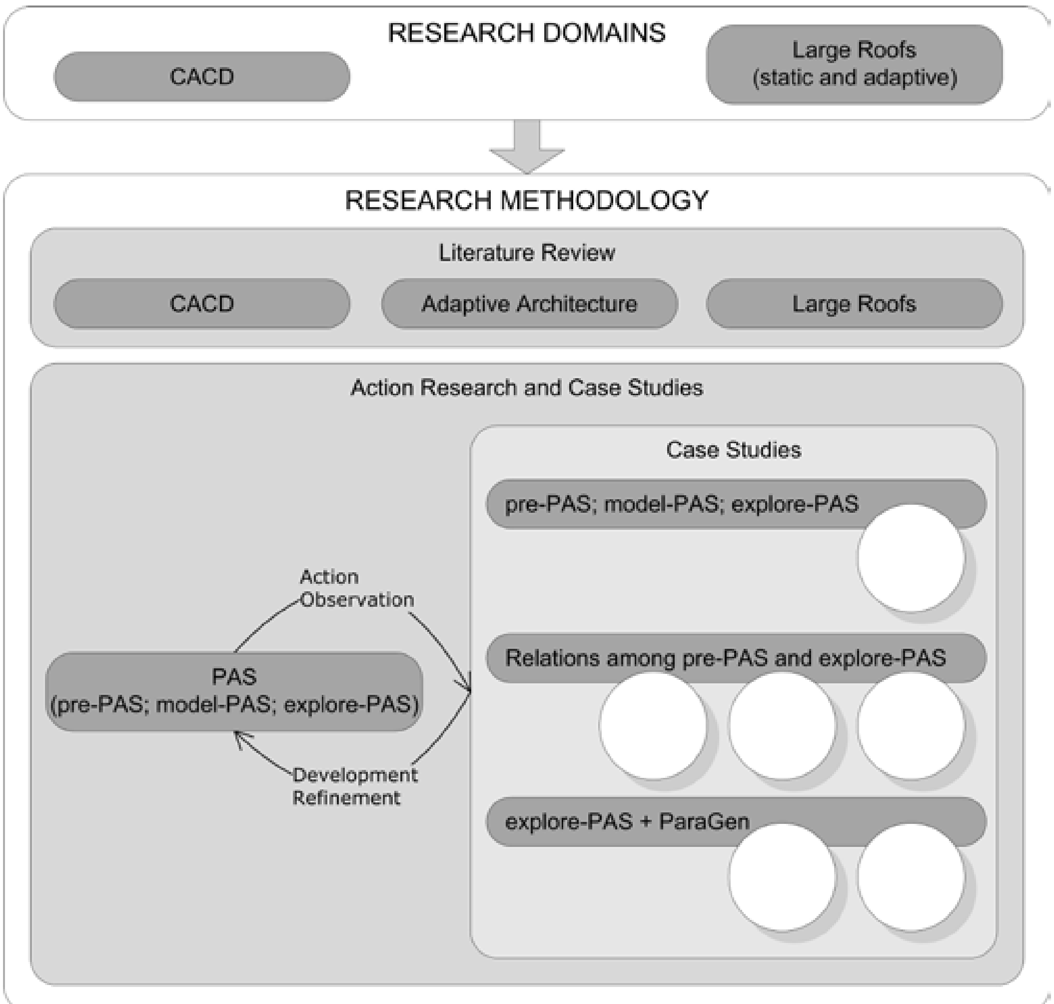

Figure 1
The figure illustrates the overall research process.

§ 1.5 Social and scientific relevance

By advocating the use of engineering performances in order to trigger the design creativity and inspire innovative design concepts, this research aims at improving performances in architecture. In this light, supporting the integration of technical requirements with aesthetic and iconic values is possibly the ultimate social benefit. When considering this overall goal, additional benefits are identified in its individual aspects. Specifically, the chances to improve design concepts in each of their performances is indeed beneficial. Since this research is highly grounded in practical applications, these social benefits have been a clear driver of this work.

The scientific contribution of this research is also multifaceted. Ultimately, it lies on a scientifically consistent method for integrating different disciplines within the design process. Despite fundamental novelty is not added to the scientific state of art of each discipline, these do benefit from the overall scientific contribution. This is not only related to the new perspective that is proposed for design integration, but also to the explicit knowledge extraction and representation within each field involved in the design process. In this light, the design approach developed in this research aims also at facilitating the reusability and scientific elaboration of the knowledge-intensive tasks performed during the design processes.

§ 1.6 Overview of the dissertation

After this introduction, chapter 2 focuses on architectural performance in CACD. It introduces the concept of architectural performance and of performance oriented design, which searches for design solutions based on measurable performance already in the early phase of design. The nature and the focus of conceptual design is presented; the aspects of traditional conceptual design inhibiting performance oriented design are discussed. Precedents and references in the domain of CACD are presented, first with reference to a broad concept of conceptual design, then by narrowing into conceptual design in architecture. General limitations of current CACD methods are identified; and specific requirements for a design methodology and support tools are formulated. The overall goal of this chapter is an overview on the state of art of CACD; the discussion of its current limitations; and the formulation of desired research objectives.

Chapter 3 presents the concept of adaptivity in architecture. Various ways in which architectural and structural elements may respond to the dynamic nature of the context are discussed and classified. Three different groups of adaptive architecture are identified based on the level of automation with which architecture detect, elaborates and react to changes in the context; and various subgroups are identified based on the different actions that are automated. As alternative classification, two main groups of adaptive architecture are identified based on the way in which architecture can adjust to achieve the desired changes; and six sub-groups are identified within one of these two domains and further sub-classifications are discussed. With the same logic, a brief set of classifications is proposed also for adaptive structures. The overall goal of this chapter is to provide a clear overview and reference vocabulary for the domain of adaptive architecture, which is from time to time re-called throughout the overall thesis.

Chapter 4 presents the topic of large roofs. The specific field of large roofs is chosen as application field for this doctoral research. Focus is given to the design of the envelopes covering the spaces underneath the roofs, by emphasizing the importance of the early integration of performance evaluations in the design process. Beside the traditional attention on structural performance, the control of climatic environmental factors is considered crucial for improving the passive achievement of climate comfort. Based on this, a number of aspects to be considered during the conceptual design is identified. The overall goal of this chapter is introduce the topic of large roofs and to bound the research within a meaningful and selected number of aspects related to their performance.

Chapter 5 introduces and defines parametric modelling; and presents PAS, which is a parametric design approach for performance oriented design of large roofs. PAS has been iteratively derived from the theoretic studies presented in chapters 2, 3 and 4; and form action research based on case studies, which are presented in chapters 6 and 7. PAS is structured on three parts: pre-PAS; model-PAS; explore-PAS. Pre-PAS provides guidelines for a strategy-definition phase. It is organized in four sub-phases, during which analytical investigations make explicit the geometric properties that affect the satisfactions of certain design requirements. This phase aims at outputting a list of meaningful geometric properties and their attributes. Based on these attributes, models based on parametric geometry can be built. Model-PAS provides guidelines, procedures and scripts for building parametric models. Subsequently, explore-PAS supports the solution-assessment phase, which concerns the evaluation of different design solutions in search for well performing options (desired solution space) among the ones embedded in the parametric model (actual solution space). This exploration can involve different methods, mainly according to the breath and meaningfulness of the solution space, both of which depend on the strategy-definition phase. The overall goal of this chapter is to present and discuss PAS.

Chapter 6 presents a case study from practice, which deals with the whole process and focuses on each step of PAS. An interdisciplinary team, including the author, worked on the design of a long span roof, the Vela Roof in Bologna, Italy. With regards to this project and according to PAS, preliminary analyses for the strategy-definition are presented and discussed, in order to contribute to the passive reduction of summer overheating of the covered spaces. Based on these, parametric models are presented, which aimed at investigating different scales of the project. Finally, performance simulations are presented and their results are discussed, as part of the solution-assessment phase. The overall goal of this chapter is to present and discuss the case study in relation to PAS.

Chapter 7 presents case studies from teaching, which deal with the relations between different parts of PAS; and specifically between the knowledge available to the designer in the pre-PAS phase of the process and the challenges of the solution space exploration in explore-PAS. In the first case study, a process is presented in which only a few relations between geometry and performances were formulated during pre-PAS; as a consequence, the parameterization broadened the number and range of parameters, enlarging the solution space of the model. In the second case study, the knowledge available during strategy-definition was also initially limited, but different ways to increase the knowledge in this phase were explored. Specifically, analytical numeric calculations were joined with physical measurements and testing in order to gain knowledge and extract the meaningful geometric parameters, and therefore narrow the solutions space, to be explored during explore-PAS. In the third case study, this process is further developed, until it allows the definition of a deterministic, possibly bijective, relation between performance and geometry. This leads to a correspondence between the desired solution space and the actual solution space, by limiting, sometime annulling, efforts in explore-PAS. The overall goal of this chapter is to present the three case studies; and to discuss the implications of the three different routes exemplified by the case studies.

Chapter 8 tackles the challenge of exploring large solution spaces. As presented in chapter 7, large solution spaces are common especially when little knowledge is available in pre-PAS. In case of large solution spaces, an exhaustive, systematic exploration is not possible in explore-PAS, due to the breadth of the solution space. In order to face this challenge, additional computational supports are investigated; various search techniques and precedent tools searching for suitable solutions in large design solution spaces are discussed based on literature studies. The solution for exploring large solution spaces is then addressed based on the use of genetic algorithms. ParaGen is presented, which is a method originally developed at Michigan University and further implemented as part of this thesis. It couples parametric modelling, performance simulations, genetic algorithms and an on-line database. This method is also suggested for extracting knowledge to be re-used in the pre-PAS phase of further processes; moreover, its use is proposed also in case fully automated generations driven only by the criteria of the genetic algorithm process are not wished by the designer. The overall goal of this chapter is to present a possible solution in order to support explore-PAS in case of large solution spaces, without the mandatory necessity of fully automated processes; and to extract knowledge that can be re-used in further strategy-definition phases.

Chapter 9 presents two case studies, focusing on the use of PareGen during explore-PAS. Based on the case studies, potentials and limits of ParaGen are discussed regarding the identification of optimal and sub-optimal solutions; the extraction of knowledge from optimal and sub-optimal solutions; the chance the designer has to interact with the genetic algorithm system during the generation of the design solutions. The overall goal of this chapter is to discuss potentials and limits of ParaGen in explore-PAS based on case studies.

Chapter 10 presents the conclusions of the research and recommendations, in which results and original contributions of the research are stated and future work is addressed. Moreover, the suggested future work is addressed.

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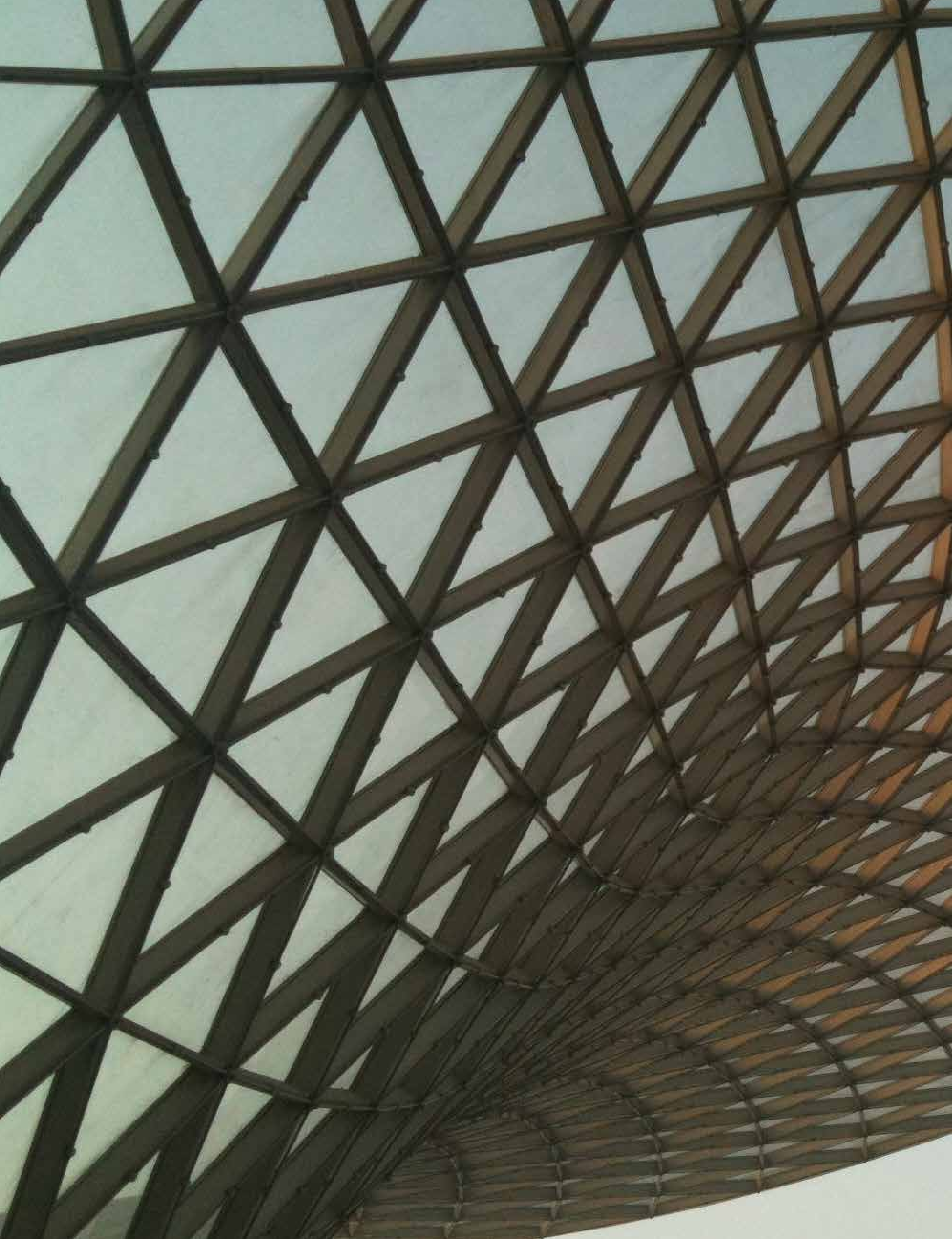

2 Architectural performance in Computer Aided Conceptual Design (CACD)

This chapter introduces the concept of performance oriented design, which searches for design solutions based on measurable performance from the beginning of the design conception. Considering the relevance of the choices made in the early phase of design, being able to visualize the link between form and performance during the early phases of design is taken as a key aspect to reduce the investment in poor performing solutions. Broadening the range of performance assessments in the conceptual phase, and supporting the assessment with numeric evaluations is stressed as crucial. To support such process in the conceptual phase, the role of computer aided design is presented. Precedents and references in the board domain of design (including industrial and product design) are provided. Focusing on architectural design, the current lack of enhancement to the design process in the early convertion of abstract definitions into measurable criteria; and the consequent lack of information from numeric evaluations and performance simulations in the early phase are stressed.

After an introduction on the concept of performance in architecture, the focus of the chapter narrows from the breadth of any conceptual design to conceptual design in architecture and finally to the conceptual design of performance oriented architecture. Following this structure, the peculiarities of a CACD design method suitable for the conceptual design of performance oriented architecture are discussed.

§ 2.1 Introduction

This research focuses on performance oriented design in CACD and targets well performing design concepts. Performance oriented design searches for forms and materializations based on their multidisciplinary performances and measurable performance values already during the design conception. It belongs to the domain of performative architecture. According to Branko Kolarevic, performative architecture can be defined as *the one in which building performance, broadly understood, becomes a guiding design principle* (Kolarevic, 2003).

In this light, the whole of research refers therefore to the concept of performance. When referring to architecture, the concept of performance embraces a wide range of different fields, involving both soft and hard issues. This concept of performance is addressed in section 2.2.

A second aspect of relevance regards the early integration of quantitative performance assessments during the design conception. With this respect, the conceptual phase of the design process is addressed in section 2.3.

Section 2.4 introduces methods and tools for computer aided conceptual design, by emphasizing potentials and limitations of precedents and leading to the identification of the key aspects for which improvements are needed in order to support a performance oriented process. This is specifically grounded in architectural design in section 2.5; and summarized into a list of key design process requirements in the conclusions presented in section 2.6.

§ 2.2 Architectural performance

In this section, the definition of performance is given. Moreover, the concept of performance in architecture is defined as the capacity of a building to fulfil the architectural requirements, in relation to human needs and environmental factors. The ensemble of human needs and environmental factors is here called context.

§ 2.2.1 Definition of performance

Stein (1983) defines performance as *the manner in which or the efficiency with which something reacts or fulfils its intended purpose*. Dealing with performance leads therefore to consider both the identification of the intended purposes of the subject and the capacity the subject has to accomplish such expected tasks.

When focusing on architecture, the intended purposes of a building or other architectural structures are numerous, interrelated and dynamic; this results in a concept of performance that is complex and multi-composed. As Sevil Sariyildiz (2012) states, *architecture refers to the science of designing and constructing buildings and built environment to meet people's physical, moral and spiritual needs, and cultural values making use of alpha beta and gamma sciences*. Beta sciences deal with the objective world of facts and logic; according to rational mind. Alpha sciences deal with the subjective world of aesthetics and moral values, according to artistic attitude and intuition. Gamma sciences consider the interest of society and culture, with humankind perspective. Therefore architecture is the combination of arts and sciences; and architectural performance embeds both soft and hard aspects. (Sariyildiz, 2012). Specifically, the definition of performance in architecture is proposed through three steps, from human needs to architectural requirements and to performance assessment; further, the key role of the environment in contrasting or supporting the fulfilment of the requirements is also indicated.

§ 2.2.1.1 Human needs and architectural requirements

Each architectural work has a large variety of intended purposes. The intended purpose of a building takes into account the great impact that the built environment has on human life, both from a daily and long term perspective. This confronts various levels of human needs, from basic to higher levels. On one hand, architectural purposes deal with the primary needs, like protecting the human body from adverse weather conditions and from potential dangers. On the other hand, architectural purposes also refer to higher levels of needs, like the ones related to social relationships, esteem and self-actualization. By referring to the Maslow pyramid, these latter are vertex needs including recognition from the others, self-respect, creative expression of personality, many of which can be mapped into architectural purposes (Bittermann, 2009).

Such needs are determined by people, called here *human actors* of the process. For simplicity, human actors are subdivided in three groups, based on the aspects they are mainly involved in: occupancy, finance and society. The first group (occupancy) includes mainly the users of the building. This refers to the people physically and directly using the building and its spaces. The needs of the users focus on functionality, safety, security and comforts, to mention a few. The second group (finance) regards all economic and financial aspects of the building market. It therefore includes the owners, developers, portfolio managers and other figures related to the profit given by the building. Their perspective looks at the building as an investment. Their needs also concern financial evaluation of the investment, such as the construction and maintenance costs of the building, its value, the adequate life expectancy of the building and its parts and so on. The third group (society) broadly includes the part of human beings interested in the impact of the building. The perspective of this group looks at the building according to the global interest, which embeds sustainability, overall social benefits, etc. A well-known example of this latter can be found in the need of reducing carbon emission or other negative factors related to the construction and life of the building. As a whole, these three groups represent a spectrum of needs that goes from the individual and/or collective expectations of the people using the building, to the individual and/or collective expectations of the people investing on the building, to the overall social expectations regarding the global level of direct and indirect aspects related to the building.

Based on human needs, architectural requirements can be defined. Translating human needs into architectural requirements is a complex operation, the difficulty of which depends on various facets. The high level of synthesis used in formulating human needs is one of them. The formulation of human needs usually refers in fact to the human perception of complex factors. In order to determine the architectural requirements to satisfy specific needs, these generally have to be decomposed and understood in their subparts. This process is quite evident for high level needs. For example, the requirements to satisfy human needs related to emotional reactions, esteem and self-actualization are complex to define. But this process is undeniable also for basic needs. For example, the requirements to satisfy human needs related to thermal comfort are also complex to define; especially when considering thermal comfort (like daylight comfort, fire safety, etc.) depends on an extremely high combination of different factors. This means that formulating the design requirements to satisfy human needs must be based on high expertise through which phenomena are understood and modelled.

Architectural performances are assessed upon the satisfaction of architectural requirements (and therefore of human needs). Figure 2 illustrates the chain connecting human needs and performance assessment. The multitude of architectural performances is therefore widened all over the requirements given by the three groups of human actors mentioned above. This stresses how much the whole system leads to a very wide spectrum of expectations that are asked to be satisfied by the building, as Becker (1999) clearly recalls in his work.

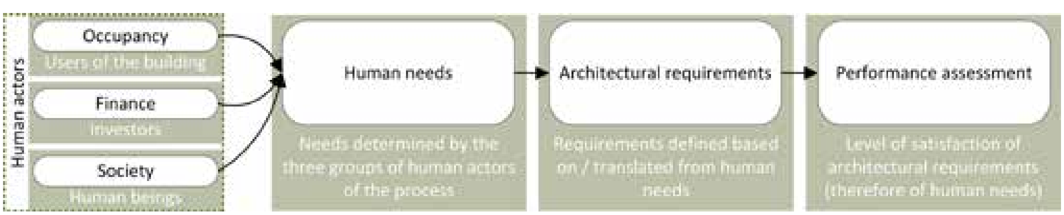

Figure 2
The figure schematizes the chain leading from the human needs of buildings' users, financial actors and society to the assessment of architectural performances, passing through the definition of architectural requirements.

To conclude concerning the breath of architectural performances, it is mentioned here that in his work, Becker (1999) provides an effective description of the wideness of the performance concept:

"*the performance concept is supposed to enable the design and execution of buildings that are highly suitable for the functions and activities of their occupants, provide thermally, acoustically and visually comfortable and healthy internal conditions while conserving energy and the environment, are pleasant and harmless from the tactile point of view, are sufficiently safe under regular and extreme loads that may occur during the life expectancy of the building, do not compose a fire hazard to their surroundings and are sufficiently safe when a fire starts within their spaces, are easy to evacuate upon emergency, do not leak and are not inflicted by moisture, condensation or mold, are free of cracks and frequent mechanical damage, do not have any of the symptoms of the sick building syndrome, are maintenance friendly and can easily be modified in order to cater for new demands. All these qualities are expected to be realized during the service life of the building without excessively increasing its lifecycle cost*". (Becker, 1999).

§ 2.2.1.2 Environmental factors

So far, the concept of performance has been introduced here with respect to the human actors, their needs and the assessment of the architectural requirements. However, the capacity of a building to satisfy the architectural requirements does not depend only on the building in relation to the human actors, but is directly related also to its natural, built, social, cultural (and other) surrounding environments. Any factor that is property of these environmental conditions is referred to as environmental factor. Environmental factors have a great impact on the accomplishment of the architectural requirements and need to be taken into account when assessing architectural performances. In other words, in order to define a range of performance requirements, both data sets need to be identified, the human needs to be satisfied and the environmental factors that may either hinder or facilitate the accomplishment. The distinction between hinder and facilitate emphasizes the positive role of environmental factors, which do not necessarily offer obstacles, but often provide great potentials to be used by the building.

The understanding of the required performances needs a solid basis of quantitative criteria defined as a combination of data regarding the human needs and the local environment. From this point of view and since the collection of performances does not offer a sharp borderline between the subjects, environmental factors can also be early integrated in the definition of the architectural requirements, as represented in figure 3.

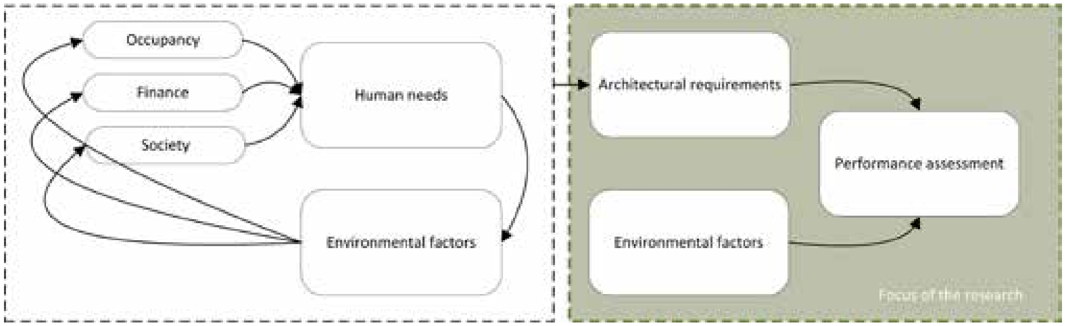

Figure 3
The figure schematizes how environmental factors are integrated in the definition of architectural requirements as well as need to be considered during the performance assessment.

This perspective of early integrating environmental factors into architectural requirements is mentioned since it implies an early awareness of the environment. According to this perspective, architectural requirements can already embed the influence of the environment on the human needs. Still, other environmental factors can affect the performances. Form this point of view, environmental factors play a role both in the human needs and in the building performances.

In order to clarify the above, an example can be taken from the field of daylight. When considering basic human needs, daylight requirements might be defined upon the quantities of light necessary for different activities. When considering higher human needs, daylight requirements might be defined upon emotional effects determined by different daylight conditions (such as higher or lower contrasts creating different atmospheres). In both cases, environmental factors (such as local climate conditions), can facilitate or challenge the achievement of the desired performance (achieving sufficient levels of daylight in winter in northern latitudes is usually more challenging than at the equator; etc.). Moreover, especially when considering emotional effects, local environmental factors (such as cultural aspects) might influence the daylight-related human needs themselves (since different cultures are dealing differently with daylight emotional effects; with transcendent meanings of light; etc.). In this respect, environmental factors play a role both in the building performances and in the human needs.

Studying the influence of environmental factors on human needs is outside the scope of this thesis. Instead, this thesis focuses on the capacity of a building to satisfy the architectural requirements depending on a given set of human needs and on the surrounding environmental conditions.

§ 2.2.2 Performance and adaptivity

Given a specific data set describing the context (environmental factors and human needs) in its parts, identifying a design solution which satisfies the expected performances is already a challenging task. The challenge of this operation increases even more when considering that the data set does not offer a fixed frame. Firstly, human needs and demands change over time, in the short and long term use of the spaces. This occurs for each of the three categories of human actors (occupancy; finance; and society) and concerning both basic and high level needs. Secondly, the environment also changes both in the short and long term. Changing environmental factors such as daily and seasonal climatic conditions affect the daylight and thermal performance of the building; changes in the number of occupants affect its functionality, but also aspects like its thermal load or its acoustics; functionality is affected by changes in the surrounding built environment, but those directly interfere also with aspects such as the solar radiation or daylight reflection. Examples regarding the previous and other aspects can be numerous. The result is a situation with several layers of changing needs in changing conditions.

The approach to it is not simple and cannot be univocal. The different aspects require an analyses and an evaluation process based on the overall system defining at each moment the specific contextual conditions. However, as a general consideration, it is possible to affirm that the idea of a building able to properly react to changing needs and environmental factors should be considered among the possible solutions. Traditional buildings are quite static and are usually designed based on the average satisfaction of the most common or predictable conditions. In contrast to this, the concept of adaptivity in architecture is considered as a possible way to satisfy changing needs in changing environments.

While adaptivity in architecture will be specifically addressed in chapter 3, the following sections tackle the concept of performance during the design process.

§ 2.3 Performance and conceptual design

The previous sections highlighted the broad and complex nature of performance in architecture. But how is this complex collection of performances approached during the conception and development of an architectural design? Looking at how the performance assessment is conducted in practice and at which stage the performances are considered during the design process, various critical aspects emerge. In reference to the complex system of performances described in the previous sections, it appears evident that a relevant part of them is addressed only during a relatively advanced phase of the design process. There is a rather high discrepancy between the breadth of architectural performances and disciplines involved in the whole process and those that are involved in the early phase of the traditional architectural process. The research work presented here questions the suitability and acceptability of this tendency. In fact, this stands highly in contrast with the near unanimous consent given to the importance of the early phase of the design, when the design is actually conceived. The most influential design decisions are actually taken during this early phase (Sariyildiz, 1991; Tuncer, 2009) and more specifically during the so called conceptual phase. For this reason, attention is here focused on the conceptual design phase.

In order to understand the conceptual process in the context of the whole design process as well as the importance of this early design phase, a definition of conceptual design is presented here. Moreover, problems in the traditional design process are identified that hinder performance oriented architecture. This regards the design alternatives that are evaluated, the evaluation system, and the evaluated performances.

§ 2.3.1 Definition of conceptual design

Cross (1982) defines design as “the conception and realization of new things”. With this respect, conceptual design is a phase of design conception, as part of the whole design process.

More specifically, in various fields, numerous studies aimed at charting the route of the design activity share the idea that such process is structured in identifiable phases (Lawson, 2006). George Broadbent (1969) defines the design process as the entire sequence of events which leads from the inception of a project to its completion; this includes individual loops of briefing, analysis, and synthesis, as appraisal and decision sequences. These sequences proceed at increasingly detailed levels (Markus, 1969), from definition of requirements, through conceptual design and embodiment design, to detailed design (Pahl, 2007). A different subdivision but with similar meaning is provided in the Architectural Practice and Management Handbook (1965). According to Pahl (2007), conceptual design is the phase in which the requirements and design objectives defined in the first phase are synthesized into conceptual alternatives; these are then ranked based on preliminary analysis to select viable concepts to be enhanced into more clearly defined designs in the third phase and fully defined in the fourth one. Near unanimous consent is given to such a definition. O’Sullivan (2002) also includes into conceptual design the phase during which the designer takes specifications for a product to be designed and constructs a statement (sometimes incomplete and subject to further modification) upon which the generation of many broad solutions is initiated. From a methodological point of view, Horváth (2004), defines conceptual design as a "creative problem solving process, enabled by human knowledge, intuition, creativity and reasoning"; from a cognitive point of view, it is a process in which "ideation, externalization, synthesis and manipulation of mental entities, called design concepts, takes place in symbiosis in a short-term evolutionary process"; from the aspects of information science and technology, conceptual design is "an iterative search process in which designers gather, generate, represent, transform, manipulate, and communicate information and knowledge related to various domains of design concepts" (Horváth, 2004). According to Okudan (2008), conceptual design corresponds to the phase of concept development, which is seen as a "series of divergent and convergent steps, completed at different levels of solution abstraction." In the divergent steps, concepts are generated, in the convergent steps, concepts are evaluated and selected. The idea of divergent and convergent steps has been elaborated by Liu et al. (2003), aiming at providing methodological support for the divergent steps.

In conclusion, it can be summarized that, irrespective of the discipline (architectural and urban, product and industrial, engineering design or other) in which the design process is performed, a principal aim of conceptual design is the generation of promising concepts, which meet the design requirements and are to be further developed and revised in the embodiment and detailed design phases; and that such generation is obtained based on creation and selection of concepts, through phases which are mostly iterated.

A second point of near unanimous consent is the importance of the conceptual phase. Roozenberg (1993) points out that adapting, improving, working out or detailing, presupposes a fruitful 'principal solution' or 'concept', to start from. The importance of the conceptual design phase is well documented for example in product design. Research has shown that about 75% of the product life-cycle cost is determined during the conceptual design phase (Wang, 2002); according to Duffy (1993), 80% of the cost of a product is determined by the design; and a poor concept can rarely be compensated in a later phase (Wang, 2002). Even detail design of the highest standard cannot compensate for a poor decision made during the conceptual design phase (Chong, 2009). In architectural design, the costs of the design process usually consist of 5-8% the overall costs, while the 60-80% is for the construction costs (Miller, 1993); however, the largest impact on lifecycle performance comes from the choices made during the conceptual phase (Ellis and Torcellini, 2008; Gane and Haymaker, 2011).

§ 2.3.2 Current limitations of conceptual design

Limitations and difficulties of usual processes in architectural design have been variously pointed out. Attention is given here to the limitations that hinder performance oriented design. Four main facets of this are identified and discussed below.

§ 2.3.2.1 Limitations in generating design alternatives

The importance of exploring different design alternatives is commonly recognized as a major characteristic of the conceptual design process (Wang, 2002; Liu et al., 2003; Okudan and Tauhid, 2008; Chong, 2009), providing key advantages, which could be more beneficial to architectural design processes than what current limitations allow. As stated by Wang (2002), conceptual design proceeds as an incremental learning process, in which it is impossible to develop a proper solution in one shot. Instead, steps of divergence generate design alternatives; and steps of convergence select the most promising solutions (Liu et al., 2003). According to Woodbury and Burrow (2006), there are two main benefits related to the exploration of design alternatives: revelation and comparison. On one hand, alternatives reveal things you have not considered, and thus suggest future avenues of exploration, by making new parts of the design solution space accessible to further investigation. On the other hand, comparison plays a key role in understanding whether a design satisfies the criteria and is the best among those being considered, instead of simply claiming that it satisfies these criteria (Woodbury and Burrow, 2006). However, while this is a well-established practice in other design disciplines, when looking at traditional architectural design processes, these lack the diverging steps, and designers typically explore only a very small number of alternatives in their work, commonly considering only a small subset of the possible design candidates. As a result, most design processes are focused only on a relatively narrow range of possibilities. There are many reasons for this. First of all, this is explained in architectural design, as in other design disciplines, by restrictions of time and other limitations (Josephson et al., 1998; Liu et al., 2003) as well as by cognitive limits (Woodbury and Burrow, 2006). Moreover, Darke (1984) emphasizes that, unlike in other disciplines, early in the architectural design process the architect tends to identify a strong preferred design direction, with limited design objectives and a clear concept, a so called primary generator.

The concept of performance oriented architecture attributes crucial importance to the search for well performing solutions. This is in contrast with limiting the design exploration to a preferred design direction only. A primary goal of the work presented here is therefore to support a larger generation and use of design alternatives, overcoming restrictions of time without necessarily conflicting with privileged design directions.

§ 2.3.2.2 Limitations in vertical design explorations

A second aspect deals with a double directionality of the exploration of design alternatives. Design explorations transversally cross a number of possible design directions, which include different design concepts. This is called lateral transformations (Meniru et al., 2003). A range of poor concepts might be quickly eliminated from further consideration, and other solutions are selected as suitable for further improvement until the identification of a design solution for further refinement in the next design stage. Traditional architectural processes rely the most on such transversal exploration, with only imprecise design information available (Wang, 2002), and subject to interpretation based on the knowledge and expertise of the designer alone. As an alternative to this process, design explorations may proceed depth-wise, where the pre-selected concepts are investigated based on additional variations of their geometry and performance assessments. This corresponds to the so-called vertical transformations described by Meniru et al. (2003), occurring in successive detailing of design data. The relation between lateral and vertical transformations is represented in figure 4.

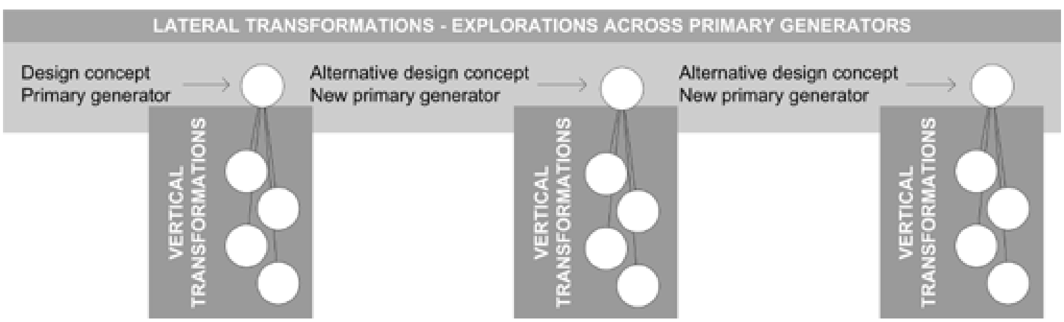

Figure 4
Lateral transformations correspond to transversal explorations across different design directions, each of which has a primary generator; vertical transformations correspond to vertical explorations across variations of the primary generators.

Considering vertical transformations and explorations as a key support for performance oriented design, the work presented here aims at intensifying them in the context of conceptual architectural design.

§ 2.3.2.3 Limitations in ranging considered performances

As previously discussed, conceptual design is initiated based on a set of design requirements. However, in traditional architectural design this set actually comprises a rather limited selection of requirements. Traditional processes tend to consider only a limited number of performances to be addressed during the conceptual phase, among which, in most cases, functional and aesthetic aspects prevail. As a consequence, a large number of requirements are considered only later on during the process; and key disciplines tend to be entirely omitted from the conceptual phase and their integration postponed to a later stage of the process.

The concept of performance oriented design is strongly in contrast with this tendency and aims instead at considering a large range of design requirements beginning in the early phase. This can be identified as a third key need to support performative architecture.

§ 2.3.2.4 Limitations in using measurable performance values

According to the definition given by Van Langen and Brazier (2006), a design process generates a design object description satisfying a given set of design requirements and fulfilling a given set of design process objectives. However, it has been largely discussed whether design decisions can be based on measurable criteria or not. Bryan Lawson (2006) criticizes the definition given by Matchett (1968) about design as "the optimum solution to the sum of the true needs of a particular set of circumstances" since he does not agree that the results of a design process can be measured against a set of established criteria. According to Bruce Archer (1969), the activity of designing is a goal-directed activity, in which the satisfactory level of the artifact can be expressed in conventional units. These can be measurable units or simply scales of merit, these latter for example for perceptual and aesthetic criteria, the measurability of which is largely intended as arguable (Martin Starr, 1963). While concerning perceptual and aesthetic criteria the debate is still active, in the latest research there is a large recognition that during the design process, not only the partial descriptions of the design artefact, but also the design requirements and the process objectives can change, often evolving from an abstract definition toward measurable criteria (Van Langen and Brazier, 2006).

Focusing on conceptual design, the fourth aspect here described concerns the rather high discrepancy between the importance of the decision taken during the conceptual phase, recalled in the previous section, and the lack of precise information that characterizes the conceptual phase. George Broadbent (1969) points out that the amount of a priori knowledge available at the beginning of each design process highly depends on the design case, being quite limited when innovation is highly involved in the process. From another standpoint, Hubka and Eder (1987) emphasize that design has been traditionally carried out by using intuition, know-how and judgment. This highlights the importance of means of judgments during the conceptual phase as well as the importance of generating knowledge. More specifically, it includes the need of measuring and numerically assessing the capacity of the design in satisfying the various requirements; supporting the exploration of design alternatives by means of multidisciplinary measurable performance values as guiding criterion; and extracting knowledge from the performance values.

A fourth key need to support performative architecture is therefore identified in the use of measurable performance values and numeric assessments.

§ 2.4 Performance and computer aided conceptual design (CACD)

Despite the fact that a number of relevant aspects of conceptual design remain partially unexplored (Horváth, 2004) and despite the large debate on the existence of a scientific nature of design (Gregory, 1966; Kuhn, 1962; Jones, 1992; Bayazit, 2004), systems of logically connected knowledge and categorizations of design problems (Hubka and Eder, 1987) have been largely developed in design methods (Cross, 1993; Pahl et al., 2007; Okudan and Tauhid 2008; Chong et al., 2009). The identifiable phases (Lawson, 2006) in which the design process has been decomposed and represented have been variously modelled to externalize the internalized thinking of the designer. Independent of the means (be it diagrams, mathematics, or other), augmenting the transparency of the process is meant to support the activity of the designer, and to open it to contributions beyond the designer's own knowledge and experience (Jones, 1992). Moreover, lately, the importance of this design phase had design support systems developers switch their attention from detailed design to conceptual design (Horváth, 2004). This has led to the development of numerous information and computational methods, and tools, conventionally named CACD (computer aided conceptual design) methods.

Such large development of design methods is common through the different fields of design activities. Meaningfully, the definition of design given by Cross (1982) and cited in section 3 is rather general, but highlights one face of the design activity: its universal nature. With this respect, Bruce Archer (1969) emphasizes there is no distinction in tackling architectural, engineering and industrial design; even more so, Sidney

Gregory (1966) extends the consideration to any other discipline. In this light, such a universal nature is actually almost unanimously acknowledged; and this also implies the possibility of exchanging design knowledge and methodologies across disciplines. Certainly, this allows sharing a common pool of experiences and expertise, the value of which is here stressed.

However, in each discipline there are design specificities that cannot be ignored. This is widely recognized also historically. By building upon a specification initiated by Rittel (1973), Cross (1993) identifies a first generation of design methods (1960s), mostly based on systematic and rational approaches shared among disciplines; while a second generation moved in the early 1970s toward a softer recognition of satisfactory and appropriate solutions in architectural design and urban planning; this clearly diverged from the engineering and industrial design development in the 1980s (Archer 1979; Roozenburg and Cross, 1991). Even though this and other possible examples do not negate the existence of a common nature across disciplines, it actually calls attention to the importance of the peculiarities that need to be considered for the various design processes in different disciplines.

In the nature of design, the existence of both a general nature and peculiarities is here acknowledged. In this research, while focusing on architectural design and emphasizing the specificities of its issues, design approaches and methodologies used in different disciplines are therefore also considered. This section is structured with this intent. Specifically, first, a number of key works in CACD are introduced considering the nature of the design process as independent from the nature of the designed output. This leads to a broad focus on architectural, engineering and industrial design. Secondly, the limitations of CACD methods are discussed, both in their general nature and specifically concerning applications in architectural design.

The motivation and viewpoint in approaching the concept of design process and design is shared with Bruce Archer (1979), who emphasizes his ultimate interest in the design process, not for the means, but for the end product. This latter is here intended in terms of performative architecture. In this respect, this section should be read as preliminary to the next one, in which the peculiarities of design methods and digital supports for architectural design as performance oriented process are discussed.

§ 2.4.1 Precedents in CACD methods

Some key CACD methods are briefly presented below, a more complete review can be found in Chong et al. (2009) and in Okudan and Tauhid (2008), the latter with specific focus on concept selection methods.

Decision matrices have been largely developed (Pugh, 1991; Terharr et al., 1993) with success in embedding preferences among alternatives, but with limitations in including relative importance of criteria (Okudan and Tauhid, 2008). Among the examples, Quality Function Deployment (Hauser and Clausing, 1988) is at the basis of The House of Quality design tool for product design, a conceptual map using a set of planning and organization routines to coordinate skills to design and manufacture goods (Hauser and Clausing, 1988). However, according to Chong (2009), it does not document the evaluation of alternative solutions and does not capture their multiple abstraction levels, from first principle to more detailed sub-solutions.

An overview of knowledge representation models can be found in Camelo (2010), in which a computational framework to improve knowledge exploration and the possible ways of guiding the synthesis process is also proposed. Methodologies based on function-means map model designs with respect to their functions, and catalogue how functions can be provided by means (Andreasen, 1992). They have been used, among others, by Bracewell (1996) and O'Sullivan (2002). Bracewell developed a knowledge-based design environment, named Schemebuilder. It is an integrated suite of software tools to support the development of product design models during the conceptual and early embodiment phases, storing decomposition principles by using function-means tree-like information structures for generating qualitative alternative schemes. The approach used by O'Sullivan, instead, models various aspects, such as the design requirements and the environment of the product, and structures them in a computational reasoning environment based on constraint filtering offered to the designer as an interactive design tool. Other examples can be mentioned, such as the one developed by Van Wie (2005); and by Erden et al. (2008). As emphasized by Chong (2009), such tools mostly do not allow integrating customer voices during the generation of the map.

Among the argumentative process models, Rittel and Webber (1973) developed the Issue-Based Information System method for organizing and documenting design discussions in a quasi-hierarchical system of question answering. McCall (1991) further developed this method into the Procedural Hierarchy of Issues, introducing a hierarchical structure in the argumentative process of deliberation and offering a process of decomposition. The work has been used as a conceptual basis for a range of tools, such as MIKROPLIS, ViewPoints and JANUS, this latter including integrated CAD (Fischer et al., 1989; McCall, 1991). These and other critique expert systems act with acknowledged success, but have relevant limitations when dealing with complex designs (Liu et al., 2003). Other examples based on analytic hierarchy processes (Okudan and Tauhid, 2008) are found in Saaty (1994), Marsh et al. (1993), Mullens et al. (1995), King and Sivaloganathan (1999).

A prominent class of conceptual design research work has been dedicated to the steps referred to above as convergent and divergent steps of conceptual design. For a computational framework, Liu et al. (2003) propose an approach based on repeated divergence and convergence along different levels of abstraction (from vague to detailed), in which a series of generation and evaluation steps is preferred to a single step process of generation and evaluation. A relevant motivation comes from the need for balance between the conflicting goals of the generation of concepts, which must be applied to the widest possible range, and their meaningful management, which must be applied to the minimum possible number in order to be feasible.

For the converging phase, a large set of different approaches combining methods and tools for concept selection has been developed (Okudan and Tauhid, 2008), the latest developments of which are currently having a significant influence in design disciplines (Saridakis and Dentsoras, 2008). These also include uncertainty modeling, i.e. with the use of fuzzy logic, probabilistic mathematics, fuzzy clustering, etc. (Zimmermann, 1993; Chang, 1996; Ayag, 2004; Tauhid, and Okudan , 2007; Ciftcioglu, et al., 2007). Among the tools for identifying design concepts (e.g., optimize, evaluate, or select), based on a pre-determined range of solutions, modelling the design process as a problem-solving process (Archer, 1969; Thomas et al., 1977) usually prevails, by also including the notion of ill-defined problems (Reitman, 1965; Thomas and Carroll, 1979). Simon (1979) postulates that the designer starts with a function often represented as a set of goals and constraints and attempts to discover a form that will support the desired function, using deductive search strategies (Kalay, 1999) and emphasizes that such problems require relevant knowledge to be approached and solved, and yet they can be decomposed into a series of sub-problems solvable as well-structured problems (Simon, 1973). Optimization techniques, such as GAs, can be used to support the design process when conceived as a goal oriented activity, specifically, as a search for a suitable or optimal construction, where a search problem consists of a desired state (goal state), a search space and a search process (Renner and Ekart, 2003). Saridakis and Dentsoras (2006) integrate soft-computing techniques, including GAs, and parametric modeling in order to facilitate the computer-aided collaborative design, and developed a system called CopDeSC (Collaborative parametric Design with Soft-Computing). Goldberg (1991) reads the design challenge as a problem to solve. He regards the designer as solver, and the competition of conceptual designs as a means of comparison. Goldberg sees a strong parallel between the tasks of the designer and the structure of GAs. Gero and Kazakov (2000) use GAs for enlarging the design space. Mattson and Messac, (2003) use Pareto frontiers for multi-objectives optimization, as do also Caldas (2006; 2008). Wang et al. (2005a; 2005b) integrate

GAs into an object oriented framework for green buildings. Chouchoulas (2007) combined shape grammars (Stiny 1980; Flemming, 1987) and GAs by developing an algorithmic method for conceptual architectural design. Generally, these methods all strive to identify the best solution with respect to the defined design goals. This issue is more specifically addressed in chapter 8.

Finally, approaches based on concurrent methods (Andreasen, 1991; Pugh, 1991), puzzle making (Alexander et al., 1977), and abduction (Roozenberg, 1993; Tomiyama et al., 2003) can also be mentioned. While detailed tables which compare the approaches and conclusions of many CACD methods can be found as mentioned above in Chong (2009) and Okudan (2008), it is worth noting that the majority of the methods focus on the function of the design rather than on its shape, and that most of them do not allow for backtracking in the process.

§ 2.4.2 Limitations of CACD methods

According to Chong (2009), most of the methods mentioned in the previous section have two major limitations: they focus on the design criteria rather than on the relations between criteria and design shape; they do not allow for backtracking in the process. In addition to these two considerations, a third one regards the specificities proper to the discipline, which cannot be ignored despite the recognition of a common nature shared with other design activities. These three considerations have to do respectively with:

- shape and visual communication;
- the learning process of the designer;
- the specificities of architectural design.

All three points will be discussed briefly below. The latter point will focus on conceptual design and, more specifically, in section 5 on performance oriented design

§ 2.4.2.1 Shape and visual communication

In the majority of CACD methods, there is not always direct emphasis on the relations between design criteria and design shape. Differently, this aspect is crucial to designers.

“Designers in all disciplines live in a very visual world” and visual information is prominent in the design process (Goldschmidt and Smolkov, 2006). More specifically, the designer thinks and communicates mainly by graphic images and visual languages, rather than verbal, numerical and literary modes (Cross, 1982). This concerns the entire design process, from sketches of ideas to diagram of information. While the role of graphic representation has been immediately largely acknowledged for what concerning the advanced phase of the design process (which includes the final graphic deliverables of the design), it used to be less emphasized for the conceptual phase. However, the use of graphic and visual information is an integral part of the conception process and includes visual analogy (Goldschmidt, 2001) and visual stimuli, in general, having a great effect on the design performance (Goldschmidt and Smolkov, 2006). Recently, this has been made even more explicit by integrating data and visual representations. The transition from the use of two-dimensional drawings to three-dimensional models further increased the potentials of visual communications. The use of three-dimensional models does not simply allow using visual communication to focus on the design more than on its representations (which occurs since technical drawings, representations and related information can then be extracted from the model at any moment and do not require manually propagating the design changes). It also allows for embedding and exchanging information other than geometric based on the three-dimensional representation of the design as well as enhances communication and feedback from non-experienced design professionals and from non-professionals.

Based on these considerations, the importance of visual communication and even more of the use of three-dimensional models is stressed through all phases of the design process and problem solving sequences. It is here strongly believed that CACD methods should make the maximum use of such potentials. In this respect, it is also important to distinguish the development of the conceptual design separate from the analysis and representation of design requirements, wherever possible.

§ 2.4.2.2 Learning process of the designer

Geoffrey Broadbent (1969) refers to four types of design methods, which he calls pragmatic, iconic, analogical and canonic. Pragmatic design makes use of available techniques without relevant innovation; iconic design recalls existent solutions and tends to replicate them; canonic design relies on rules and regulations as guidelines; analogical design makes use of analogies with other fields to define new ways for structuring the problems and their solutions. A classical example of this latter consists of inspirations from nature. Broadbent emphasizes that all these four methods can be used to generate design alternatives by exploring various concepts, but it is especially the last one that allows for major innovation. Looking for innovative solutions toward new design concepts deeply relays not only on the previous experience of the designer, but also on his/her real time learning process. The importance of prestructures, presuppositions or protomodels as the origins of solution concepts (Roozenburg and Cross, 1991) is recognized, but leads to an evolving design path. The learning process is integral part of the exploratory design activity, and is nearly unanimously recognized, independently from the way the design process is being modelled. In a puzzle-making approach (Alexander, 1977), designers begin with a kit of forms, including materials and shape, subject to modification according to certain rules until they achieve some desired functional qualities; inductive reasoning is used with the aid of metaphors, symbols, and case studies (Kalay, 1999). Analogical reasoning implies learning from previous or other problems similar to the actual problem by retrieving and transferring chains of reasoning and knowledge to the actual problem (Veloso, 1994) and is quite beneficial to problem solving processes including design (Goldschmidt , 2001; Goldschmidt and Smolkov, 2006). A number of design methods are based on abduction (Tomiyama, 2003), using logic and abductive reasoning; according to this, a design solution is defined by means of axioms and theorems, respectively intended as design knowledge and properties of other design solutions. Specifically, following Roozenberg (1993) distinction, 'abduction' in design theory and knowledge-based design systems is explanatory abduction while the reasoning towards new solutions for design problems follows the pattern of innovative abduction.

These and other examples emphasize the need for flexibility as a major property of any method and support for the design process. The primary scope consists in allowing the designer to review the formulation of problems, criteria and goals in a constantly dynamic manner. This has been already largely pointed out within a number of research efforts, the first of which were presented at the Conference on Design Methods in London in 1962 (Jones and Thornley, 1962; Broadbent, 1969; Mitchell, 1990; van Leeuwen, 1999; Tuncer, 2009). On the other hand, the benefits of documenting the on-going design processes are crucial for augmenting the potentials of the learning process and creative associations as well as reasoning during any design activity (Tuncer, 2009; Saridakis and Dentsoras, 2008). This leads to the importance of storing, organizing, retrieving, associating and mapping design solutions, including the ones that have been (temporarily) eliminated during the design process. With respect to this, techniques for back-tracking in the design process are especially relevant.

§ 2.4.2.3 Specificities of conceptual design in architecture

Roozenburg and Cross (1991) point out how, after sharing a common origin, models of architectural and industrial design processes have diverged from models in engineering design, as supported by both theorists and practitioners. A review of similar as well as divergent approaches in the disciplines is out of the scope of this research and can also be found in Roozenburg and Cross (1991). Moreover, a systematic analysis of similarities and differences between architectural design and the more general product design (intended as design of any outcome for production) has been developed by van Leeuwen (1999). Hereby two aspects that distinguish conceptual architectural design are stressed:

- the prominence of un-structured problems;
- the unpredictable order in which activities happen in design.

Having to deal with un-structured problems concerns the whole discipline of design. By referring to the definition given by Reitman (1965), we term 'well defined' the problems having specified initial conditions, necessary operations and goals, 'ill-defined' the problems without such inherent specificity. Even the authors that describe the design process as a problem solving process (Archer, 1969; Thomas and Carroll, 1979) recognize that most of the problems involved in the activity are not well-structured in the initial phase, they evolve during the process and they are highly ill-defined. According to Thomas and Carroll (1979), design is a type of problem solving in which the problem solver views his/her problem or acts as though there is some ill-definedness in the goals, initial conditions, or allowable transformations. This can also be described as a conjecture-analysis cycle (Cross, 1984). In architectural design this nature is especially prominent due to the breadth of the disciplines involved and the number of tasks to be satisfied. This aspect is even more extreme since the disciplines involved belong to alpha, beta, and gamma sciences (Sariyildiz et al., 2002) and the process strongly blurs the edges of the disciplines.

Based on the same considerations as well as on the relevance of the learning process (section 4.2.2), also the unpredictable order of the design activities can be explained. This includes the high non-linearity of the design process, be it a spiral path (Cross, 1984) or other structure.

§ 2.5 An aspiration: integrating performance assessments in architectural CACD

From the above sections, general limitations of current CACD methods emerge. In addition to these, when moving the attention onto the conceptual phase of the performance oriented design process in architecture, some further considerations with respect to the design process and related methods need to be specifically pointed out. These are directly related to the limitations of traditional conceptual design, which have been discussed in section 3.2 and which contrast the idea of performance oriented design. As a consequence of them, among the many aspects characterizing performance oriented design processes, the following ones are emphasized here:

- geometry has a large impact on the realization of the performance related goals and needs to be investigated concerning the integrated disciplines, based on explorations of geometric alternatives;
- since the integration of a range of disciplines is moved to early phases in the process, the level of interdisciplinarity of the conceptual phase is increased;
- the level of complexity of the conceptual design phase is also increased;
- dealing with measurable criteria, simulation based design performance simulations can be used to assess the performances since the early phase.

§ 2.5.1 The key role of geometry

The first aspect focuses on the key role of the architectural geometry, here intended as the defining shape of a project and its major components. In line with the fact that only a limited selection of requirements are considered in the conceptual phase, traditional design processes tend to address the form mainly based on a limited range of performances. As explained above, these are commonly related to soft issues concerning visual and functional aspects, while the fulfilment of engineering requirements is usually delegated to post-engineering adjustments and material properties. Very few engineering disciplines have a large impact on the conceptual phase of architectural design, which is actually the moment in which most of the choices concerning shape are addressed. And yet, technical and engineering performances are strongly related to geometry. Structural form-finding is an example of a process of performative morphogenesis which makes evident the relevance of geometry in achieving a high level of technical and engineering performance. Moreover, it must be noticed that even in the cases in which such performative morphogenesis are used, they rely heavily on mono-disciplinary investigations. In contrast with these positions and according to performance oriented design, performative architectural geometry is discussed here as the potential synthesis of a larger range of performance evaluations, which can take into account both ill-defined and objective problems as well as measurable and un-measurable (or difficult to measure) criteria. In this way they integrate engineering aspects from the early phases of the design. Geometry, therefore, is here intended as a core aspect of architectural performance in its broader sense, and leads to the importance of exploring different geometric design alternatives by searching for performance driven solutions.

§ 2.5.1.1 Digital geometric modelling

Unarguably the development of CAD systems has resulted in a large production and availability of 3D models during the design process; and certainly a major advantage was immediately recognized in visualization tasks and automatic extraction of technical drawings that are constantly updated to the design changes. However, also other advantages are being more and more acknowledged. These are related to the management of information (be it linked or embedded in the geometry); as well as to the use of 3D models for performance simulations (by importing 3D models into Building Performance Simulation Tools (BPSTs) or by using BPSTs integrated into or connected to the geometry modeller). For all these aspects, the use of 3D geometric models during the design process is currently a crucial and undisputable point. Differently, the way in which geometry is built and organized in relation to these aspects becomes an essential aspect of the design process. Two points can be raised in concern to this.

The first point refers to the idea of structuring geometry in relation to information. In Building Information Modelling (BIM), this issue has been largely addressed. The concept of BIM relies in fact on 3D graphic data expanded into an nD environment (Mahalingam, 2010; Taylor and Bernstein, 2009) though information. An evident example is the possibility to link geometry to external databases, regarding manufacturing data, material properties, requirement specifications, budgeting, conformance checking, etc. (van Leeuwen, 1999). In information modelling methodologies that increase the dimensions of 3D geometric models by means of integrated information, geometry needs to be structured and managed according also to interconnections with other data. This means that geometry is structured also in relation to the way non-geometric information is modelled and integrated. At an operational level, this includes a large set of issues such as, for example, the layering of the geometry and the classification of geometric entities in respect to the building elements and components and so on. At a conceptual level, this requires relating the geometry with the building and process models, based on different abstraction levels. In this respect, not only the decomposition in geometric entities of the final artefact is considered, but also the different levels of abstraction based on which the design process is articulated. BIM addresses these aspects for the relatively advanced phases of the design process, which include the modelling of detailed information. When focusing on performance oriented design and specifically on its conceptual phase, geometry needs to be interconnected with the information regarding the various performances by privileging the dynamic nature of a conceptual model.

Following the idea of flexibly structuring geometries by either embedding or being guided by information related to performance criteria, the second point focuses on the use of procedural and parametric geometry. According to van Leeuwen (1999), procedural geometry allows integrating procedures and algorithmic rules into the geometry generation and involves capturing design knowledge into procedures of geometric modelling. This also allows automating tasks and generating complex geometry on the basis of design decisions since the manipulation of geometry and maintenance of relationships can be programmed into procedures. Parametric geometry "allows creating the model by means of geometric objects defined by parameters" (van Leeuwen, 1999).

§ 2.5.2 Interdisciplinarity

Interdisciplinarity characterizes the majority of design activities, but it is surely exceptionally high in architectural design, which is expected to provide pleasant and widely comfortable environments for people. As introduced in section 2, each architectural project requires the convergence of social, financial, artistic, engineering and other disciplines toward a design solution satisfying requirements from structural and thermal, lighting and acoustics, aesthetics and perception, maintenance and economics, to name only a few. As discussed in section 3.2.3, following the idea of performance oriented architecture, a number of them, consisting at least of the most significant performances, has to be assessed already in the conceptual phase. As a consequence, in a performance driven design process, the interdisciplinarity of the conceptual phase refers to the wide range of different domains embraced in the definition of architectural performance.

Dealing with interdisciplinarity implies dealing with management of people and information (Chiu et al., 2002) in a set of collaborative processes that can occur simultaneously together (synchronously) or separately (asynchronously) (Kolarevic et al., 2000). This includes communication and exchange of data among experts from different disciplines as well as possible negotiations on design solutions according to the level of satisfaction against different design criteria. Large effort has been invested in research to understand and model the collaboration among experts based on each of the mentioned aspects (Kvan, 2000; Simoff and Maher, 2000). Possible supports have also been variously developed to improve the collaboration (Maher et al, 1997a; Maher et al, 1997b; van Leeuwen, 1999; Kolarevic et al., 2000; Chiu and Lan, 2005). Large attention has been and still is given to the integration of different disciplines in the advanced phase of design, while less attention has been given to the interdisciplinarity of the conceptual phase.

When focusing on the conceptual phase of performance oriented design, relevance is given to testing the concepts against criteria that meet the requirements coming from different disciplines as well as to feed back the results into the process. Feedback also aims at inspiring or even driving the concept improvements or the generation of new alternative concepts. In this light, multiple interdisciplinary criteria need to drive the conceptual design exploration. For succeeding in such a goal, two main aspects require a quite important consideration. On one hand, conceptual design is an activity based on dynamicity and unpredictability of design directions. On the other hand, design exploration driven by specific criteria requires investigations that can be time consuming, especially when numeric analyses are integrated into the process. As a consequence, when increasing multidisciplinary investigations in the early phase of the process, a critical balance is needed between on one hand accuracy and deepness of the analysis and on the other hand their quickness and communicability. As Christopher Jones (1969) already pointed out, a major problem in integrating knowledge during the design process consists in fact in the difficulty to combine the complexity and speed of the creative designer's thoughts with the scientific and rational approach of doubts and analysis. This aspect leads to the need of a series of discrete activities integrated into the design process. In this respect, the conceptual process can be seen in accordance to the writings of Gero and McNeil (1988) and Kvan (2000) that look at collaboration as cyclic loops. Such loops can involve horizontal and vertical integrations, respectively defined as "integration of information and tasks that belong to multiple participants", and integration of "information and tasks in different phases of the design process" (van Leeuwen, 1999). Also, the loops can involve mutual, exclusive or dictator collaborations, respectively based on shared work, work on separate parts of the problem and requiring occasional negotiation, and work under a clearly driving leadership (Mahler et al., 1997b). In this research, these types of collaborations are not considered as mutually exclusive, but instead as alternating within the cyclic loops.

Finally, mention must be made of BIM methods to support collaborative processes, in consideration of the quite large investment of current research efforts on it. BIM is an "emerging technological and procedural shift within the Architecture, Engineering, Construction and Operations industry" (Succar, 2009) and consists of a set of interacting policies, processes and technologies generating a methodology (Succar, 2009). Such methodology is meant "to manage the essential building design and project data in digital format throughout the building's life-cycle" (Penttilä, 2006). Succar (2009) presents also a comparative vocabulary concerning methods and models related to BIM or similar to it. Despite the fact that BIM can offer research models for collaborative design and possible operational frameworks, it must be noticed that current BIM capabilities "seem to lie in the area of design documentation and post-design rationalization than triggering new design solutions" (Holzer, 2007).

A short introduction of models for interdisciplinary collaborations in CAD and BIM, at various phases of the design is given below, including an overview of possible references to be considered for the conceptual phase. Despite the fact that this research does not aim at approaching interdisciplinarity in its own, nor at specifically contributing to models for interdisciplinarity, interdisciplinary is an aspect that must necessarily be considered during the process.

§ 2.5.2.1 Models for interdisciplinary collaborations in CAD and BIM

Among the different collaborative models that have been developed for data exchange, six major models from product design are recalled here, in accordance with Hannus Karstila and Tarandi (1995) and van Leeuwen (1999).

- Inter-application mapping: it maps data from one model to another among different disciplines; it is a traditional approach widely applied in practice.
- Neutral model: it is based on a central model acting as intermediary among the applications and being independent from them. This allows a single data mapping between each specific model and the neutral model. In practice this ideal full interoperability between a neutral model and any other application is not fully achieved.
- Application domain model: it uses neutral models only for groups of applications during the process, in a set of multiple neutral models. In practice, this approach is being developed based on application protocols.
- Common resources: it is based on sharing resources among models. Specifically, when using application domain models, adding common resources allows the various neutral models to communicate among them. It aims at solving interoperability among applications outside the applications themselves.
- Common core model: it aims at truly integrating data into a shared core model, though which data are commonly exchanged with any other applications. In practice, this is being used and is the basis of many BIM techniques, as mostly shaped at the moment.
- Mutually exclusive common models: it is based on the idea that not all applications might be interested in sharing all the data and it combines the idea of sharing data with the inter-application mapping approach, by limiting the shared data based on it. In practice it is used especially into consolidated enterprises and partnerships.

The position taken in this research embraces the inter-application mapping, with integrated aspects from the neural model. This does not intend to exclude the validity of the other models or to demonstrate the highest suitability of the chosen models. The potentials seen in the proposed direction mainly refer on one hand to the well-established use in practice of the inter-application mapping and on the other hand to the use of independent information as a currently accepted limit. Overcoming this limit is considered suitable for the future, but outside the scope of this research.

§ 2.5.3 Complexity

Due to the broad and complex nature of performance requirements, the design process is highly complex. The breath of performance requirements implies a large amount of data, which needs to be managed in order to define and assess the design. Moreover, different requirements and different data are interconnected by a dense network of relationships, through which they affect each other. For each discipline, both from engineering and other domains, the data and information sets concern the overall context. Since the context is defined as the combination of the users of the project and of the environment where the project is located (see section 5.2), data and information sets concern both the human requirements that need to be satisfied, and the environmental conditions that may either inhibit or facilitate the realization. When given a specific data set that describes the context in its parts, identifying a well performing design solution that satisfies the expected performance is a challenging task. This challenge is commonly acknowledged.

In addition to the breadth of performance requirements, there are also other reasons for which the design process is complex. Among these reasons, there is the dynamic nature of the context. For each discipline, the data and information sets do not offer a fixed frame. The data and information sets but are highly dynamic since human needs and demands change over time, in the short and long term use of the space; and since the environment also changes both in the short and long term. This challenge is also commonly acknowledged.

By asserting the need of increasing the breath of performance requirements considered in the conceptual phase, this thesis advocates an attitude that further increases the challenges. Increasing the breath of performance requirements unavoidably increases the amount of data and the interrelationships to be handled; and consideration must be given to the consequent increased complexity of the conceptual phase.

§ 2.5.3.1 Models for complexity management

Complexity in architectural design has been approached from different points of view, resulting in different proposals for handling the large and interrelated data sets and information. A number of challenging requirements are largely acknowledged. One is the need of not flattening the complexity, since excessive simplification could prevent good solutions and even harm creativity; another one is the need of respecting the fuzziness that is intrinsic to this complexity. In Simon (1996), fuzziness, complexity and subjectivity are described as intrinsic characteristics of the early phase of design; vagueness and contradiction as proper of the initial design requirements. In Tuncer (2009), it is claimed the best way to handle the complexity of architectural information is not achieved by simplifying the structure of information, but by enabling simple approaches in which the complexity is embedded.

Given the needs of respecting the complexity and its intrinsic fuzziness, another important aspect regards the nature of the data and information to be handled. The aspect stressed here is the interconnection of the data with architectural design knowledge. In Makris et al. (2003), emphasis is given to the challenge of representing architectural information intended as architectural design knowledge. Architectural design knowledge has not only great richness, but also high level of implicit factors, which are embedded in the use of natural languages (such as visual and verbal descriptions expressing ideas of products).

Large effort has been invested in previous research regarding the reuse of pre-existent knowledge, especially the design knowledge embedded in precedent design cases. This ranges from the case-based reasoning approaches (Kolodner, 1993) to computational frameworks, such as ArchIMap (Tuncer, 2009). In the first case, old experiences and previous situations similar to the current one are used to understand and solve new problems; case libraries are used as intelligent resources for articulating new understanding. In the second case, representational frameworks enable creating complex adaptive systems for achieving an integrated information structure (including design precedents).

Differently, this thesis does not focus on formalizing the information structure integrated into the design process; but on the way in which the design process occurs with respect to the integration of data, information and related design knowledge in the phases of the conceptual process. Specifically, the attention focuses on the conceptualization of the design decision space and on the information handled in relation to it. Structuring the design decision space is crucial, especially when enlarging the number of design requirements considered in the conceptual phase. As Bertel et al. (2004) points out, the design decision space is a high-dimensional space, in which separate dimensions are attributed to separate types of decisions. Increasing the breath of performance requirements implies an higher multidisciplinarity, based on which the decision space should be (re)considered.

In Bertel et al. (2004), the organization of decision spaces is conducted to the one of problem spaces. It is also stated that one of the key properties of designing is that not all states of the problem space are considered during a design process. Rather than by exhaustiveness, the process is driven by consequentiality of decisions, in which each decision opens up or precludes certain subsequent decisions. Instead of looking at this aspect as a limitation, it is proposed to look at it as a possible method of exploration. In Bertel et al. (2004), this aspect is tackled by stressing the reversibility of the process: considering only a subset of all aspects for a certain design decision leads to decisions that are not irrevocable and that may serve as tentative assumptions to set the stage for further considerations and in later revisions. Katz (1994) even pointed out that this sequential exploration process is not only organized based upon outcomes of previous phases, but also about preferred sequences. Preferences may lead to choosing certain substructures of decisions by neglecting certain previous results.

A number of contemporary approaches tend to oppose this attitude and the consequent recursive segmentation of the design process. This tendency regards both design methods and computational design supports. It is often found in relation to the latest developments of multi-objective optimizations and algorithms for dealing simultaneously with a large number of design criteria. Despite the crucial relevance acknowledged to this direction, focus is given here on the benefits of (also) decomposing the design process. This thesis does not negate the potentials of deadline (and eventually computationally dealing) simultaneously with extensive numbers of criteria, but it is rather in favour of combining these potentials with the ones of subdivisions, segmentations and decompositions of decision spaces.

In order to approach complexity management, it is here suggested that decomposition is crucial. It leads to considering the design and performance variables a few at a time so that the complexity is temporarily reduced. Complex design problems are tackled by decomposing them into multiple levels of abstraction, leading to multiple levels of design solutions (Liu et al., 2003). While the design problems are decomposed into a number of levels, the models produced by the designer are meant to be in limited number, each of which embeds multiple abstract levels and allows visualizing and evaluating entire ranges of solutions based on multidisciplinary performance evaluations. In Bertel et al. (2004), emphasis is given to the difficulties of assembling into comprehensive solutions the solutions conceived to partial problems. Decomposition may imply also subdividing the design into features, delegated to solving partial problems. An example is given in Geyer (2009). Rather than toward these attitudes, Bertel et al. (2004) advocates a variant strategy in which decomposition of problems is based on the notion of a problem’s aspects; and different aspects of the problem are brought to attention at different times of the design process. While Liu et al. (2003) bases the concept of decomposition on abstraction, Bertel et al. (2004) proposes the idea of aspectualization. Quoting the authors, it can be said that ‘abstraction’ stands for “*arbitrary means of omitting types* *of knowledge in a representation"*, 'aspectualization' "*denotes the restriction to specific types of knowledge*; [...] *aspectualization stands for selection rather than for omission*". Consequently, the importance of framework to accommodate different classes of processes is stated.

§ 2.5.4 Performance simulations

As introduced in section 3.2.4, while the debate on measurability of certain design criteria is still open, there is common acknowledgement on the measurability of other sets of design performance and the related satisfaction of design requirements. This is true for most of the engineering aspects. Integrating their performance evaluations in the conceptual phase allows also using the measurements proper of such disciplines. However, their application to the conceptual phase is an aspect that needs to be considered in order to properly calibrate and review such traditional measurements, methods and related design tools. Specific attention is given here to the use of digital supports for performance assessment with reference to performance simulations.

§ 2.5.4.1 Design processes integrating Building Performance Simulation Tools (BPSTs)

According to the Oxford English Dictionary, simulating means producing a computer model of something; similarly, the Collins English Dictionary defines simulation as a representation of a problem, situation, etc., in mathematical terms, especially using a computer; and specifically referring to mathematics, statistics, and computing, as the construction of a mathematical model for some process, situation, etc., in order to estimate its characteristics or solve problems about it probabilistically in terms of the model. Meaningfully, the Cambridge English Dictionary a model of a set of problems or events that can be used to teach someone how to do something, or the process of making such a model. In addition to the intention for assessing, the one for learning is stressed here as crucial component in using simulations in design processes. This section briefly addresses both aspects.

The recognized value of assessing performance based on measurements and analyses led to an increased integration of performance simulations during the design process (Augenbroe, 1992; Lam et al., 2002). This is already very common in large parts of the advanced design phases. According to Mahdavi and Lam (1991), systematic 'front-end' studies based on digital simulations to aid preliminary design decisions should be preferred to the traditional approach, in which the role of building simulation is relegated to the 'back-end' of the design process. As Caldas and Norford (2002) point out, *by "using simulation tools, it is possible to engage in a design practice based on feedback loops between making design decisions and evaluating their environmental impact, as a way to inform the on-going process of design*".

The value of utilizing simulations for a learning process is also commonly acknowledged. In Simon (1996), simulations are specifically discussed as a source of new knowledge, for two reasons. They help discovering the consequences of premises, which otherwise may possibly be not easy to predict even when premises are clear to the designer. They help discovering consequences also when designers do not truly know about the entire inner laws that regulate the whole system, because they are based on abstract models representing only the essence of phenomena.

The idea of using simulation tools as design support, instead of as a confirmation means, is at the basis of performance oriented design; despite the fact that it has been discussed for a number of years, it still does not belong to the majority of architectural practices, nor does it find homogenous distribution among disciplines. As Teuffel et al. (2009) point out, while a lot of research has been carried out in the relation of structural form finding in conceptual design, the consideration of other performance criteria has been considered only recently.

A number of studies have been conducted on the use of BPSTs in architectural practice, in general as well as in specific contexts. Goncalves (1993) focuses on Portugal, Plokker and Soethout (1997) on The Netherlands, Lam et al. (1999) on Singapore, Mahdavi et al. (2003) on Austria, Weytjens and Verbeeck (2010) on Belgium, and Hand (1991) approaches the subject with a larger view. A large discrepancy between the research efforts invested in BPSTs and their actual integration in practice is almost unanimously recognized. It is particularly significant that 24,2% of architects interviewed by Mahdavi (2003) do not use BPSTs since they do not perceive a need for them, 16,4% since they see a lack of know-how in their staff, and 14,5% since BPSTs do not accelerate the design process. In all cases, a large responsibility is attributed to the education architects received (Mahdavi et al., 2003) as well as to the lack of an architect-friendly interface, which is instead designed for specialists of the single disciplines (Weytjens and Verbeeck, 2010). Now, whether BPSTs should be used by architects or by specialists remains a question that will be marginally addressed later on in this research.

Apart from the need of user-friendly BPSTs, the conclusions that can be drawn from these studies concern the need to use BPSTs that do not consume excessive time, or even speed up the process. When focusing on the conceptual phase, it is plausible that integrating new analyses as well as new tools would possibly slow the conceptual design phase. An awareness of eventual benefits that the project acquires in terms of quality is therefore crucial; as well as it is important to take into account possible gains in time-saving for the following design phases.

§ 2.6 Conclusions

In this chapter, a number of concepts have been defined. The concept of performative architecture has been introduced; and the concept of performance oriented design has been defined, in its general meaning and specific terms. The nature and the focus of conceptual design has been discussed; and aspects of traditional conceptual design inhibiting performance oriented design have been identified. Moreover, CACD methods have been introduced, precedents have been illustrated and general limitations of current CACD methods have been identified. Finally, the integration of performance oriented architectural design and CACD methods have been tackled by discussing the specificities of performance oriented design in relation to digital supports.

Based on the general considerations on CACD methods and on the aspects specifically discussed for performance oriented design, specific requirements are formulated for a design methodology and support tools. To summarize what has so far emerged, a design approach for the conceptual design of performance oriented architecture should:

- favour the generation of geometric design alternatives,
  - i.e., by means of procedural and parametric geometry;
- favour interdisciplinarity by integrating architectural and engineering aspects;
  - i.e., by means of data exchange;
- favour the management of complexity,
  - i.e., by means of decomposition;
- favour the integration of measurable criteria,
  - i.e., by means of BPSTs;
- privilege visual communication,
  - i.e., by means of 3D models;
- support the learning process of the designer,
  - i.e., by means of backtracked data;
- allow dealing with un-structured, un-predicted, ill-defined problems.

The first five aspects are specifically addressed in a design method in chapter 5; the last two aspects are addressed in chapter 8.

§ 2.7 References

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3 Adaptivity for performance oriented design

This chapter presents the concept of adaptivity in architecture. The relation between performance oriented design and adaptivity is emphasized, based on the dynamic nature of the context to which architecture might have to respond. Various ways in which architectural and structural elements can interface the dynamic context; and various ways in which architectural and structural elements can achieve adaptivity are briefly introduced.

§ 3.1 Introduction

As discussed in section 2.2.2, changes are ordinary conditions of life, both in the short term of the daily life and in the longer term of a historical perspective. When focusing on aspects related to architecture, human needs and demands change over time, in the short and long term. Also the environment changes both in the short and long term, including factors affecting the daily, seasonal or over years performances of buildings. However, architecture is traditionally meant as static: an enduring system, sometime conceived as if it was permanent in a long time and substantially unchanging during its lifetime. When assuming this perspective, the concept of performance requires finding a balance among the different changing requirements and/or changing environments. Looking for this balance can be a solution, but it is not the only one possible. Instead, architecture could be intended as a system able to adapt by changing its status in a controlled manner. By doing so, the focus is here moved toward the topic of adaptive architecture. The attention is recalled on the need of buildings that can be varied, expanded, contracted, moved, terminated or altered in whatever else manner (Zuk and Clark, 1970), in the long term and in the short term; including concept of adaptation as an action-reaction happening in real time. This perspective is an alternative that cannot be excluded when designing, and especially when focusing on performance oriented design.

This thesis does not privileges either static or adaptive architecture; and does not exclude any of the two options. However, while the perspective of a static architecture is well establish, the perspective of adaptive architecture needs clarifications. This is the reason why a specific chapter is dedicated to adaptive architecture.

By approaching this concept, this chapter offers an overview of the state of art of past and current adaptive architecture and proposes a literature review by recalling relevant works of previous and contemporary authors and their theoretical studies. By re-exploring and reviewing these studies, the chapter proposes an exploration of today's state of the art of the domain by identifying different categories of adaptive architecture. Besides reviewing the existent work, such categorizations contain original contributions of the author, which can be recognized all over the chapter.

Specifically, after this introduction, the second section of the chapter introduces the concept of adaptivity in architecture. This topic is then discussed by following two criteria. The first criterion concerns the way in which architecture interfaces the context. This criterion includes aspects such as the detection of the changes in the context; the decision to be taken based on such changes; and the actuation of eventual architectural adjustments in order to meet the new conditions. The second criterion concerns the different ways in which architecture can react to the context. This criterion includes the nature of the adjustments that architecture can make in order to meet the new conditions, either with or without geometric variations of the building. The third section of the chapter presents the domain of adaptive architecture based on geometric variations. This topic is then discussed with respect to the aim of the geometric changes, their frequency in the time and the moment in which they occur compared to the life of the building. The proposed categorizations do not offer a sharp borderline between the groups. Examples are included in order to clarify the concepts. The list of the examples does not mean to be exhaustive. It is instead just functional in presenting the categorization. The fourth section of the chapter presents a similar categorization, but with specific focus on structures, due to their relevance in the domain of adaptive architecture.

§ 3.2 Adaptive architecture

In the previous chapter, performance in architecture has been defined as the capacity of a building to fulfil the architectural requirements. The architectural requirements have been defined with respect to the human actors involved in the building life; and the capacity of a building to satisfy them have been introduced both through the direct relation with such requirements and with the environmental conditions of the building. Human and environmental factors have been presented as components of the context. Both these groups of factors have been pointed out as a changing context, which the building has to interface and mediate.

The concept of adaptivity in architecture is defined here as the capacity of a building to satisfy varying requirements in a changing context, with specific reference to the capacity of a building to be responsive to a changing context.

By highlighting its role in interfacing and mediating between the conditions desired by the users and those present in the surrounding environment, the concept of adaptive architecture is based on the interdependence between the varying needs/demands and the capacity of a building to satisfy them in a changing environment.

Still this definition identifies a large domain including a wide range of subcategories. The current vagueness of this distinction is well known. Current literature does not univocally agree on the vocabulary of the subject and, as recalled by Lelieveld, the terms flexible, adaptive, interactive, responsive, intelligent, dynamic and others cannot be easily connoted (Lelieveld et al, 2007). Within the concept of adaptive architecture, the work here presented proposes the definitions discussed in the following sections, based on two criteria of classification: on one side the way in which architecture interfaces the changing context and on the other side the way in which architecture can adjust to achieve the desired changes.

The categorization has been based on these two aspects since they are identified as the main steps in which the process of adaptation can be subdivided. The process of adaptation requires the detection of the contextual changes, a decision concerning architectural changes eventually needed in order to meet the new conditions, the initiation of the these changes and finally their realization. The detection, evaluation and initiation are here considered as a process of interfacing between the context and the architecture; while the changes themselves are considered a process of adjustment.

§ 3.2.1 Interface-based classification

The way in which architecture interfaces the changing context involves the ways in which changes in the context are detected, information are processed and consequent changes in architecture are actuated. These three actions are called respectively:

- *detection;*
- *elaboration;*
- *activation*.

These three actions can be left to a human decision and action process based on human evaluations and manual reactions. This means the changes in the context are detected or previewed by human perception, followed by a decision making process that ends with a manual activation of the needed changes. This happens daily for example when sensing stale air and manually opening a window, being glared and manually blinding a shadow system or vice versa opening a curtain switching when the indoor is estimated too dark; but those processes are at the base also for larger actions, like when sliding a partition wall to subdivide a conference room or mounting a winter roof on a sport hall. Differently, the three actions can also be based on various levels of integrated systems for automation, such as sensors collecting data from the context, actuators that activate the architectural changes and processors computing on one side the inputs given by the collected data on the other side the outputs, which are the needed changes.

§ 3.2.1.1 Passive, active, and smart architecture

According to its level of automation, adaptive architecture is defined as *passive, active* or *smart*. This distinction regards the capability of adapting versus the capability of being adapted. Passive occurs when human actions are taken and therefore the role of architecture is mainly passive during the reaction process; its partial or total automation leads instead to partially or totally active adaptive architecture, where architecture is somehow taking an active role during the reaction process; finally smart adaptive architecture implies that adaptive architecture has the ability of self-initiative (Lelieveld et al., 2007) through a high level of integration of detection, elaboration and activation. In summary, the three groups can be defined as following:

- Passive adaptive architecture: architecture capable of being adapted by means of human actions.
- Active adaptive architecture: architecture capable of adapting itself by means of full automation.
- Smart adaptive architecture: architecture capable of adapting itself by means of full automation in a highly integrated manner.

The borderlines between these groups are not sharp. Hybrids typologies are possible and are common especially between active and passive architecture. These transitions are discussed in the following sections.

§ 3.2.1.2 Semi-passive or semi-active

The transition between passive and active adaptive architecture consists of semi-active (or semi-passive) adaptive architecture, which is defined as following:

- Semi-active (or semi-passive) adaptive architecture: architecture capable of adapting itself and being adapted by means of a degree of automation and of human action.

In order to further define this group, three subgroups are also introduced, based on the different actions that are automated. Within the domain of semi-active architecture, architecture that includes sensors to monitor and determine the changes in the context is here called *sensory architecture*; architecture that possesses actuators enabling its alteration is here called *responsive architecture*; when sensors and actuators are connected by a system elaborating, processing or computing the data to identify and actuate the proper reaction according to the changes in the context, then architecture is here defined *intelligent*. In summary, the three sub-groups of semi-active adaptive architecture can be defined as following:

- Sensory adaptive architecture: architecture capable of determining and monitoring the changes in the context, by means of sensors. This type of adaptive architecture is active in actions regarding the detection of conditions in the context.
- Intelligent adaptive architecture: architecture capable of elaborating, processing or computing data to identify changes that should occur in order to meet new conditions in the context. This type of adaptive architecture is active in actions regarding elaboration.
- Responsive adaptive architecture: architecture capable of activating its changes, by means of activation systems that enable alterations. This type of adaptive architecture is active in actions regarding activation.

The overlaps among the sub-domains are illustrated in figure 5.

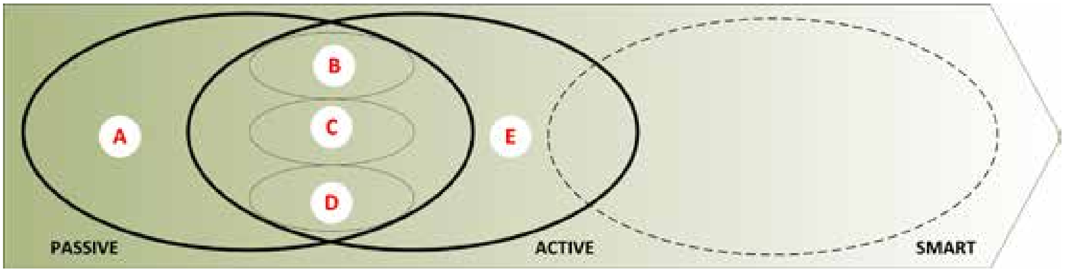

Figure 5
Representation of the possible overlaps among sub-domains.

By referring to figure 5, the group A includes the adaptive architecture that is fully passive, with means of human intervention for all the three phases of detection, elaboration and activation; group B includes sensory architecture, which has passive elaboration and activation; group C includes responsive architecture, which has passive detection and elaboration; group D includes sensory and responsive architecture with elaboration delegated to human action; while the group E includes fully active adaptivity, where all the three phases are automated. Also the transition from fully active architecture to smart architecture is gradual; this is specifically tackled in section 3.2.1.4.

Before discussing the transition from fully active architecture to smart architecture, a discussion regarding the various levels of intelligence in adaptive architecture is introduced in this following section 3.2.1.3.

§ 3.2.1.3 Degrees of intelligence

In the previous section, architecture capable of elaborating, processing or computing data to identify changes that should occur in order to meet new conditions in the context has been defined as intelligent adaptive architecture.

If we refer to intelligence as a generic ability of elaborating, processing or computing data, then intelligent architecture is a quite broad concept that includes various possible processes, starting from simple elaborations of data and coming to systems learning from the context. With this respect, examples are many in semi-active, fully active and (as it will be more specifically discussed in the next section) smart adaptive architecture. However, a proper definition of intelligence leads to the identification of different types of intelligent architecture.

What does intelligence in architecture mean exactly? According to Addington and Schodek (2005), intelligence recalls the ability to acquire knowledge, demonstrate good judgment and to possess quickness in understanding. For simplicity of categorization, the category of intelligent architecture includes instead also the basic elaboration of information, not only of knowledge. While knowledge refers both to acquired information and to their understanding, information refers to the dry learned facts themselves. This is the most crucial aspect based on which levels of intelligence can be distinguished within the proposed categorization. Examples may clarify the point and are also provided here following.

As a simple means of active detection, elaboration and reaction, even a common thermostat of a heating or cooling system is a daily example of an intelligent object integrated in architecture; however its level of intelligence is usually extremely poor and does not exceed the simple ability of comparing two values. The total sequence of detection, elaboration and activation consists of sensing the temperature, comparing its measure with a set value and switching on and off the heating or cooling system.

The first basic level of architectural intelligence is identified in an active elaboration interconnecting a contextual stimulus to an architectural reaction as simple direct response. This implies a direct straight forward relation of cause-effect between an input and a determined output. This is the case of the mentioned traditional thermostat, where switching on or off the heating or cooling system only depends by a straight forward comparison between the room temperature and the set temperature. Various systems based on a similar elementary process have been already largely integrated in architecture and are part of our daily life. But architecture currently embeds higher level of intelligence and further increasing is expected based on current developments.

Two increased levels of intelligence are identified by Vincent (2001). The first one is identified in the ability of balancing various inputs in order to determine different outputs through an articulated elaboration of if-then conditions. This goes behind straightforward relations of cause-effect. The second one is identified in the ability to learn, where this latter can lead to a patterned model of the word allowing informed prediction.

Advanced applications of learning processes in architecture are still uncommon. This differentiates architecture from other fields, such as aerospace engineering and robotics that already offer broad examples of technologies where learning processes are integrated in the artificial structures. Figure 6 shows an example.

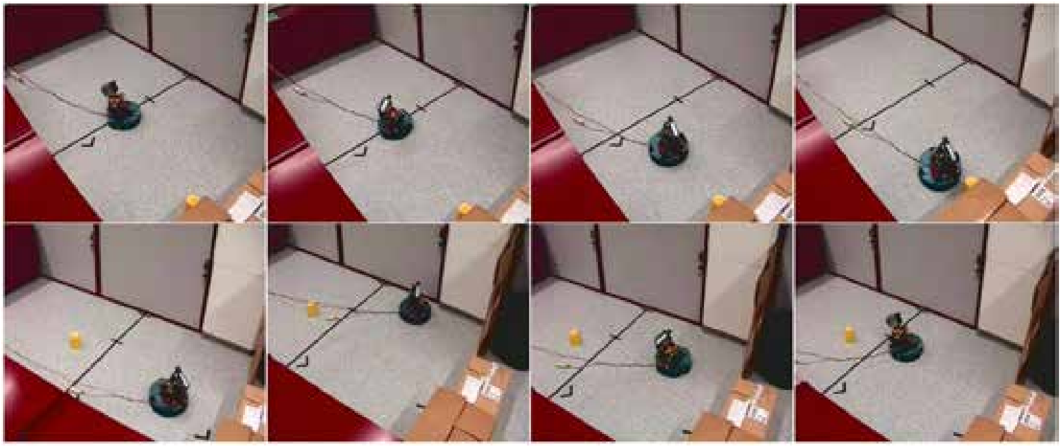

Figure 6
Example of intelligence involving learning processes, taken for the field of robotics. Snapshots of robot looking for the target object, a yellow cup. The top row shows a 20 minutes process of learning, ended in the successful approach to the cup. The bottom row shows a shorter search where the robot generalizes successfully to novel starting and target object positions (Bakker et al., 2006).

Figure 6 shows some images from experiments conducted on a robot whose task is quickly finding a yellow cup by avoiding bumping in obstacles. Its sensors detect colour and geometric information form the context and its outputs can be a series of actions (moving forward or backward, turning left or right, turning and moving). The way inputs are elaborated to define the outputs integrates an algorithm based learning process that allows the robot to find the yellow cup with less and less bumping failures (Bakker et al, 2006). Similar advanced technologies are being developed for integration in architectural applications, leading buildings to a higher level of intelligence.

§ 3.2.1.4 Degrees of smartness

In the previous section 3.2.1.3, various levels of intelligence have been described. In the different levels, the processes through which the inputs provided by the context are elaborated in outputs are various. Moreover, as described in the previous sections, active or semi-active adaptive architecture interacts with its context mostly including some receptors, one or more central processors differentiating inputs and integrating them into outputs and one or more effectors.

Due to the automation of the or some of the three phases (detection, elaboration, activation), the reactive behaviour of active and semi-active architecture is based on the concept of self-reactiveness. Self-reactiveness is the common ground shared by active architecture. Despite a high variety has to be acknowledged regarding the ways in which information is sensored and collected, processed and transmitted for activation; mostly, this self-reactiveness is based on electronically controlled processes of digital elaboration of data. With respect to that, having an active adaptive behaviour corresponds here with what Negroponte (1975) defines as the capacity of taking an active role, initiating to a greater or lesser degree changes as a result and function of complex or simplex calculations. However, it is important to call attention to the existence of self-reactiveness that are based on non-electronically controlled processes. The more the process, electronic or not, is directly integrated in the building itself, the closer this is to the concept of smart architecture.

What does smartness in architecture mean exactly? While intelligence recalls the ability to acquire knowledge, demonstrate good judgment and to possess quickness in understanding (as discussed in section 3.2.1.3), smart implies notions of an informed or knowledgeable response commonly associated to the concept of intuitive and intrinsic response (Addington and Schodek, 2005). When focusing on adaptive architecture, this distinction mainly refers to the level of integration, which is higher in case of smartness. Specifically, smart architecture implies a high level of integration leading to self-initiative sometime even without allowing a clear distinction between the phases of detection, elaboration and reaction.

Based on what said above, while this phases' distinction is relatively well identifiable in the case of active and passive adaptive architecture, their borderlines become blurred in the domain of smart architecture. This is due to the high level of integration among the phases which is peculiar of this group; and this happens when the process is not or not only based on digital processing.

A very significant example is offered by the use of smart materials. Smart materials are materials with the ability to change their physical appearance induced by external stimuli (Lelieveld and Voorbij, 2008 and 2009). More specifically, according to Addington, smart materials respond to external stimuli by changing one or more of their properties and/or by transforming energy from one into another (Addington and Schodek, 2005). In the case of smart materials, the process of sensing/detecting, elaborating and reacting/activating happens in a material instead of a system composed of separated relatively large scale parts. Smart materials therefore necessarily lead to an intrinsic integration implying the ability of highly integrated self-initiative. It is not a case these are well known in literature also as dynamic or active materials, and are defined as materials exhibiting sensing and actuation capabilities (Lagoudas, 2008). Examples of smart materials are being provided in the following sections 3.1.2.1.

§ 3.2.1.5 Conclusive summary of interface-based classification

In this section 3.2.1, three groups of adaptive architecture have been identified based on the way in which the context is interfaced by architecture. In this way, passive, active and smart adaptive architecture have been defined according to the levels of automation. Moreover, three subgroups have been identified based on the different actions that are automated: sensory, intelligent and responsive adaptive architecture. Finally, intelligence and smartness in architecture have been discussed.

In conclusion of the discussion regarding this categorization, a summary of the sub-domains described in the previous sections is illustrated in figure 7.

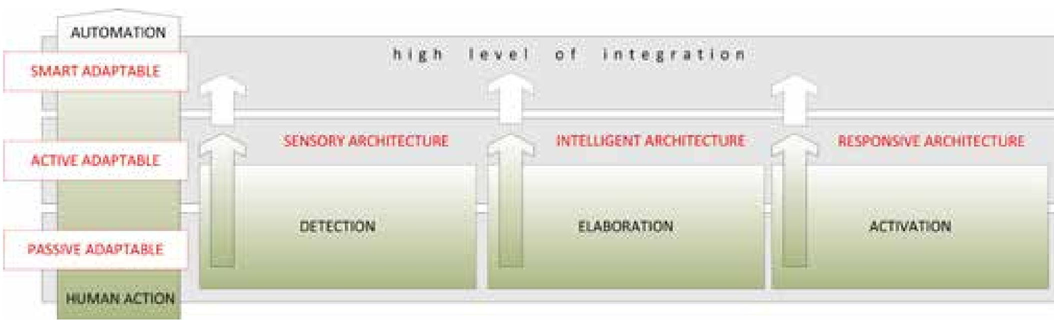

Figure 7
Categorization of adaptive architecture based on different level of automation in detecting information from the context, elaborating the collected data and activating the reaction of the building.

§ 3.2.2 Reaction-based classification

In the previous section 3.2.1, a categorization has been described, concerning the ways architecture interfaces the context. A second subdivision is given here following, based on the way in which architecture can adjust to achieve the desired changes.

According to the three actions (detection, elaboration, activation) described in the first paragraphs of section 3.2.1, adjustments of adaptive architecture are changes activated after the detection and the elaboration. Despite the nature of these adjustments is directly related to the interface process, they lead to a different perspective based on which adaptive architecture can be classified. Specifically, the nature of these adjustments is used in this section to distinguish various sub-domains of adaptive architecture.

§ 3.2.2.1 Reconfigurable and statically dynamic architecture

With respect to the nature of the adjustments, two main possible ways of adaptivity are identified. The first one regards the changes in geometry. It is based on geometric reconfigurations of elements. It requires a change in shape through the movement of one or more elements or parts of them. It is named *reconfigurable architecture*. The second one regards changes in material properties, without implying geometric variations. It bases the adaptation on the integration of materials able to vary their properties (such as their transparency, colour, porosity or others), rather than shape. This second group is named *statically dynamic architecture*. Both groups run transversally across the interface-based categorization. This means both reconfigurable and statically dynamic architecture can be passive, active or smart.

In the case of reconfigurable architecture, the distinction between passive and active is quite obvious. It refers to automated or manually controlled way of detecting information from the context, processing them and actuating eventual reconfigurations. Differently, the understanding of smart reconfigurable architecture might raise more questions, especially when related to the current state of art. In order to clarify the concept of smart reconfigurable architecture, it is important to recall how the movement in reconfigurable architecture can be achieved. It can be achieved both based on movement of rigid components and based on deformation of components. When using deformations, smart materials are also included and provide a significant example of smart reconfigurable architecture. Particularly, reconfigurable architecture can employ smart materials that exhibit a large mechanical response when subjected to non-mechanical stimuli, such as thermal, magnetic, etc. (Lagoudas, 2008). A specific example is given by shape memory materials, where an input of thermal energy alerts the microstructure through a crystalline phase change, enabling multiple shapes (Addington and Schodek, 2005). Shape memory alloys are part of this group and able of adjusting their shape under external stimuli; specifically, they can recover their shape when temperature is increased (Lagoudas, 2008). Their application is considered a new frontier in adaptive architecture and a number of current researches are exploring this field (Coelho and Maes, 2007; Addington and Schodek 2005; Lelieveld and Voorbij, 2008).

Smart materials are crucial also for statically dynamic architecture. In this case, the changing property of the material does not result in different shapes, but in other variations.

§ 3.2.2.2 Smart materials

The variety of smart materials is high as well as their current and future possible applications. Magnetorheological materials change their viscosity under application of magnetic fields. Chromogenic materials change their colour under inputs of different possible natures. Specifically, inputs are electric for electrochromics, while photochromics react to light and thermocromic materials respond to a thermal input by altering their molecular structure and, as a consequence, their spectral reflectivity. Thermotropic materials respond instead to a thermal input by changing altering their microstructure through a phase change and therefore sometime affecting properties such as conductivity, trasmissivity and others. Specifically, they switch from liquid when warm to crystallized when cold. More detailed information can be found in Addington and Schodek (2005).

The images in figure 8 exemplifies the group of thermotropic materials, as explained in the following paragraph.

Figure 8
Based on the solar exposure, the thermotropic glass of a window changes state. (Image source: Inoue, 2003).

Chromogenic materials already have large applications in various filed, among which also the building industry; well know examples are their applications in glazing, mirrors and displays; but they constitute a topic of active research through which further developments and applications are highly expected. Currently, due to their ability to change colour upon exposure to ultraviolet illumination, photochromic materials became commonly applied in ophthalmic products; while common applications of thermochromics can be found in aerospace industry where changing in heating lead to changes in emissivity of materials. Architectural applications of chromogenic materials mainly regard glazed cladding and windows (Lampert, 2004). When such materials are directly reacting to stimuli coming from the environment, they offer an example of smart variable architecture. It is the case of sun responsive thermocromic glass, which uses thin films located between glazed layers and darkening with direct sun exposure, due to the raise in temperature. Similarly, an example of smart variable architecture is provided by thermotropic glass, which switches from a clear appearance at lower temperatures to an opaque one at higher temperatures. Figure 8 shows the change in state of a thermotropic glazed window based on units of polymer gel sandwiched between two panels of glass, directly activated by the solar exposure. (Inoue, 2003; Lampert, 2004). Instead of being based on ambient temperatures, solar exposure or other stimuli directly coming from the environment, those processes can also be activated also through controlled stimuli. This happen for example in thermotropic glass when using a resistive heating layer made from film metals or conductors enabling electrical control of the physical change. Such cases lead back to the concept of active variable architecture.

§ 3.2.2.3 Conclusive summary of reaction-based classification

In this section 3.2.2, two groups of adaptive architecture have been identified based on the way in which architecture can adjust to achieve the desired changes. In this way, reconfigurable and statically dynamic architecture have been defined according to the nature of the changes. Considering the relevance for both groups, the specific domain of smart materials have also been introduced.

Despite the greatly promising perspectives of the current developments in statically dynamic architecture, the focus of the next sections is reserved to reconfigurable architecture, due to the direct relation between this sub-domain and the design exploration of geometric alternatives (which is a crucial subject of this thesis, as expressed in chapter 2).

§ 3.3 Reconfigurable architecture

This section presents the domain of reconfigurable architecture in details. As mentioned, reconfigurable architecture bases the adaptivity on changes of its shape, through geometric reconfigurations based on movement of rigid elements or deformation of deformable elements. So formulated, the concept of reconfigurable architecture is still very broad and refers to an extensive strategy that includes movements of various natures and acting at different scales. However, all of them are related by the aim of changing the architectural form in order to meet new conditions through a designed system that is conceived for such reactions.

Within this common framework, the relation between the concept of reconfigurable architecture and the need for adaptivity can be explored with respect to different criteria. Among the many, three factors strongly affecting reconfigurable architecture are emphasized. The first one consists of the performance requirements for which adaptivity is expected to allow meeting the changing conditions; the second one is the frequency of the required changes; and the third one is their collocation during the lifetime of the building. The performance requirements to which the changes in shape are addressed are defined *adaptivity requirements*. They identify the reason why the change in shape occurs, in relation to required architectural performances. The frequency can regard a daily change in shape as well as a change happening only once throughout the lifetime of the building. The collocation of the changes during the lifetime of the building expresses when the preconceived geometric changes occur, from the building site to the life end of the building.

Those three factors are crucial for reconfigurable architecture. The awareness of the designer regarding these factors plays a fundamental role in conceiving design solutions for reconfigurable architecture; and needs to be included in the conceptual phase of design. Due to their relevance, these three factors have been chosen for guiding a sub-classification of reconfigurable architecture, which is being presented in the following section.

§ 3.3.1 Performance-based classification

Based on the different adaptivity requirements, frequencies of changes and their collocations during the lifetime, a general categorization of reconfigurable architecture is described. The exploration and categorization of the topic is based on a combined criterion merging the three factors. However, among the three, the adaptivity requirements have been used as main driver for the classification.

Adaptivity requirements indicate the reasons for which the change in shape is conceived. This occurs since human needs and demands change over time and since also environmental conditions change over time; as discussed in sections 2.2.2 and 3.2. As also discussed in the same sections, adaptivity is directly related to the required architectural performances, which can be vary and very different. This implies that also the change in shape of reconfigurable architecture can be related to a wide range of different aims and can be addressed to the satisfaction of architectural performances belonging to various fields and disciplines. In simple words, geometric changes in the architectural shape range over diversely formulated need of changes in the context. This goes from functional changes satisfied by movable partitions and structural adaptivity to different load conditions. Formulating a classification based on such complex frame faces the high variety of cases and the complex interrelationships connecting them each other's. However, a few macro-categories can be defined based on simplified but consistent domains.

Aiming at this, the work done by Zuk and Clark in the seventies can be considered still a consistent guideline. The classification proposed by these authors (Zuk and Clark 1970) helps in understanding the more recent developments in this architectural field; and it has been considered a suitable starting point for its investigation in this thesis. It should be noticed that what in this thesis is called reconfigurable architecture was instead named by Zuk and Clark as kinetic architecture. The reason for which in this thesis a different name is preferred is in order to avoid unwanted confusions with the engineering and mechanical fields related to kinetics. A second difference regards the categorized sub-domains. Originally, the classification by Zuk and Clark proposed eight groups describing architectural applications of kinetics, formulated as dynamically self-erecting structures, reversible architecture, disposable architecture, incremental architecture, mobile architecture, kinetically controlled static structures, kinetic components, deformable architecture (Zuk and Clark, 1970). By reviewing these eight groups, the current categorization is at first narrowed to six categories; however starting from this first level, further classes are defined following the structure of a tree. Focusing on the first six categories, four of them directly recall the first four listed groups of the Zuk and Clark classification; one of them is based on a review and subdivision of the fifth listed group; while the sixth category collects the last three listed groups, which have been deeply reviewed and further classified.

Specifically, dynamically self-erecting architecture is conceived to be erected as a structure that achieves its final configuration through a preconceived movement occurring in the building site. Reversible architecture has the potential to be disassembled without destruction and morphological changes in this case serve architectural transformability within a long term lifecycle. Disposable Architecture makes this concept being extreme into a short-lived architecture. Incremental architecture has instead a long term lifecycle approach, allowing for the addition, subtraction or substitution of parts during the life of the building, which is conceived as an open system. Mobile architecture, also called transportable or portable architecture, allows the building to move as a total unit. The sixth group collects the changes in shape occurring with various frequencies during all over the main life-time of the building and remains more undefined concerning the adaptivity requirements, which are based on a response to short term needed performances occurring during the use. This sixth group is called form-active architecture and will be further on detailed and subdivided. Each of these groups is presented in details in the following sections.

By formulating the categories mainly based on the adaptivity requirements, their definition refers to the reason why the building has been conceived as reconfigurable. While this criterion makes the definition of the classes being univocal, the belonging of a building to a specific class is not univocal. As it was for the Zuk and Clark classification in fact, a number of classes' definitions can coexist (Zuk and Clark 1970) and the same reconfigurable building can belong to more than one group.

As for the frequencies of changes and their collocations during the lifetime, four of the six groups focus on occasional or even one time needed adaptivity involving the very early life of the building (including its construction) or its very late phase (including its destruction). This means that some of the classes can be considered reconfigurable architecture only when extending the concept to the overall life process of the building; and not only during the time it is properly used by its occupants. From this point of view, it might seem questionable whether some classes truly belongs to the domain of reconfigurable architecture. However, the choice to include them as consistent part of the domain is understandable when considering that architectural performances are not limited to the period of occupancy; instead they span through the overall life of the building. This aspect needs to be equally considered during the design process.

A brief description is proposed here following, for each of the sub-domains.

§ 3.3.1.1 Self-erecting architecture

The sub-domain of self–erecting architecture consists of settled architecture that is erected in the building-site through the predesigned movement of some of its major parts; usually its structure. Mostly, these parts are brought on the site in compact configuration and expanded into a predetermined stable form. This action does not occur again after the construction is completed. These properties can be summarized as following:

Self-erecting architecture	
Definition:	settled architecture including major self-erecting parts, usually structures
Goal:	easy first erection once in the construction site
Time;	during construction
Frequency:	once
Examples:	The Pantadome system developed by Mamoru Kawaguchi is based on partially folded space structures that are erected by unfolding into the final shape. According to Kawaguchi, the core idea of Pantadome is to make a structure become a mechanism by temporarily removing some members during the process of construction (Wang et al., 2005). The system has been applied, among others, in the erection process of the Sant Jordi Sports Palace in Barcelona (Chilton, 2000) and of the Namihaya Sports hall (Schlaich, 1998).

Table 1
Summary regarding self-erecting architecture.

Figure 9 illustrates some examples.

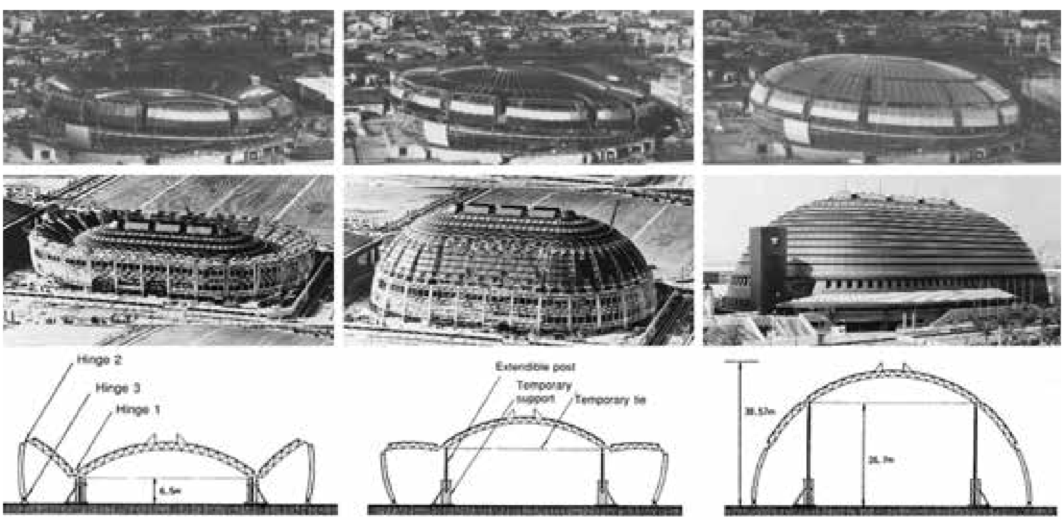

Figure 9
Examples of self-erecting architecture with Pantadome system. Top row: three stages of the erection of the Namihaya Sports Hall, designed by Mamoru Kawaguchi with Showa Sekkei Design Co. (Images source: Schlaich, 1998). Middle row: three stages of the Memorial Hall in Kobe during erection and in final configuration and transversal sections of its structure. (Image source: Chilton, 2000) Bottom row: diagrams of the Pantadome system for the Memorial Hall in Kobe. (Image source: Chilton, 2000).

§ 3.3.1.2 Reversible architecture

The sub-domain of reversible architecture consists of architectures that have the potential to be demolished or changed by being dismounted or disassembled without destruction of the components. This aims at possible reuses of the components within the building or for different constructions. The process is based on three phases: assembling, disassembling and reconfiguring the components into a new assemblage. Despite it rarely occurs, an earlier planning of this transformation process should be made. This means that morphological variations to achieve architectural changes or demolition should be planned during the design to serve architectural transformability and reusability of components within a long term lifecycle. These properties can be summarized as following:

Reversible architecture	
Definition:	architecture conceived to be demolished or changed by being dismounted or disassembled without destruction of the components in order to allow their reusability
Goal:	easy disassembly toward new assembling
Time;	mostly (but not only) end of life of a building and construction of a new
Frequency:	occasional or once
Examples:	A famous example of reversible architecture is provided by the house designed by Werner Sobek for himself, the R128 house, conceived to be built based on modular elements easy to assemble and disassemble without damages in order to make possible their reuse (Sobek et al., 2009).

Table 2
Summary regarding reversible architecture.

Figure 10 illustrates the example.

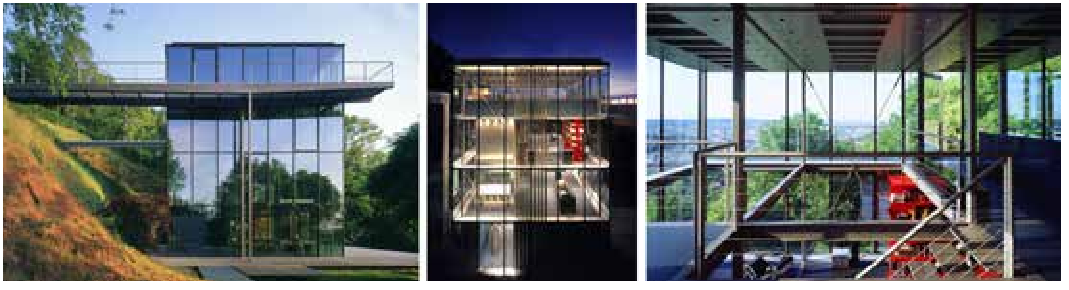

Figure 10
Example of reversible architecture. R128 house by Werner Sobek. (Images source: www.wernersobek.com).

§ 3.3.1.3 Disposable architecture

The sub-domain of disposable architecture consists of architectures that have been conceived for a short term life. It is designed as a short-lived system and uses a limited time span of the building's life as a response to the need of changes. A relevant advantage of this strategy is its broad generic nature, since the specific obsolescence of the building (functional, physical, aesthetical or other obsolesce) does not have to be previewed in advance. Independently from the kind of performance that will require the changes, the response of the building is its disposability. Although its main prerogative remains the shortness of its life, in a sustainable perspective, this category can also be combined with other strategies, such as the transformability which characterizes also reversible architecture or other recycling procedures. These properties can be summarized as following:

Disposable architecture	
Definition:	architecture conceived as a short-lived system in response to the need of changes
Goal:	easy disposability of the whole building or of every major part of it as response to its obsolescence
Time;	mostly (but not only) end of life of a building
Frequency:	occasional or once
Examples:	Among the many temporary pavilions offering famous examples of disposable architecture, cardboard architecture is recalled here. The Japanese Pavilion designed by Shigeru Ban Architects and Frei Otto with Buro Happold for the Expo 2000 in Hannover is a tube paper structure designed and constructed as short term architecture, toward dismountability and recycling. (Davey, 2008).

Table 3
Summary regarding disposable architecture.

§ 3.3.1.4 Incremental architecture

The sub-domain of incremental architecture consists of architectures designed to allow addition, subtraction or substitution of overall building's parts during the building life. According to such an approach, the building is conceived as a long term system with a wide-span lifecycle and is intended to be an open system able of accepting further changes. Reconfiguration occurs in the building life as exceptional event in taking away, adding or substituting parts. These properties can be summarized as following:

Incremental architecture	
Definition:	architecture conceived to allow for the addition, subtraction or substitution of major parts during the building life
Goal:	easy addition, subtraction or substitution of major parts
Time;	during the life time
Frequency:	occasional
Examples:	Dutch Spacebox is a modular system designed by Mart de Jong at the Dutch office De Vijf in Rotterdam. It consists of prefabricated housing units to be horizontally aligned and vertically stacked on top each other by forming and incremental building system.

Table 4
Summary regarding incremental architecture.

§ 3.3.1.5 Mobile architecture

The sub-domain of mobile architecture consists of architectures designed to be easily moved from one to another place, by allowing a total architectural mobility. This means that a mobile architecture is a transportable construction whose location can change. These properties can be summarized as following:

Mobile architecture	
Definition:	architecture conceived as a transportable construction whose location can change
Goal:	easy transportability
Time;	during the life time
Frequency:	occasional

Table 5
Summary regarding mobile architecture.

Due to its large range of historical as well as contemporary applications, the possible examples of mobile architecture are very numerous. Looking at the past, collapsible tents offer a quite ancient example of nomadic architecture. Nowadays, there are even offices and academic research groups specifically focusing on the topic of transportable architecture. To mention some of them: Omd Office for Mobile Design in Venice, Los Angeles, California; Transportable and Adaptable Architecture Research Unit at University of Liverpool. This sub-domain is actually a broad category and includes a wide range of buildings. The uses of this typology of architecture are various and include, among the others, emergency shelters, repairs during expeditions through extreme climate areas, military storages, travelling huts for tourists, scenography for itinerant shows, etc. Based on the state of the building during its transport, three main sub-groups can be identified within this domain. The first one includes buildings that can be moved as an overall unit that does not need major changes to be transported. These buildings are refers to as *movable units*. The second one includes buildings that can be moved as a total unit after easy disassembly followed by an on-site reassembly once at the new location. These buildings are refers to as *rapidly assembled units*. The third one includes buildings that can be moved as a total unit after being compacted without disassembly of relevant parts, being then re-expanded to its usual configuration for use in the new location. These buildings are refers to as *deployable/foldable units*. For each of the three groups defined above, systems to achieve the needed reconfiguration are many. However, each of the three groups is mainly characterized by recognizable typologies. In case of movable units, buildings transported as units on wheels, on rails or floating on water are the most common systems; light units movable when hanged from helicopters are also becoming of use. In the case of rapidly assembled units, buildings are usually conceived based on prefabricated components assembled with no use of irreversible conjunctions. In the case of deployable and foldable units, as the name recalls, mainly deployable, foldable or similarly collapsible systems are used as main component of the building. These properties can be summarized as following:

Groups of mobile architecture	
Movable units	
Definition	architecture is transportable as an overall unit without major changes
Goal	easy transportability as a whole and unchanged unit
Systems	wheels, rails or floating devices, etc.
Examples	The Mobile Eco Lab by Omd Office for Mobile Design is a working mobile classroom designed as a travelling workshops laboratory and exhibitions pavilion focusing on ecology. In order to achieve its mobility, the system has been built by using a pre-existent cargo truck trailer. The Portable Construction Training Center by Omd Office for Mobile Design is a transportable classroom for learning construction skills and is conceived as a mobile unit moving on wheels by being pulled by a track. The same system is used in the case of the ShowHouse, a mobile building for housing by the same design office.
Rapidly assembled units	
Definition	architecture is transportable as a unit disassembled for the transport and re-assembled for the use
Goal	easy transportability in disassembled state
Systems	prefabricated and disassemble systems
Deployable/fodable units	
Definition	architecture is transportable as a total unit compacted for the transport and expanded for the use
Goal	easy transportability in compact state
Systems	deployable and foldable systems
Examples	Among several possible references, the structures presented in 1986 by Foster and Krishnakumar (1986) offer a relevant example of temporary portable structures based on foldable principles. Equally relevant in the same category are the pantographic structures proposed by Perez Pinero for mobile theatres, pavilions and exhibition buildings, like the deployable space grid erected in Madrid in 1964 and later moved to San Sebastian and Barcelona (Chilton, 2000). As a recent example of deployable/foldable unit, Globetrotter is a project for a travelling truck cab that can be deployed into theatre, including inflatable rooms, on any relatively flat site and compacted again for further transports.

Table 6
Summary regarding sub-domains of mobile architecture.

Figure 11 illustrates some examples.

Figure 11

Examples. Top top row: mobile architecture as movable units: Mobile ECO LAB, Omd Office for Mobile Design. Second top row: mobile architecture as movable units: ShowHouse, Omd Office for Mobile Design. (Images sources: www.designmobile.com). Third top row: mobile architecture as movable units: Portable Construction Training Centre, Omd Office for Mobile Design. (Images sources: www.designmobile.com). Middle bottom row: mobile architecture as deployable unit: structure for a transportable theater by Perez Pinero. (Images sources: Chilton, 2000). Bottom bottom row: mobile architecture as deployable/foldable units: Globetrotter, Omd Office for Mobile Design. (Images sources: www.designmobile.com).

§ 3.3.1.6 Form active architecture

The sub-domain of form-active (sometime called also shape-active) architecture consists of architectures conceived for adjusting their shape while in use, during their life in a specific location, with possibly high frequency of shape changes according to the short-time or real-time needs. The changes in shape are responses to performance requirements; the wide range of possible performances implies a high variety of aims for which the movement is designed and used. These properties can be summarized as following:

Form active architecture	
Definition:	architecture conceived as a unit able to change shape during its use in order to satisfy short term performances
Goal:	easy change in shape to meet performance requirements
Time;	during the life time
Frequency:	from frequent to occasional

Table 7
Summary regarding form active architecture.

Two main directions for exploring this sub-domain are proposed. The first one uses the nature of the performances to be satisfied. Based on them, the domain can be subdivided into an extensive list of possible sub-domains. This includes emotional architecture when shape changes are addressed to users' emotions. The list includes also functional architecture when shape changes are mainly addressed to pure functional needs, such as a room's capacity when variously partitioning an indoor space through sliding walls, or a change in use when switching from a theatre to a cinema room by adjusting the scene; or many other cases. Adjustments in shape in order to meet requirements concerning the building physics behaviour of the architecture are at the basis of a third group of form-active (FA) architecture. This includes thermal, acoustical and other aspects. A fourth group includes changes in shape occurring according to structural performances. Beside these four main groups, the list remains open to embed other performance based subdivisions of the domain. These properties can be summarized as following:

Groups of form active architecture based on the aim of the movement	
FA Emotional architecture	
Definition	architecture adjusting its shape for emotional effects on users
Goal	easy change in shape in relation to emotions of users
Examples	Among traditional buildings, rotating restaurants are well known examples of emotional architecture, aiming at changes in the outside view enjoyable by the users; while among more innovative buildings, the Trans-ports pavilion by Kas Oosterhuis, exhibited at the Venice Biennale in 2000, has been one of the first relevant examples of such architecture, by adjusting its shape according to a real time game collecting data from the users.
FA Functional architecture	
Definition	architecture adjusting its shape for functional requirements
Goal	easy change in shape in relation to functionality
Examples	The Rietveld Schröderhuis in Utrecht is a famous example of FA functional architecture, especially in its living area dividable through sliding and revolving panels.
FA Building physics architecture	
Definition	architecture adjusting its shape for building physics performances
Goal	easy change in shape in relation to factors of building physics
Examples	Any building integrating orientable lamellas regulating sunlight; adjustable shading devices regulating solar gain; movable elements for acoustic absorption or diffusion; etc. are examples of FA building physics architecture.
FA Structural architecture	
Definition	architecture adjusting its shape for structural performances
Goal	easy change in shape in relation to structural behaviour
Examples	A notable example is offered by a bridge developed by Patrick Teuffel, where the stress peaks caused by dynamic loads can be reduced thanks to the geometric adjustment of the system (Sobek and Teuffel, 2001); a second example is the reconfigurable roof proposed by Massimo Majowiecki for the Oita Stadium, in which reconfigurability was considered also for reducing the wind load in case of strong wind.
Others - the list is open to other performance requirements	

Table 8
Summary regarding sub-domains of form active architecture, based on the aim of the movement.

The sub-categorization presented here above uses the aim of the movement as main driver to identify the subgroups. A second possible criterion of subdivision is discussed here following, based on the extensiveness of the shape changes compared to the scale of the building. When changes in shape occur without reaching a visible level of change of the building, the class is called *kinetically controlled static architecture*; vice versa, when changes in shape visibly involve the overall building, the class is called *deformable architecture*; in between these two extreme categories, a third class concerns the cases of changes involving only parts of the buildings and is called *movable components architecture*.

The sub-domain of kinetically controlled static architecture consists of architectures embedding parts able to guarantee good performances through small-scale movements. These parts can consist of every element of the building. Very well-known are the cases of structural components able of performances optimization regarding different loads; these often consist of adjustable structures guarantying structural responsiveness to various load conditions, like for changing overloads or in response to dynamic loading conditions like earthquakes and wind. However, this class involves also changes that are not structural-oriented adjustments; and intersects each of the four performance-based categories described here above.

The sub-domain of deformable architecture consists of architectures allowing for changes that fundamentally affects the whole form (Zuk and Clark, 1970). The deformation takes place among the parts without adding or subtracting them. The definition of this class brings it very close to the homonymous class identified by Zuk and Clark. However, within this category, these authors distinguish two types. In the one type, the reconfiguration takes place prior to use as necessary step to establish the initial form of the architectural structure; in the second type, the deformability takes place after the architectural structure has been used. When compared to the moment of the building life where the movement occur, neither one of these two indicated groups are part of the domain defined here as deformable architecture. This class is here instead meant to consist of buildings where the deformability takes place during the use of the building itself. Even if still quite experimental, it is for example the case for the E-motive Architecture proposed by Kas Oosterhuis, as in the already mentioned Trans-port and in the Muscle Body Project where the shape directly interacts with its users' behaviour.

The sub-domain of movable components architecture consists of architecture allowing for changes that affects some of its parts. Differently than the previous sub-group, the reconfiguration is restricted to a part of the shape without affecting the entire form. According to the scale of the movable or deformable components of the building, three further subgroups can be identified as large, medium and small scale movable components architecture.

These properties can be summarized as following:

Groups of form active architecture based on shape changes	
FA kinetically controlled static architecture	
Definition	architecture embedding non visible parts able to optimize their own performance through small-scale movements
Examples	numerous examples of buildings integrating springs in order to limit the impact of earthquakes
FA deformable architecture	
Definition	architecture which has the potential to allow for change which fundamentally affects the whole form
Examples	Trans-ports pavilion by Kas Oosterhuis
FA movable components architecture	
Definition	architecture which has the potential to allow for change which fundamentally affects parts of the whole form
Examples	Kuwait Pavilion, Hemisfèric and Milwaukee museum by Calatrava

Table 9
Summary regarding sub-domains of form active architecture, based on shape changes.

Doors, windows and small shadow systems are the most evident small-scale examples that find their origin in the past of architectural history, but also medium-sized movable partitions are historically well known; although not numerous, historical large-scale examples of movable systems can be thought of, like the Velarium of Roman Theatres and the movable sail-like shadow systems used in between buildings and in courtyards. Contemporary architecture offers relevant examples for each of the three scales. Famous buildings by Santiago Calatrava can be mentioned, among both his experimental designs and his realized projects. Just to mention a few, the Kuwait Pavilion built at the Expo 1992 in Seville, Spain is composed by large movable elements that rotate by variously shaping part of the project. Few years after, the Hemisfèric was built for the Ciudad de las Artes y las Ciencias in Valencia; this opens and closes the bottom parts of its envelope like an eye.

As for the medium and large scale, retractable (sometime know as convertible) roofs can be considered a specific sub-domain of this category. Considering their relevance, retractable roofs are specifically discussed. Retractable roofs are designed to allow both a covered and an uncovered state of the spaces underneath. This means these roofs can be open, by being in a retracted position allowing open sky view; and they can be closed, by fully carrying out their covering function. This topic is not going to be deeply presented in this context, since out of the main research focus. However, it has been largely explored and presented in a number of publications by other authors (Maiowiecki, 2005; Ishii, 2000a and 2000b). Particularly, a categorization of retractable roofs has been made (Ishii, 2000b). It is based on a matrix crossing the direction of the movement (parallel, central, circular, peripheral) with the typology of the construction system (bunching and rolling membranes with stationary supporting structure, sliding, folding and rotating either membranes with movable supporting structure or rigid elements); a distinction is also made between overlapping and non-overlapping systems. This thesis refers to this categorization only as a reference while tackling the scale of the moving elements. This is due to indirect relations existing between the scale of the elements and the criteria of the categorization. In the case of retractable roofs in fact, the scale of the main components usually can be medium or large depending by the dimensions of the roof, but especially and even more, by the way in which the roof retracts. At first, this simply means that when subdivided in a high number of parts to be moved, the systems usually belongs to the medium scale components; while when the roof moves jointly or it is subdivided in a few parts only, then it belongs to the big scale components. However at a deeper level of analysis, the relations with the construction system become evident. Membranes, for example, tent to be large scale, for reasons that include the weakness of their conjunctions and their lightness. Although there are relevant examples of large scale rigid roofs, these latter are often subdivided in smaller components. For example, the moveable roof made by sliding pneumatically supported foil cushions designed by Planinghaus Architekten and Schlaich Bergermann und Partner for the Landschaftspark Duisburg-Nord can be considered a medium-scale example. This system is based on a parallel movement of the sliding panels. Among the many, another example of medium scale components used for a retractable roof is offered by the roof designed in Bologna by Massimo Majowiecki for the Carmen Longo swimming pool. Also this project uses a set of sliding panels, but instead of moving parallely as in the previous case, the panels switch from overlapped to adjacent positions to retract and expand the roof. Figure 12 illustrate some examples.

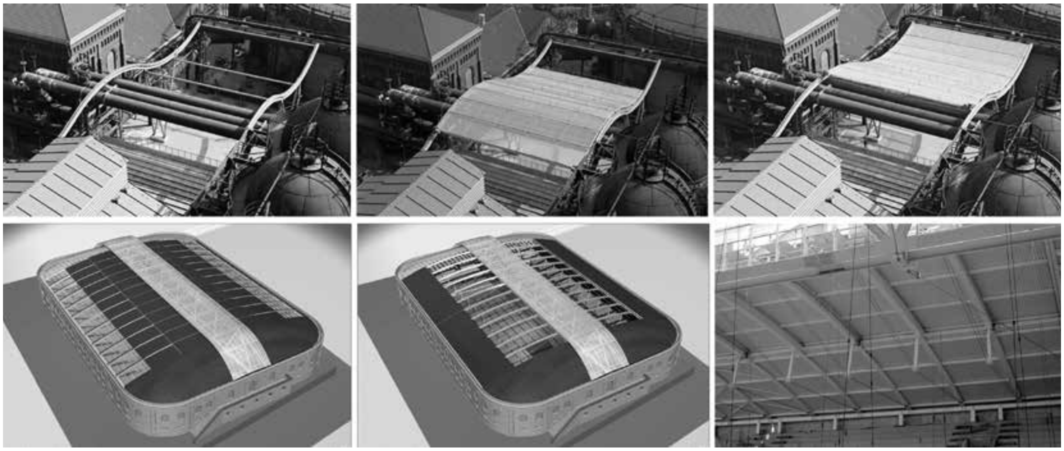

Figure 12

Two examples of retractable roof based on sliding panels and belonging to the domain of medium scale movable components architecture. Roof made for the Landschaftspark Duisburg-Nord by Planinghaus Architekten and Schlaich Bergermann und Partner (Images source: www.planinghaus.de); roof built for a swimming pool in Bologna (Italy), designed by Massimo Majowiecki (images courtesy of Massimo Majowiecki).

Roofs of swimming pools offer also numerous large-scale examples and the scale of the movable components is even larger in the well-studied area of movable roofs for stadiums and sport arenas. Among the most famous, the roof for the Olympic Stadium in Montréal (Canada), designed by Roger Taillibert Architect and Schlaich Bergermann und Partner. The roof consists of an elliptical deployable Kevlar-membrane suspended from a tower and opening all in once to cover an approximately 200x140 meters area. The movement is in this case based on the deformability of the material and happens by following a central scheme. An example of rigid movable large scale component is instead offered by the roof of the well-known Roger Centre in Toronto, Canada, also known as Skydome; the roof is decomposed in only four large scale moving elements, two of which slide by overlapping over a static one and the fourth slide and rotate by fitting underneath them. A parallel movement to lift up the entire central half of a 100 meters diameter roof is instead used in the roof for Bullfight Arena of the Centro Integrado de Vista Alegre in Madrid, designed by the architect Jaime Pérez (Ayuntamiento de Madrid) and Schlaich Bergermann und Partner.

§ 3.3.1.7 Conclusive summary of reconfigurable architecture

In this section 3.3.1, six groups of reconfigurable architecture have been identified based on performance requirements. In this way, self-erecting, reversible, disposable, incremental, mobile and form active architecture have been defined according to the goal of adaptivity. Moreover, three sub-domains of mobile architecture have been defined based on the state of the building during its transport, which are movable, rapidly assembled and deployable/foldable units. Finally, an incremental number of sub-domains of form-active architecture have been defined according to two criteria. Firstly, based on the aim of the movement, the sub-domains of emotional, functional, building physics and structural architectures (and possibly others) have been defined within form-active architecture. Secondly, based on based on the extensiveness of the shape changes compared to the scale of the building, the sub-domains of kinetically controlled static architecture, deformable architecture and movable (small, medium, large) components architecture have been defined within form-active architecture.

In conclusion of the discussion regarding this categorization, a summary of the sub-domains is illustrated in figure 13.

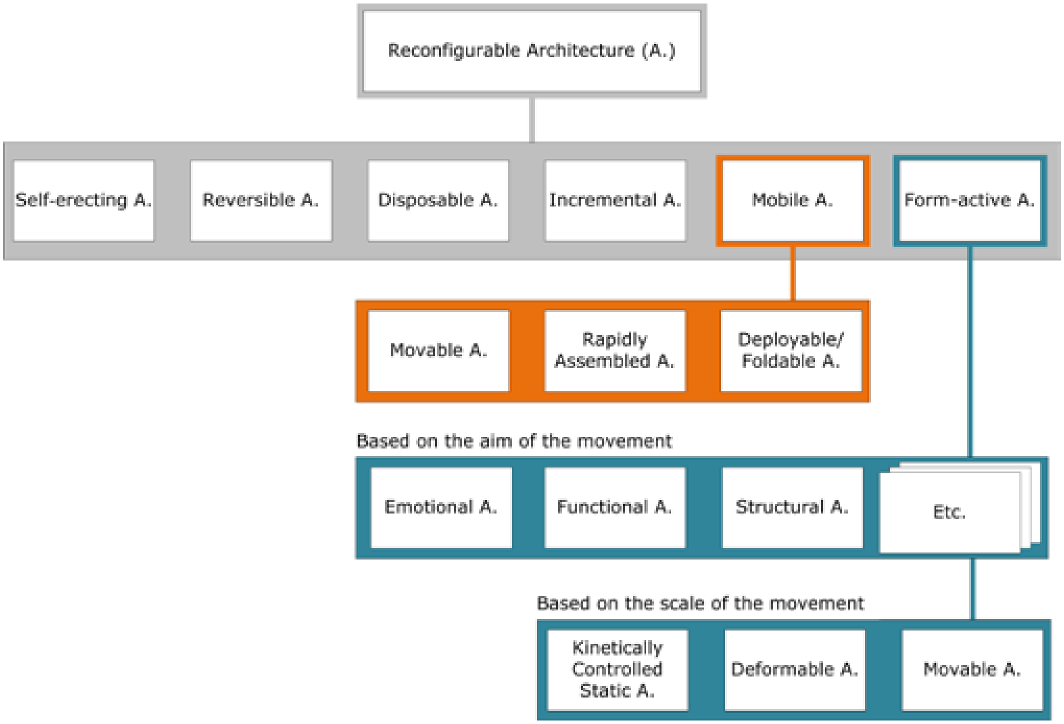

Figure 13
The subdomains of reconfigurable architecture.

When approaching the topic of adaptivity, the following chapters of this thesis will regard mostly some specific sub-domains of reconfigurable architecture. These are especially the sub-domains of deformable architecture and, even more, movable (small, medium, large) components architecture within the domain of form-active architecture.

§ 3.4 Adaptive structures

In the previous sections, various classifications of adaptive architecture have been discussed. This section presents the topic of adaptive structures. Two are the reasons for which this topic is discussed here. First of all, a number of sub-domains of adaptive architecture implies the use of adjustable components, for the whole building or for part of it. Additionally, in the following chapters the topic of architectural adaptivity is approached with emphasis on movable components architecture and on deformable architecture, for which the adjustability of components is crucial. This emphasis on adjustable components leads into the domain of adaptive structures (not limited to load-bearing structural systems of buildings). Considering the relevance of the topic, a short discussion regarding adaptivity is proposed in this section 3.4, according to engineering points of view.

§ 3.4.1 Definition

Adaptivity in structures is defined here as the ability of a structure to be responsive to a changing context. In this thesis, all the structures having this ability are called *adaptive*.

The goals of adaptivity in structures can be grouped into two main domains: the one of load-bearing requirements and the one of non-load-bearing requirements. This is explained as following. According to Miura, a structure can be defined as *a device which determines the relative position of numbers of points in space*, where the reciprocal position of the points depends on the geometry of the structure and on its dynamics, meant as system of forces (Miura, 1989). By recalling the definition provided in section 2.2.1, performance is the manner in which or the efficiency with which something reacts or fulfils its intended purpose (Stein, 1983). By referring to this definition, the performance of a structure is related to its ability (manner or efficiency) in determining the position of points in space. The position of the points includes the overall geometry (by referring to the reciprocal position of the points of the structure) and the overall position (by referring to their position in the space). For simplicity, these two aspects are referred here as configuration and position. Having clarified these aspects, it is understandable that what configuration and what position are suitable depend on the requirements. The requirements may be related to the load-bearing capacity of the structure; or might be related to other aspects. In other words, a structure might be expected to adjust in order to better react to wind, earthquakes vibrations, collisions, fire, water pressure, etc., with the ultimate goal of remaining stable. In this case, the goal of adaptivity is related to load-bearing requirements. This case leads to the search of structures flexible in changing properties connected to their carrying capacities. In architecture, very classical examples are adaptive structures for earthquakes and the ones for dynamic wind loads. Moreover, a structure might be expected to adjust in order to achieve configurations or positions that better fulfil other requirements, such as architectural requirements related to functions. In this case, the goal of adaptivity is related to non-load-bearing requirements. This case involves the geometric configuration of the structures in relation to their functions other than purely load bearing. This is the case, for example, of retractable roofs; outside the architectural field, this is the case of deployable antennas for outer-space applications. In conclusion, it can be said that adaptive structures allow meeting requirements coming from the field of application; and/or meeting structural (load-bearing) requirements under different environmental conditions. In architectural fields, adaptive structures allow meeting structural requirements under different environmental conditions and/or architectural requirements necessitating variable configurations or positions.

Both these aspects are recognized as drivers for structural adaptivity since the origin of adaptivity in engineering structures. The formal origin of adaptivity in engineering structures is located around the eighties in the twentieth century (Miura, 1989); while the majority of the previous engineering structures have been mainly statically standing still or moving as a vehicle with configurations substantially unchanged during the movement (Miura and Furuya, 1988; Miura, 1989). Miura (1989) identified two main factors as driving reasons of substantial research in the field of adaptive structures. Both come from aerospace engineering. One is the changing payload requirements of spacecraft and space stations during their lifetime. The other one is the highly precise geometric control needed for the configuration of space structures.

§ 3.4.1.1 Definitions in literature

Due to the relevance and the recurrence of this term in engineering literature, it is important to give attention to various definitions of adaptive structures. An overview is provided here and different authors are referenced. The overview is not expected to be exhaustive; but it is meant to provide a meaningful description of the concept in its various acceptations. In the vast literature focusing on adaptive structures since the last three decades, Miura and Wada have been assumed here as main references due to the relevance of their pionieristic studies.

The first article explicitly mentioning and defining the concept of adaptive structures is most probably the work presented by Miura and Furuya at the 36th IAF Congress in 1985, 'Adaptive Structure Concept for Future Space Applications' (Miura and Furuya, 1988). In it, adaptive structures are defined as structures that "can purposefully vary their geometric configuration as well as their physical properties" (Miura and Furuya, 1988; Miura, 1992). This ability is called by Miura intelligence of the structure; and a structure that has intelligence and active mechanism can be called either intelligent or adaptive structure (Miura, 1989). This distinction is further explained by the author when pointing out as an adaptive structure is expected to have both actuation and intelligence (Miura, 1990).

The second relevant definition that is recalled here has been given by Wada. According to this author, "adaptive structures are defined as those which possess actuators that allow the alteration of system states and characteristics in a controlled manner" (Wada et al., 1990). The author also points out how his definition and the one given by Miura and Furuya are essentially the same; his work presents the group of adaptive structures as part of a larger categorization that will be described in the next section 3.4.1.2.

Among the other definitions that have been provided by different authors during these last three decades, a few of them are recalled. According to a more recent definition provided by Clark, Saunders and Gibbs *an adaptive structure is defined to be a structure configured with distributed actuators and sensors and directed by a controller capable of modifying the dynamic response of the structure in the presence of time-varying environmental and operational conditions* (Clark et al., 2001). In their book 'Adaptive Structures, engineering applications', Wagg, Bond, Weaver and Friswell define an adaptive structure as any structure that can alter either its geometric form or material properties (Wagg et al., 2007).

One last note regards the use of references from biological life, which are shared across the domains variously defined by the different authors. Significantly, Miura (1990) commented as the majority of books possible to be found concerning adaptation were related to biological lives; especially regarding changes in physical/chemical properties that biological life can achieve in order to inhabit the environment for optimal survival (Miura and Furuya, 1988; Miura, 1992). A large number of specific studies have also related engineering domains of adaptive structures to biological models (Vincent, 2000; Vincent, 2001; Vincent and Mann, 2002; Hachem et al., 2004; Hachem and Hanaor 2005a; Hachem and Hanaor, 2005b; Hachem et al., 2005).

§ 3.4.2 Classification

The concept of adaptive structures is not exhaustive for the overall nomenclature of the topic, which is much larger and the entire nomenclature used to be, and still partially is, undefined. Significantly, in 1990 Miura points out as there was a whole bunch of candidate names covering overlapping and not fully distinguished concepts; these names include intelligent structures, intelligent and material systems, smart structures, controllable structures, active structures and others (Miura, 1990).

Over the entire topic, the concept of adaptive structures is here considered the key concept used in literature when dealing with adaptivity in structures. As a consequence, a number of sub-domains can be classified. Two classifications are proposed. Both of them aim at fitting architectural applications, in relation to the concept of adaptive architecture.

§ 3.4.2.1 Interface-based classification

A parallel with adaptive architecture is proposed for the first classification, which is based on the way in which structures interface the context. With analogy to adaptive architecture, the level of automation for detection, elaboration and activation is used as a direct criterion for categorizing the domain. Also in the case of the structures, detection, elaboration and activation refer to the ways changes in the context are detected, information is processed and consequent changes in the structures are actuated. There is no reason to present here again the overall classification, since it coincides with what discussed in section 3.2.1, just applied to structures instead of to whole buildings. Only two specifications are opportune. First of all, the classification is valid both for structures with active detection, elaboration and activation as separated function and for structures with active detection, elaboration and activation as part of the structural functionality. Secondly, despite this classification is possible for both cases, it is not recommended for the case of structural functionality; since it can create confusion with the well-establish vocabulary in contemporary structural engineering. According to this latter, passive systems are systems activated by the structural motion, with no need of applying external force or energy; active systems requires external activation in order to respond (Datta, 2003). This definition is preferred in all the cases in which adaptivity targets load-bearing requirements.

§ 3.4.2.2 Reaction-based classification

In the previous section 3.4.2.1, a categorization has been described, concerning the ways structures interface the context. A second subdivision is given here following, based on the way in which structures can adjust to achieve the desired changes.

As already pointed out for adaptive architecture, also in the case of adaptive structures such changes are the adjustments activated after the detection and the elaboration; and the nature of these adjustments is therefore directly related to the interface process. According to the approach proposed for adaptive architecture, two main possible ways of adaptation are identified. In the first one, adjustments are based on the changes in geometry of the structure, with geometric reconfigurations of the structure. In the second one, adjustments are based on changes in the properties of the materials composing the structure, without implying geometric variations of the structure. Similarly to adaptive architecture, these sub-domains are called respectively *reconfigurable structures* and *statically dynamic structures*.

Statically dynamic structures are, for example, those which use smart materials to solve vibration problems or respond to earthquakes, like in the case of fibre reinforced concrete structures with shape memory properties, capable of adjusting their response to different levels of overload. Reconfigurable structures are exemplified by mentioning the well-known domain of deployable structures, which have the ability to varying their geometric configuration from a compact to an expanded configuration.

Within the sub-domain of reconfigurable structures, the ability of assuming multiple configurations can be reached by reciprocal movement of rigid bodies or by deformations of bodies. The first case includes for example bars and plates; the second case includes for example cables and membranes. One additional sub-group can be located in between these two cases, as explained here following.

To understand the case of rigid bodies, it is useful to refer to the basic definitions of structures and mechanisms. Elements whose deformations are negligible, can be represented as rigid bodies. Rigid bodies can be reciprocally connected at joints by constraints that limit the freedom of the system. In this respect, a mechanism is defined as a system of rigid bodies mutually interconnected that can reciprocally move congruently with the constraints that limit their reciprocal movement. While a structure is defined as a system of rigid bodies mutually interconnected that transmit external actions to the surrounding bodies. This means that under the action of external loads, a mechanism moves. Differently, relative rigid-body motion is not allowed for a structure and the structure reacts to the loads by transferring them without movement (there are of course deformations, but they are negligible from a static point of view). Reconfigurable structures need to allow movement, but also to be stable at selected configurations. The transition between behaving like a mechanisms (in order to allow reconfiguration) and behaving like a structure (in order to achieve stability) can be reached by adding and removing constraints or by maintaining the actuation force holding the structure in the desired configuration.

To the case of rigid-bodies, the concept of a compliant mechanism has to be added. While traditional rigid-body mechanisms consist of rigid links connected at movable joints, *compliant mechanisms gain at least some of their mobility from the deflection of flexible members rather than from movable joints only* (Santer, 2006). The behaviour of sliding or rotational elements is replicated through the flexure of elastic components known as compliant (or living) hinges. In terms of structures, this leads to the concept of multi-stable structures. They are structures that possess more than one stable configuration. It means that they are in a stable equilibrium, without the need for any external forces, in at least two different configurations. The configurations that the structure assumes during the transition between two stable configurations are un-stable. *The transition between states during reconfiguration must be enabled by higher than normal loads either applied externally or reacted internally by integrated actuators* (Seffen, 2004). The possibility to switch back and forth from one to another stable configuration without any damage is a required property. Therefore these structures can cycle between different stable configurations an indefinite number of times, without structural failure. A relevant number of advantages and possible applications of multistable structures, such as consumer products, deployable structures, robotics and micro-structural systems, have been pointed out by Santer (2006) and Ye (2007).

Each of the mentioned sub-groups can be further subdivided. A systematic classification of these sub-domains is out of the scope of this dissertation. However, as an example, some sub-categories are named within the case of rigid bodies. Among the structures based on plates, the case of foldable plates is recalled. Among the structures based on bars, the case of pantographic structures is recalled. A deeper discussion on pantographic structures is presented in appendix AI.

§ 3.4.2.3 Classifications in literature

In addition to the classifications proposed above, other classifications are also acknowledged here. Particularly, the ones presented by Miura and Wada, which locate and sub-classify the domain of adaptive structures from a strict engineering point of view. Although originally referred to structures for space applications, these categorizations are a relevant guideline for understanding the domain of adaptive structures also when applied to architecture.

In order to locate and classify adaptive structures, Miura points out two key aspects. The first one is the ability of the structure to change. By mentioning the examples offered by him, this refers to variable geometry trusses able to change their geometric configuration; or to active dumping beams able of suppressing vibrations using piezo-electric effects; or to aircrafts able to repair their damaged parts. This capacity of changing is called by the author ‘actuation’. The second one is the ability of the structure to measure the actuation, store and process the data and give new orders to actuators to meet new requirements; in other words, an information network which operates a system of sensors, processors and actuators. This is called by the author ‘intelligence’ of the structure. Miura stretches the importance of a terminology explicitly based on these key aspects and proposes a categorization based on the sharing of the domains of structures, actuation and intelligence. Specifically, he calls intelligent (or sensitive) structures the intersection between structures and intelligence; active (or deployable) structures the intersection between structure and actuation; control systems the intersection between actuation and intelligence; finally, the intersection among the three domains corresponds to the domain of adaptive structures (Miura, 1990). Figure 14 illustrates the overview proposed by Miura.

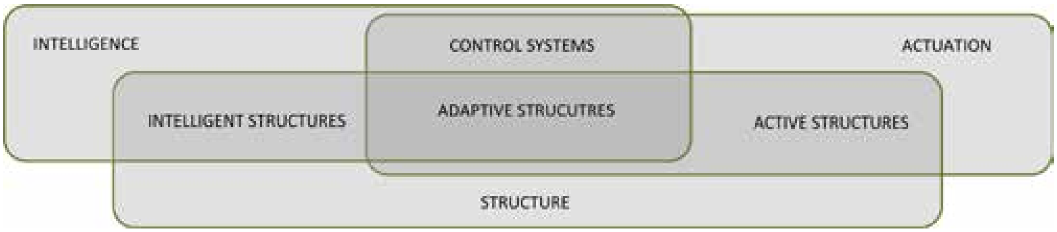

Figure 14
Overview of domains proposed by Miura.

According to the overview proposed by Wada, the broad context of structural control through structures able to adjust can be divided in two basic categories, sensory structures and adaptive structures. These intersect each other on the shared group of controlled structures. Sensory structures possess sensors that enable the determination or monitoring of system states or characteristics. Adaptive structures possess actuators that enable the alteration of system states or characteristics in a controlled manner. The subset of adaptive structures belonging also to sensory structures is called controlled structure. In other words, these are structures that possess both sensors and actuators, which feedback in order to control the system state or characteristics. Within this latter group, Wada identifies further subgroups. Specifically, when the sensors and/or actuators are highly integrated into the structure and have structural functionality in addition to control functionality, the structure is called an active structure. Active structures are therefore the subset of controlled structures where sensors and actuators are integrated with the structure to such a degree that the distinction between control functionality and structural functionality is blurred. Additionally, if these highly integrated sensing and control elements have electronic components involved in signal conditioning, computing and power regulation, then the structure is called an intelligent structure; intelligent structures are therefore the subset of active structures where the control system is highly distributed and high distribution concerns not only sensing and control elements, but also the electronics components involved in signal conditioning, computing and power regulation. Figure 15 illustrates the overview proposed by Wada (Wada et al., 1990). This classification has been further elaborated by Wada with other authors (Das et al., 1991).

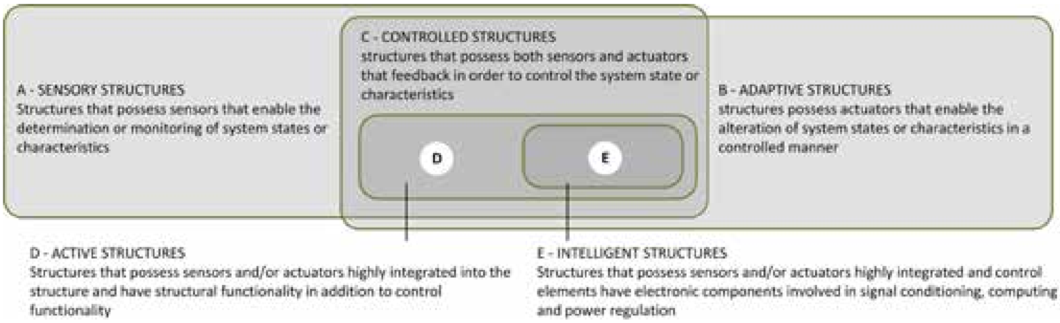

Figure 15
Overview of domains proposed by Wada.

§ 3.4.3 Conclusive summary of adaptive structures

In this section 3.4, the topic of adaptive structures has been briefly introduced. Adaptive structures have been defined; and a number of definitions from literature review has been also mentioned. The domain of adaptive structures has been subdivided in sub-domains, especially by assuming an architectural point of view. An interface-based classification and a reaction-based classification have been introduced; and a number of engineering classifications have been mentioned from literature review. By doing so, an overview of the domain has been provided, to which this thesis will refer in the following chapters, when dealing with adaptive structures.

§ 3.5 Conclusions

In this chapter, the domains of adaptive architecture and of adaptive structures have been presented. The domain of adaptive architecture has been described according to an interface-based classification and to a reaction-based classification. The first one considers the way in which architecture interfaces the changing context; it involves the ways in which changes in the context are detected, information are processed and consequent changes in architecture are actuated. The second one considers the way in which architecture can adjust to achieve the desired changes; it involves two main natures of adjustments, one based on changes in geometry (reconfigurable architecture), the other one regards changes in material properties, without implying geometric variations (statically dynamic architecture). Focusing on reconfigurable architecture, a performance-based classification has been proposed, which includes six sub-domains. Each sub-domain has been described and examples have been provided. Finally, the domain of adaptive structures has been defined and described based on literature and according to an interface-based classification and to a reaction-based classification. In this overall discussion, the main contribution of this research work has consisted of organizing and mapping the domains. This chapter has aimed at providing guiding references and terminology for the thesis. Both the domains of adaptive architecture and adaptive structures and their related sub-domains will be used as reference in the following chapters; especially in chapters 6 and 7.

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4 Performance of large roofs

In this chapter, the topic of large roofs is approached, with a specific focus on halls, atria, shopping galleries, public squares, leisure facilities, and other covered spaces that are integrated into the built environment and the urban fabric. While the concepts illustrated in the previous chapters are identifiable within the entire range of architectural design, the specific field of large roofs is chosen as application field for the work presented in this thesis. Focus is given to the design of the envelopes covering the areas, by emphasizing the importance of the early integration of performance evaluations in the design process, with the goal of developing performative skins. The role of performative skins is highlighted for the mediation between the conditions desired by the users of the spaces and those present in the surrounding environment. Beside the traditional attention on structural performance, their capacity of controlling and filtering environmental factors is emphasized particularly in the context of strategies for passively achieving climatic comfort.

The domain of large roofs is introduced in section 4.1, while, in section 4.2 the expected performances are discussed, with specific reference to structural and climatic performances. Passive strategies for climatic comfort in large indoor and semi-outdoor spaces are briefly introduced in section 4.3, in which an overview of the factors which are affecting the climatic comfort is also provided. Finally, integrating considerations for structural and climatic comfort in the early phase of the design is discussed.

§ 4.1 Large roofs

Large roofs are structures covering wide areas (such as urban public spaces, squares, entrance halls, courtyards and galleries), which can be completely or partially enclosed. Historical cities bear testimony to the traditional importance of spaces covered by large roofs in urban areas. The Umberto I public covered gallery in Naples is just one of many examples of Mediterranean shaded squares, streets, courtyards, and historic commercial galleries. Contemporary cities increasingly integrate large roofs in the urban fabric. Various rationales and motivations for the creation of large roofs exist. One is the increased demand for representative structures that mark the built environment, such as in the case of representative halls and atria. Another is the need for outdoor spaces that can be used independently of the weather conditions, such as in the case of covered squares, stations and shopping centres. It therefore has become more common for architects and engineers to engage in the design of large roof structures, both for indoor and semi outdoor spaces. Among the many possible references, the roof of the Palazzo Lombardia (Milan) designed by Pei Cobb Freed & Partners, and the roof of the Cour Visconti at the Louvre (Paris) designed by Mario Bellini Architects can be mentioned. These are illustrated in figure 16.

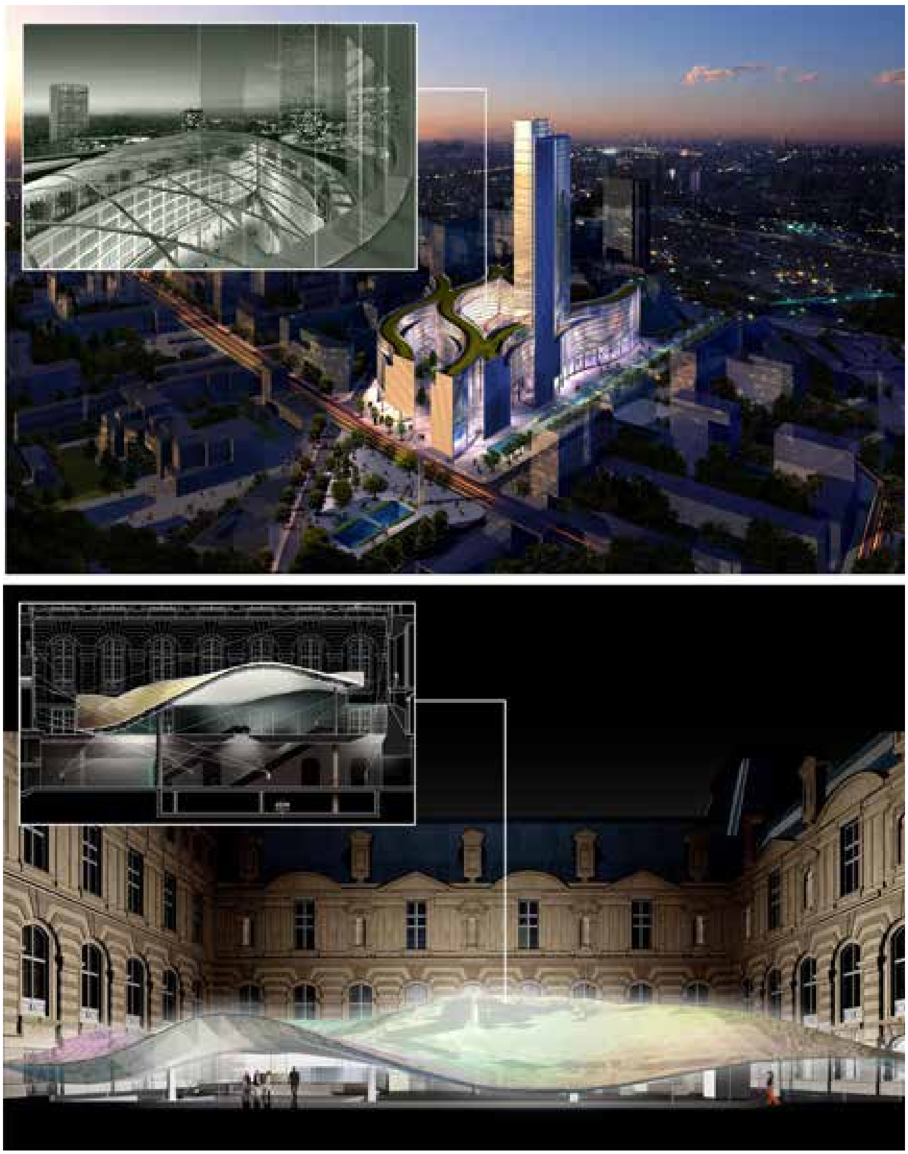

Figure 16

Examples of large roofs in urban areas. Top: the roof of the Palazzo Lombardia (Milan). (Images published with permission of Pei Cobb Freed & Partners, copyright holder). Bottom: the roof of the Cour Visconti, Louvre, Paris. (Images published with permission of Mario Bellini Architects, copyright holder).

Considering their importance, large roofs are chosen as field of application for the performance oriented design studies of this research.

This section frames the relevance of this application field and the performances considered during the process. Specifically, among the many and with an approach transversal to different disciplines, structural performance and performance criteria related to climatic comfort are taken here as the main focus, with specific reference to the passive use of on-site energy resources.

§ 4.1.1 Indoor and semi-outdoor covered spaces

Large roofs can cover or enclose areas that are isolated from the outdoor, commonly defined as indoor areas. These are traditionally well known as spaces whose conditions can be controlled because they are entirely separated from the outdoor conditions. The case of large roofs covering or enclosing indoor areas can be exemplified by the Golden Terraces complex in Warsaw (Anderson et al., 2008); the Lac Mirabel in Montreal (Goldsmith, 2008); the two buildings of the Gardens by the Bay in Singapore (Davey et al., 2010), illustrated in figure 17; among many others.

Figure 17
Examples of large roofs enclosing indoor spaces. The conservatory complex at Gardens by the Bay in Singapore includes two large glasshouses: the Flower Dome and the Could Forest; designed by Wilkinson Eyre Architects.

In addition to the well-known distinction between outdoor and indoor spaces, the topic of large roofs draws attention also to the case of areas commonly recognized as semi-outdoor (or semi-indoor) spaces. These are areas whose conditions are between indoor and outdoor; more specifically, according to Spagnolo and de Dear (2003), semi-outdoor spaces can be defined as locations that, "while still being exposed to the outdoor environment in most respects, include man-made structures that moderate the effects of the outdoor conditions." Examples include roofs acting as radiation shields or walls acting as vertical windbreaks.

Both historical and modern cities bear testimony to the traditional importance of semi outdoor spaces in the built environment. These include examples from vernacular architecture of a large majority of cultures, such as partially enclosed courtyards or shaded streets and squares; from historical and traditional constructions, such as the mentioned public commercial galleries in Italy (among the most famous, also the Vittorio Emanuele II in Milan besides the Umberto I) or the Mediterranean porticos and courts (like the Court of the Lions in the Alhambra). In contemporary cities, a specific group of semi-outdoor spaces can be identified as covered by large roofs or partially open envelopes, leaving a relevant direct connection with the outdoor environment. Museums, cultural centres, university campuses, shopping and leisure areas, hotels and resorts, are just a few examples of built environments where covered semi-outdoor spaces are commonly integrated. Well known examples can be named, such as the recently built roof for the Fair in Milan in Italy (figure 18) designed by Fuksas (Sanchez-Alvarez, 2005); the Kurayoshi Park Square in Kurayoshi in Japan; the roofed forum of the Munich Airport Centre, in Germany, designed by Helmut Jahn (figure 18).

Figure 18
Examples of large roofs for semi-outdoor spaces. Left: roofed forum of the Munich Airport Centre, by Helmut Jahn. Right: roof of the Fair in Milan, by Massimiliano Fuksas.

§ 4.2 Performances of large roofs

The design of large roofs deals with their overall shapes, the materialization and related material properties (structural, thermal, acoustic, visual, etc.), the rationalization and modularization of the geometry (which depends on the level of geometric complexity, and includes the relationships between cladding panels and structure, both in terms of reciprocal morphology and technical systems and components), and other aspects closely relating geometry and performance. Only some of these aspects are commonly tackled in the conceptual design phase. Mostly, in the early phase all aspects are addressed based on a limited number of key performances, conventionally dominated by economics, aesthetics and structure. Focusing on engineering performances, this research has given attention to structural aspects, which are discussed in section 4.2.1. Besides the well-established structural investigations, the theme of climatic control is being increasingly considered. It is introduced here in relation to the topic of on-site energy resources, which are discussed in section 4.2.2.

§ 4.2.1 Structural performance

In chapter 3, structural performance has been defined as the capacity (manner or efficiency) to determine the position of points in space; it confronts the positions that are expected for the points; the factors that can affect these positions, by contributing to or opposing them; and the structural properties, such as morphology, dimensions, materials and others. When focusing on large roofs, structural performance is a well-covered topic in the literature and in realized projects, with regards to a large variety of load challenges, such as snow and wind. Some of the challenges are common to different structural systems, other are more specifically dependent on the structural typology.
In each case, a large number of requirements can be expected to be satisfied by the structural system, which do not only include load bearing capacity and safety, but also other interrelated aspects. With this respect, Bollinger et al. (2008) intend the structure as an integral part of architecture, in which the overall performance balances a complex network of multifaceted, interrelated requirements; this makes each structural design being somehow unique (Billington, 1983). Among the many requirements, some are here considered based on their common occurrence. Particularly, besides being often wanted due to aesthetic intentions, limiting the number of supports is commonly desirable since usually providing advantages for the use of the covered spaces. As a consequence, a relevant sub-domain of large roofs belongs to the challenging group of wide span structures, often connected to the field of light weight structures.

§ 4.2.1.1 Wide span lightweight structures

The field of wide span roofs and enclosures is a domain widely explored for a range of structural challenges (Barnes and Dickson, 2000).

On one hand, its historical trend in design and construction is the minimization of the dead weight of the structure. With this respect, a substantial reduction of the ratio between dead and live loads has been allowed by the recent development of special high-strength materials, in combination with structural systems where bending moments are minimized (Majowiecki, 2005b). An overview can be found in Bradshaw (2002) and a review of the latest developments in long span structures subject only to tension can be found in Knudson (1991). Among the most commonly used, some of these structural systems are space structures (Kawaguchi, 1991), cable structures (including suspended roofs, cable trusses and others), hybrid systems (including for example tensegrity and beam cable systems), and membrane structures (including tensile and pneumatic membranes). A special class of structural systems for large roofs is also traditionally identified for the domain of convertible roofs (Majowiecki, 2005b; Ishii, 2000).

On the other hand, the reduction of dead weight has to deal with considerable challenges, increased by the scale effect of wide span structures. These can be exemplified by referring to the snow distribution and accumulation (i.e., Lazzari et al., 2008); the wind pressure distribution and the cross-correlated wind actions (i.e., Lazzari et al., 2008; Xie et al., 2000; Kawai et al., 1999); structural instability, non-linear and dynamic behaviors (i.e., Kasperski, M., 1992; Lazzari et al., 2008; Bradshaw et al., 2002); and risk of progressive collapses. All these and other challenges (Majowiecki, 1990; Majowiecki, 2005a; Kawaguchi, 1991) are further increased in the case of large movable elements (Ishii, 2000).

Among the many structural typologies, in this research focus is given specifically to the structural behaviour of discontinuous systems, such as plate and bar systems, with key attention to space frames. The reticulated roof for the new Milan Fair in Italy (Sanchez-Alvarez, 2005) and the roof of the inner courtyard of the British Museum in London (Williams, 2001) are just two of the many recent examples of discontinuous systems, through which the importance of the lightweight structure is made evident.

§ 4.2.2 Climatic comfort

Climatic comfort refers to both thermal and daylight conditions. Lately, both aspects have received increasing attention in the field of large roofs. To mention two relevant examples, the climatic comfort of large spaces has been investigated with regard to installations (Cullen, 2000) and relations with environmental factors (Fordham, 2000; Goldsmith, 2008). The climatic comfort under large roofs is actually a crucial aspect that needs to be taken into account in the design process, at the various scales of the design. This regards both new developments and the chance to improve the conditions of existent building and urban settlements. With this respect, large roofs can be integrated in the built tissue with relevant effects on the microclimate. Moreover, the importance of climatic comfort in the case of large roofs increases even more when considering that climatic control does not apply only to the case of indoor areas, but also to semi-outdoor spaces. While great attention has been given to climatic comfort of indoor spaces, less scientific attention as well as design consideration has been given to climatic comfort of outdoor and semi-outdoor areas in urban environments. Nevertheless, the importance of climate comfort in outdoor and semi-outdoor urban spaces can be argued with respect to different criteria. Among the many possible criteria, it should be noticed that the climatic comfort plays an important role in the appeal of the spaces for the users. This happens independently from the level of enclosure of the spaces. Focusing for example on thermal comfort, specific studies show the significant influence of comfort on the utilization rate of outdoor environments and in the behaviour of the users (Nikolopoulou et al., 2001;

Nikolopoulou and Lykoudis, 2006). Such influence of thermal comfort on the number of people using an outdoor public area emphasizes the need to confront thermal comfort during the design of such spaces. It should be however noticed that, even though it does not diminish the importance of climate comfort, the level of enclosure affects the criteria for the performance evaluations. More specifically, the expected level of comfort is different when comparing indoor, semi-outdoor and outdoor areas. By focusing again on thermal comfort, a number of studies show, for example, that occupants of semi-outdoor and outdoor environments could tolerate a wider temperature range than the one expected for indoor thermal comfort (Spagnolo and de Dear, 2003; Givoni et al., 2003; Nakano and Tanabe, 2004; Nikolopoulou et al., 2007). From the field surveys conducted by Spagnolo and de Dear (2003) in locations such as railway stations, bus shelters, ferry terminals and parks, it emerges that the standard of acceptable thermal conditions relevantly exceeds the one in indoor spaces; similarly, the studies conducted by Nakano and Tanabe (2004) demonstrated that occupants of semi-outdoor environments tend to tolerate a two to three times wider temperature range than what is commonly determined based on standard thermal comfort models. A possible explanation may also be based on the psychological predisposition to more easily accept discomfort when standing in spaces not offering the controlled environment of the indoor areas (Hoppe, 2002).

A last important consideration concerns the way climate comfort can be achieved. This recalls the current increased emphasis on energy-related aspects, which confronts the designer with the additional challenge of reducing energy consumption and even investigating the potential for energy production. Particularly, attention is given to the use of on-site renewable energy resources, which contributes to limiting the dependence on traditional fossil fuel resources and imported energies. Aiming at that, the design of large roof structures enclosing, covering or partially sheltering the underneath spaces can consider both active and passive systems. When focusing on active technologies, large roofs can offer large surfaces to be used for the collection of solar energy to be converted and used in the covered spaces or in adjacent buildings and indoor areas. When focusing on passive systems, large roofs are expected to mitigate the climate factors for the spaces underneath, both for thermal comfort and daylight, allowing the artificial energy requirements for achieving a given state of comfort to be diminished. An introduction to both active and passive systems is provided below.

§ 4.2.2.1 Active and passive systems for on-site energy resources

This section aims at briefly introducing the potentials of large roofs with respect to both active and passive systems for the use of on-site renewable energy resources. In general, while active strategies address the production of energy that can be devoted to different uses, passive strategies are usually meant for improving local conditions, such as the thermal comfort and daylight. When focusing on large roofs, they play a key role mostly in controlling the microclimate beneath the structures and/or in adjacent buildings. With this respect, active strategies aim at producing energy for supply, while passive strategies for improving daylight and thermal comfort have the potential to reduce energy consumption and cover the remaining energy need through the passive use of on-site renewable resources.

Concerning active technologies, opportunities are considered for example in relationship to large surfaces often exposed to the sun, depending on their geometry, orientation and surrounding elements. The integration of photovoltaic cells exemplifies the use of active technology for energy production, which is used in recent projects, such as the large roof of the so called Solar Stadium in Kaohsiung, Taiwan and the roof designed for the Masdar Headquarters by Adrian Smith, Gordon Gill and Robert Forest with their team (figures 19 and 20). Both cases provide a meaningful example of active energy-oriented use of large structures. In the first case, the energy produced from the panels is meant to supply the entire need of the stadium; in the second case the integration of photovoltaic solar collectors is meant to provide the energy necessary for the construction of the buildings underneath (Nader, 2009).

Figure 19

Diagrams of the roof of Masdar Headquarters. Top: Diagram of the overall system; Bottom: Integration of active systems, such as photovoltaic panels. (All images published with permission of Adrian Smith + Gordon Gill Architecture, copyright holder; Adrian Smith and Gordon Gill are the design architects of the project and author of the design).

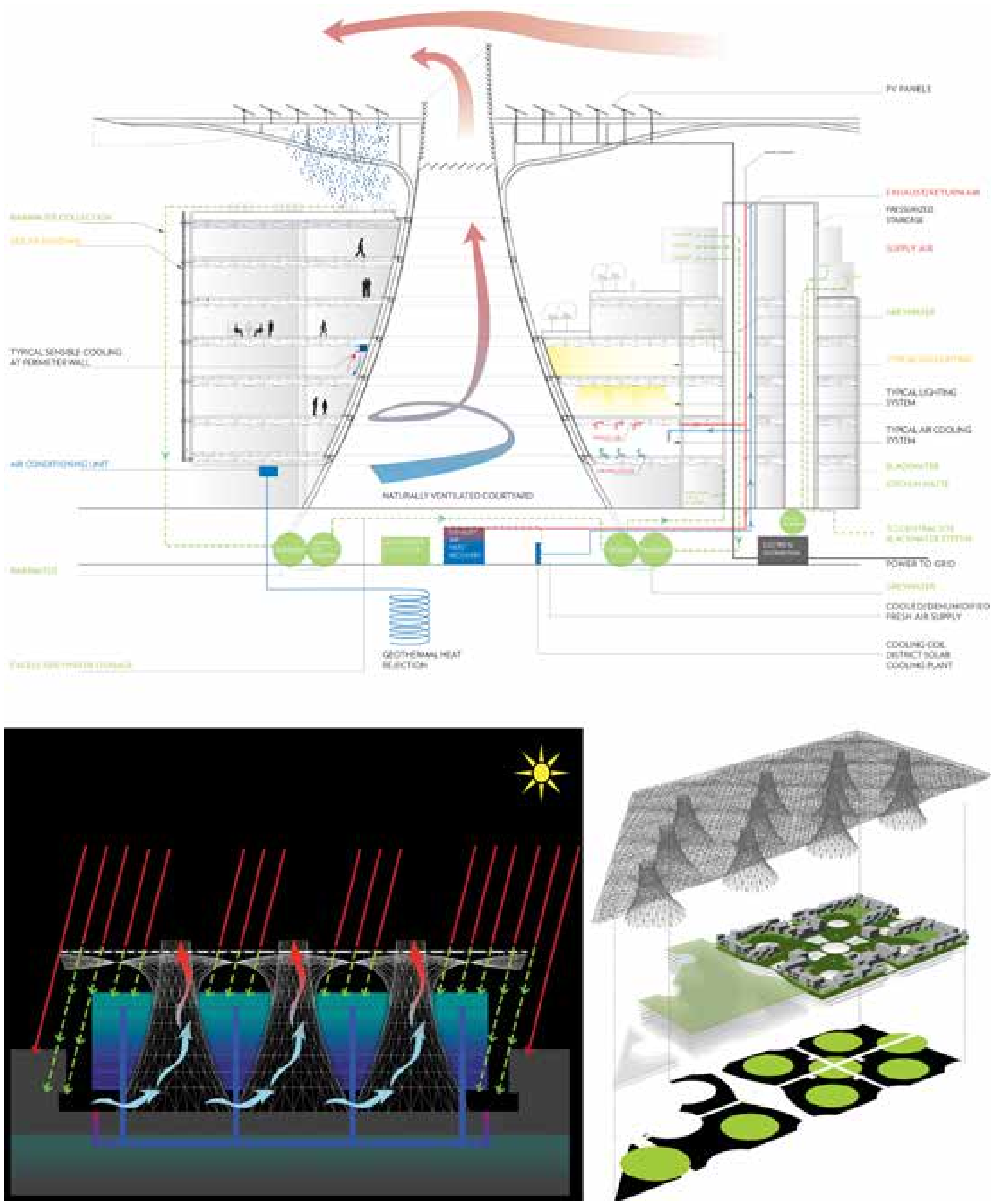

Figure 20

Diagrams of the roof of Masdar Headquarters. Top: Diagrams of the cones, with schemes of the natural ventilation system and installations; Bottom Left: Diagram of the natural ventilation and shading; Bottom Right: Integration of the modular roof with the underneath system of buildings. (All images published with permission of Adrian Smith + Gordon Gill Architecture, copyright holder; Adrian Smith and Gordon Gill are the design architects of the project and author of the design).

More broadly, the roof of the Masdar Headquarters offers a great example of integration between active and passive strategies. When looking at passive systems, large roofs play a key role in the interaction between the built system they are part of and the surrounding environment and climate factors. Even more than for active technologies, passive design requires emphasis on the concept of an entire system whose energy behaviour is based on interrelated aspects. This relevantly depends on a large number of aspects influencing the interaction between the built environment and climate factors. By integrating shading and ventilation for cooling, the design of the Masdar Headquarters offers a prime example of the consideration of such interacting aspects, the understanding of which is the needed starting point when aiming at performance oriented design. Other examples of such interaction can be found in a number of projects, among which the design of the Eden Project domes in Cornwall (Jones, 2000) and of the Esplanade Theatres in Singapore (Sanchez-Alvarez, 2002) exemplify design processes where great attention was given to climate comfort of the enclosed indoor spaces and energy related aspects, such as solar gain and ventilation for cooling. Also in the case of semi-outdoor areas great attention is currently being given to energy related aspects; the Cabot Circus in Bristol exemplifies a system designed with attention to natural ventilation, daylight and rainwater collection.

In this research, the main focus has been given to passive systems. The reason is the crucial role of such strategies within the larger picture of reducing energy use. Energy use reductions can be achieved by minimizing the energy demand, rationalizing the use, recovering heat and cold and using energy from the environment (Omer, 2008). While active systems are meant to use the energy from the environment to fulfil the need of energy consumption, passive systems allow a reduction of the need for artificial energy requirements, which is a priority task in view of rational use of energy.

The next section provides a more detailed introduction to each of the aspects of passive strategies that are considered in the context of this research for passively achieving or improving thermal and daylight comfort.

§ 4.3 Passive strategies for climate comfort

The common reliance on lighting and heating based on supplemental energy and air conditioning is responsible for the disconnection of the indoor comfort from the outdoor climate. In contrast to this, passive strategies for climate comfort are directly based on the relation between the outdoor climate and the spaces where thermal and lighting comfort are required. They aim at passive heating or cooling based on thermal comfort requirements by making use of the local climate conditions, and at using natural daylight to satisfy the lighting requirements. Despite the fact that passive strategies use the relation with the outdoor to improve both thermal and daylight comfort, it must also be noticed that these two are differently approached as well as sometime conflicting. The following sections introduce them both, through the selected aspects that are of relevance for this research. A more complete overview of strategies for both daylight and thermal passive comfort can be found in Brown and Dekay (2001), among others.

§ 4.3.1 Passive strategies for thermal comfort

As mentioned by Omar (2008), the energy required to achieve and maintain the thermal comfort of a space is high and accounts for as much as 60–70% of total energy use in non-industrial buildings. Detailed information concerning energy consumption due to heating and cooling can be found in Lombard et al. (2008). Adopting passive design strategies for thermal comfort means "using building design techniques to aid the natural heating or cooling of a building and so reduce or eliminate the need for heating or air conditioning" (Foster and Oreszczyn, 2001). As emphasized by Nicol and Roaf (2007), in spaces subjected to passive strategies for thermal comfort, the temperature is not decided by the building engineer, but by the physics of the form, by the amount and location of its mass, the size and orientation of the openings, the shading, the material properties of the envelope, and the effect of any passive technology. Focusing on indoor spaces, a well-designed system integrating such aspects would lead either to a zero-energy space, where no need for extra heating or cooling is needed to achieve a state of thermal comfort, or to a relevant "moderation both of the diurnal swings and seasonal changes in the indoor temperature" (Nicol and Roaf, 2007). An analogous principle can be applied for semi-outdoor spaces, where the enlarged comfort zone can also be considered.

By referring to thermal comfort, the following two sections emphasize some of the key factors affecting the comfort level which can be controlled by the physics of the buildings, and more specifically, of the large roofs.

§ 4.3.1.1 Thermal comfort and environmental factors

The most commonly known definition of thermal comfort is the one given by ASHRAE (1997), which defines thermal comfort as the "state of mind that expresses satisfaction with the surrounding environment". The possible formulations of thermal comfort are however numerous, and vary according to the taken approach. Peter Hoppe (2002) recalls three different approaches: psychological, thermophysiological and the one based on the heat balance of the human body. The ASHRAE definition refers to psychological aspects, and includes subjective factors. These play a key role in the thermal comfort of semi-outdoor and outdoor spaces, where psychological adaptation of users acts quite strongly (Nikolopouloua and Steemersb, 2003). Focusing on the heat balance of the human body a definition of comfort can be given based on energy exchanges. In this sense, comfort "is reached when heat flows to and from the human body are balanced and skin temperature and sweat rate are within a comfort range, which depends only on metabolism" (Hoppe 2002; Fanger 1972). Various heat-balance models of the human body allow taking into account the large variety of interrelated factors; among them the Physiological Equivalent Temperature[1] (PET) (Hoppe, 1999) and the predicted mean vote, PMV (Fanger, 1972).

Considering the latter approach, passive strategies aim at achieving or contributing to thermal comfort by influencing the heat balance equation of the human body based on the interrelations between the meteorological parameters and the built environment. Due to the faceted ensemble of environmental factors affecting the heat balance, this means that air temperature, air humidity, air velocity and mean radiant temperature are expected to be controlled by means of interaction with the elements of the design. In general, this can occur by using thermal mass, air circulation (exchange and speed),

1 Concerning the need of measuring these aspects and their final effect on the thermal comfort during the design process, a few considerations need to be mentioned regarding the use of the Physiological Equivalent Temperature (PET) as possible design support. Based on the complexity of modelling the thermal interactions occurring between an individual (with specific activity, psychology, physiology, clothing) and a certain environment (with specific air temperature, humidity, wind velocity, solar and infrared radiation and other thermal inputs), Bouyer et al. (2007) emphasize the current lack for a simple comfort index for the thermal conditions, providing designers, architects and town planners with an easily understandable system to evaluate the effects of their design choices (material, building shapes, colours, etc.) on thermal comfort. However, their work relies on the advantages of using PET. PET quantifies "all thermal inputs of a particular outdoor environment and summarize[s] them into a single ambient indoor temperature that would induce the same thermal environment as it is felt by a 'standard' person" (Bouyer et al., 2007). More precisely, citing Hoppe (1999), PET is defined as "the air temperature at which, in a typical indoor setting (without wind and solar radiation), the heat budget of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed. This way PET enables a layperson to compare the integral effects of complex thermal conditions outside with his or her own experience indoors".

seasonal and daily patterns of wind and solar radiation, and, in case of cooling, also adiabatic cooling (direct evaporative cooling and indirect evaporation cooling). The use of thermal mass is meant to reduce the fluctuations of temperatures by mean of thermal inertia. This can consist, for example, in cooling the mass at night to absorb the daytime heat gain and reduce the cooling load, or in storing the solar gain to reduce heating load. The use of seasonal and daily patterns includes the control of solar heat gain by maximizing it or minimizing it according to the needs, the control of air speed based on wind driven or on buoyancy driven air flow. Finally, adiabatic cooling consists of water evaporation with consequent reduction of the air temperature due to the absorption of energy for the evaporation process (Givoni, 1992; Santamouris and Asimakopoulos, 1996; Artmann at al., 2007). Studies have been conducted also for semi-outdoor and outdoor spaces. Cheng et al. (2010) focus on outdoor comfort in the tropical climate of Hong Kong by emphasizing that air temperature, wind speed and solar radiation intensity are the most influential factors in determining the thermal sensation.

Finally, a conclusive reflection should be provided concerning the overall strategies guiding the modulation of these aspects in order to reach the desired level of thermal comfort. Despite the fact that there is no general set of principles universally applicable, strategies for passive thermal comfort in various climates can be briefly defined, with awareness that a real generalization is mainly not possible. According to Haase and Amato (2009), generally four different climates can be identified for the purpose of building design: cold climates, with lack of heat; temperate climates, with seasonal variation between under heating and overheating; and hot-dry and warm-humid climates, with overheating problems, the last aggravated by humidity and a small diurnal temperature variation. Depending on the climate, passive strategies adopt different techniques, whose origin emerges usually from the vernacular architecture. As an example, in hot climates, emphasis is given to passive cooling by means of induced draft for ventilation and wind, water evaporation and use of thermal mass. Traditional wind towers, the use of water and vegetation and massive walls have ancient origins. Focusing on European temperate climates, passive strategies for thermal comfort are based on capturing maximum solar radiation during the winter days, on the internal preservation of the accumulated heat during the winter nights, and on avoiding over-heating during the summer days. This approach is frequently integrated with natural ventilation at night to cool the thermal mass of the building. With respect to solar energy, passive solar systems used in European moderate climates can be divided in three categories: passive solar systems with direct gain, indirect gain and isolated gain. In the case of direct gain passive solar systems, the solar radiation goes through the served spaces before being accumulated by the thermal mass. In the case of indirect gain passive solar systems, the thermal mass accumulates the solar thermal energy before it reaches the served spaces. In the case of isolated gain passive solar systems, the solar radiation is collected and accumulated in a separated space and only later distributed to the served spaces. The direct gain passive solar system is the most basic and most used system and makes the whole building behave like a solar collector. Concerning solar thermal energy, commonly, these systems are based on three phases of regulation of energy exchanges: collection, accumulation and distribution. The collection phase controls the solar thermal exchanges from the outside. The accumulation refers to the indoor thermal mass. The distribution controls the exchanges from the accumulator to the served spaces. In relation to the cyclic daily and seasonal climatic changes, different types of regulation systems are used to control these exchanges, among which systems that allow regulating the solar energy flows by natural ways.

§ 4.3.1.2 Performative skins for passive thermal comfort

When focusing on large roofs, the air temperature of the spaces underneath is largely affected by the solar exposure of the spaces, which directly depends on the geometry of the roof and its components as well as on the properties of its materials. The radiant temperature is affected by the temperature of the inner surface of the roof, being higher or lower than the air temperature of the spaces underneath; this depends largely on the absorption factor of the roof. The air velocity in the spaces underneath depends on the incoming wind as well as on other airflows, such as convective circulation; both are directly affected by the shape and openings of the roof, whereas the latter is also affected by temperature differences between zones. Large attention is required to the balance between ventilation for cooling and the risk of uncomfortable drafts. The air humidity is directly related to the moisture levels in the air and necessitates attention to balancing adiabatic cooling and uncomfortable levels of moisture, the former lowering the acceptable highest temperatures. Adiabatic cooling can be integrated based on water flowing or sprayed on the roof, which aims at reducing the temperature of the roof and, as a consequence, the long wave radiation from it, or on water located under the roof, in the form of ponds or fountains; moreover, the use of vegetation is also an option. Figure 21 illustrates these aspects. Both ancient and contemporary architecture, including instances from vernacular and traditional buildings, show how the interrelated effects of these aspects can be used for climate comfort purposes.
As an example, the presence of vegetation and water from the ancient irrigation techniques integrated in the Moorish courtyards can be mentioned as system through which evaporative cooling takes place. Contemporary examples are numerous, including the microclimate created underneath the well-known large domes of the Eden project in Cornwall, as well as the recent Dolce Vita Shopping Centre in Lisbon and, among atria where specific attention to climate issues was needed, the atrium spaces in the Wynn resorts in Las Vegas.

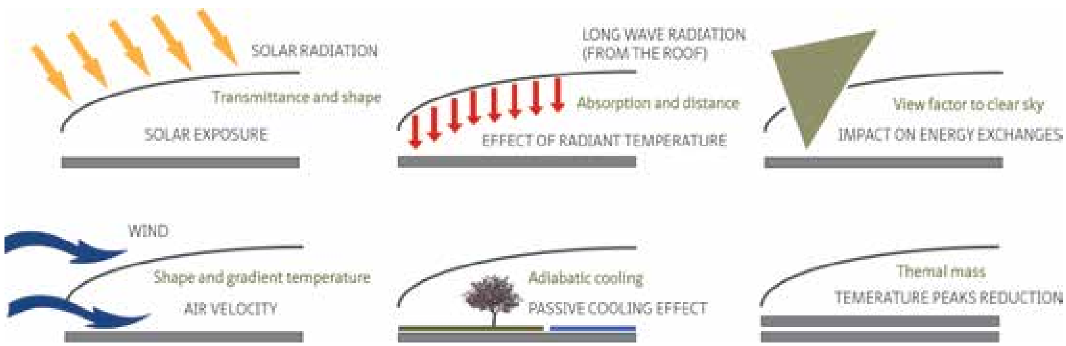

Figure 21

The control of the solar exposure of the covered spaces depends from the solar transmittance of the roof and form its shading shape; the effect of the radiant temperature on the covered spaces depends on the absorption factor of the roof and its distance from the spaces; the air velocity underneath the roof depends on the way the roof influences the airflow (including wind) and the gradient temperatures; the reduction of fluctuations in temperatures can also be controlled by integrating thermal mass and adiabatic cooling in the system.

§ 4.3.2 Passive strategies for daylight control

Like heating and cooling, also artificial lighting is highly energy demanding and one of the major electricity consuming items in buildings (Lombard at al., 2008). Similar to the principle expressed for passive thermal comfort, passive strategies oriented to daylight aim at reducing the use of artificial lighting based on the physics of the form and the proper use of the reflectance to achieve suitable lighting conditions by means of daylight. With this respect, suitable lighting refers to daylight comfort, which is introduced below. However, the use of light needs to be recognized as strongly essential also to the design intentions, since light reveals form, space, texture and colours, which are key architectural considerations (Steemers, 1994). Aiming at passively lighting spaces, therefore, it is insufficient to consider daylight comfort only, instead, a broader spectrum of aspects concerning light and light effects need to be taken into account. Finally, using daylight as primary light source is widely recognized not only as an important strategy to reduce building energy demand but also to enhance indoor environmental quality, improving the comfort and satisfaction of occupants (Steemers, 1994; Hua et al., 2010).

As part of this larger context, this research focuses on key aspects of daylight comfort, emphasizing how the control of daylight needs to be integrated with thermal comfort strategies, due to the connection between daylight and solar gain.

§ 4.3.2.1 Daylight comfort

When focusing on daylight comfort, the daylight requirements are related to the illumination levels needed according to the visual tasks taking place within the different spaces. As recalled by Baker and Steemers (2002), daylight can be considered to have two components: the diffuse light from blue sky and clouds, and direct light from the sun. Moreover, when focusing on the diffuse light falling on a point, this has three components: the sky component, consisting of light coming directly from the sky; the externally reflected component, consisting of light being reflected from external surfaces; and the internally reflected component, consisting of light reflected by internal surfaces. The amount of total light reaching a specific point in a space is a first fundamental requirement, and can be quantified according to various models. Among the many, a commonly used simplified approach is based on the 'daylight factor' (Tregenza, 1980) and focuses on the skylight and provides a measure of relative illumination within a space compared to that of a standardized overcast sky condition (Mardaljevic et al., 2009). Even though the discussion of daylight comfort and its related measurement is beyond the scope of this thesis, it needs to be pointed out that the daylight requirements cannot be defined purely in terms of a needed amount of light. In this regard, the daylight factor is a quantitative parameter that does not express any quality measurement; while a complete assessment of daylight comfort should aim at providing a healthy and pleasant environment for the occupants (Mardaljevic et al., 2009). Considering all of these aspects, the importance of the orientation of openings, their location and their distribution can be seen to be of heightened importance. Various approaches are based on the levels of illuminance, which does not simplify the result in a percentage and can provide prediction for every daylight hour of the year for each point considered. Different approaches propose different ways to deal with the large amount of information provided by this kind of analyses (i.e., Nabil and Mardaljevic, 2006). A comparison of different daylight prediction methods is provided for example in Reinhart and Herkel (2000).

§ 4.3.2.2 Performative skins for daylighting

When focusing on large roofs, three aspects are highlighted here. On one hand, areas underneath large roofs often offer the advantage of possible zenithal lighting, which disconnects the covered spaces from the constraints of depth, normally found in multi-storey spaces. On the other hand, the configurations of the openings can include inclinations and consequent orientations that allow balancing the income of direct and indirect light, related not only to daylight requirements but also to influences on thermal comfort from solar gain (Baker and Steemers, 2002). It must also be noted that courtyards and atria are often integrated in buildings in order to increase the amount of daylight for deep buildings and building blocks. This implies that daylight requirements and consequent strategies for meeting them do not come only from the covered spaces (where the comfort zone might be enlarged), but also from the adjacent spaces (often indoor rooms with well-defined comfort requirements). Examples of related studies can be found in Calcagni and Paroncini (2004).

§ 4.4 Geometry and design process

Both concerning structural and climatic aspects, the performance behaviour resulting from the above described interconnected factors is subjected to large influences coming especially from two key factors of the built system: its geometry and its material properties, which both highly condition each of the mentioned aspects. Concerning structural performance, a number of precedents can be identified, in which the analysis of the structural behaviour was taken into account during the early morphogenesis. Some of them are exemplified in section 4.4.1. Despite this, still a deeper and more extensive integration into the conceptual phase is lacking for a large majority of design processes. This is even more important in the case of climatic comfort, which is directly affected by both the geometry and the material properties of large roofs, but very little considered in the conceptual phase. This aspect is tackled in section 4.4.2.

§ 4.4.1 Conceptual design and structural performance

When focusing on performance-oriented design integrating performance evaluations early on, a classical example on structural aspects is provided by the numerous experiences concerning form finding processes. According to classical form finding the structural shape is defined based on the ‘form follows force’ principle, where the form derives from the relationship between force and structures by means of hanging models. Besides projects by Antoni Gaudi and Heinz Isler, well known examples can be found among the projects developed by Frei Otto based on physical models for form finding, such as the wide-spanned structure of the Multihalle for the Federal Garden Exhibition in Mannheim (IL 13, 1978) and the roof of the Olympic Stadium in Munich (figure 22). Despite the fact that classical form finding has relevant limitations in possible applications and is mainly limited to a restricted range of structural typologies, it offers a great example of integration between morphogenesis and early considerations on performance.

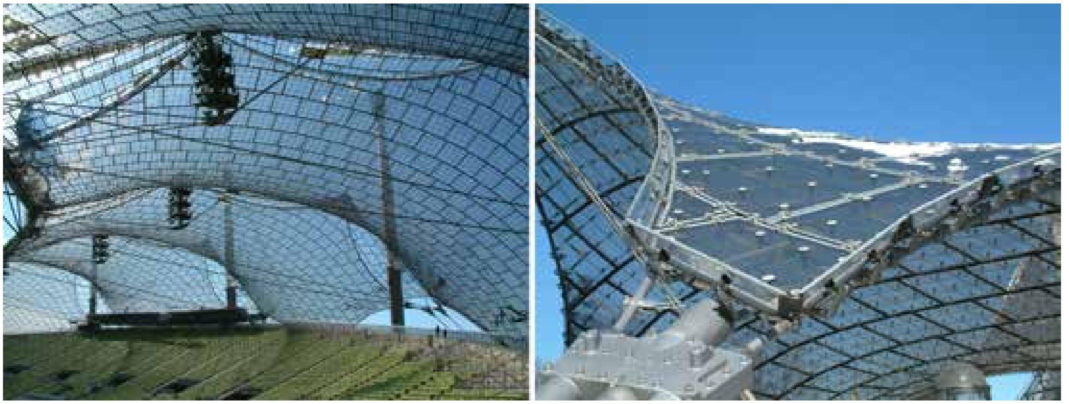

Figure 22
Examples of large roofs designed based on structural form finding: roof of the Olympic Stadium in Munich, whose structure was designed by Frei Otto.

Contemporary form finding refers to a broader set of design methods, including methods based on optimization techniques. Mostly, such design methods and optimization processes are however applied, only, once the overall shape is defined. An example of such approaches can be found in Winslow et al. (2008), where a method to map grids into a given surface is described and integrated with an optimization process to locate the structural nodes (Winslow et al., 2010). With a similar goal, Bollinger et al. (2008) analyse and identify the regions of given shapes that can be altered to satisfy the structural performance without affecting other architectural performances. Such methods have been consistently used for large projects, such as for the structural design of the BMW Welt project by Coop Himmelb(l)au. Apart from the classical form finding, less common are instead methods that allow considering structural performance while defining the early conceptual shape of the overall roof.

§ 4.4.2 Conceptual design and climatic performance

When focusing on performance-oriented design of large roofs, there are very few precedents concerning climatic aspects. Despite the traditional lack of attention to this aspect, the understanding of the role of large roofs on their surroundings is a key issue, which needs to be actively considered during the design. Traditional design approaches tend to face energy related aspects in an advanced stage of the design by delegating most of the expectations concerning performances to material properties. In this way, a given geometry is often expected to fulfil energy performance requirements mainly based on technical construction systems. The material properties that are needed in order to fulfil the expected performance requirements are deducted based on an inverse computing that relates a given geometry and its given environmental conditions. In such a process, performance requirements, environmental conditions and geometry of the project are given little prospect for variation, while the entire search for suitable solutions is focused on a large set of alternative materials and constructive systems.

In section 4.3.1.2, a number of factors for which the geometry is relevant have been discussed. More precisely, the role played by the geometry has been also investigated in a number of studies, which have shown the importance of geometric aspects. Outdoor climate studies pointed out that the bioclimatic conditions expressed by means of PET are strongly dependant on the radiation exposure and wind velocity. According to this, studies concerning thermal comfort conducted by Bouyer et al. (2007) on large roofs and envelopes of stadia, offer an example showing the importance of geometry with respect to these factors. Analyses were made on the Stade de France (Paris) and the Ataturk Olympic stadium (Istanbul). Specifically, considering the different lateral porosities (which is related to the capacity of the envelope and the structure to slow down the wind flow penetration into the enclosure) and sky opening (which evaluates the sky view from the sheltered spaces), relevant differences in PETs have been detected.

According to this and differing from the traditional approach, in this research the importance of the geometry is stressed, treating it has a key variable in the search for energy related design alternatives. The generation of the shape is proposed as a process directly driven by the simulations of the related energy performance, by applying a process of inverse computing also to the geometry. This means that both geometry and material properties are computed in order to fulfil the expected performance requirements of a large roof in given environmental conditions. An approach addressed toward a performance-oriented definition of the geometry and based on such energy-related inverse computing based processes is the design of the dome of the Louvre Abu Dhabi museum. In this project the structure has been designed based on a perforation ratio derived from the perception and the variation of the light, the variation of the temperature levels and the user's comfort (Tourre and Miguet, 2009).

§ 4.4.3 Integrated performance

When looking at both structural and climatic performance, what is emphasized here is the interdisciplinary nature that is required for the process to converge toward geometric solutions that are pretty good overall and at the same time for each individual discipline. Early performance evaluations during the design process are presented, blurring the boundaries between single mono-disciplinary geometric inverse computing. Referring to this context, emphasis is placed on the connections between energy related aspects and structural morphology. When focusing on the interrelations between structural morphology and energy related aspects, geometry becomes also a key interdisciplinary interface. The envelopes for the already named Esplanade Theatres in Singapore exemplify the subject based on the geometric and constructive relations between the structural double layer space frame and the shading system (Sanchez-Alvarez, 2002). Similar relations are shown in the Flower Dome of the Gardens by the Bay, again in Singapore. The Eden project in Cornwall, in turn, exemplifies the subject based on the integrated studies though which the pattern of the space frame was enlarged as much as possible to increase daylight and to minimize the costs related to the length as well as the number of connections of the aluminium frame to the cladding (Thoday, 2000). Figure 23 (next page) illustrates the examples. In all of them, both for energy-related performances and structural behaviours, geometry offers a basis for structuring a number of interrelated aspects during the conceptual phase. This becomes even more evident when adaptive elements are integrated.

A last note concerns the iconographic value of the roof systems. In fact, while in facade applications, usually, an important requirement is the compactness of such (adaptive) skins in order to avoid the extra thickness and to allow a more intensive use of the buildable space, the case of roof envelopes is often different. Especially for representative spaces, such as halls, commercial galleries, showrooms, and covered public squares, the design intent commonly deals with an iconic value of new sculptural objects. In such design contexts, structure and shape become more and more integrated through design explorations leading to complex geometries, allowing to exceed the minimal thickness.

The following section recalls the concept of adaptivity, in this case for passive climatic comfort by focusing on skins (for envelopes and roof systems). Some precedents in design solutions to make the built environment adaptive to changing conditions, such as sun and wind, and to the comfort needs of the occupants are briefly mentioned, without any intent of exhaustiveness.

§ 4.4.3.1 Adaptive geometry for climatic comfort

Using adaptivity and more specifically geometric reconfiguration to make the skin able to react to climate conditions and the needs of the users is a quite ancient architectural tradition, both concerning aspects related to thermal and daylight comfort. The topic has been variously approached (i.e. Zeiler, 2006). Examples of natural lighting control through adaptive systems can be found in the already named Flower Dome of the Gardens by the Bay; in Calatrava's Milwaukee Art Museum; as well as in Jean Nouvel's Institut du Monde Arabe. In the first example, adaptation happens through rolled fabric sails with light-sensitive sensors, which expand from the arcs of the structures visible in figure 23. In the second example, adaptation happens through a set of big rotating linear elements that open and close making the envelope more or less permeable to the natural light. The envelope of the third one includes smaller scale diaphragmatic elements that regulate the incoming light.

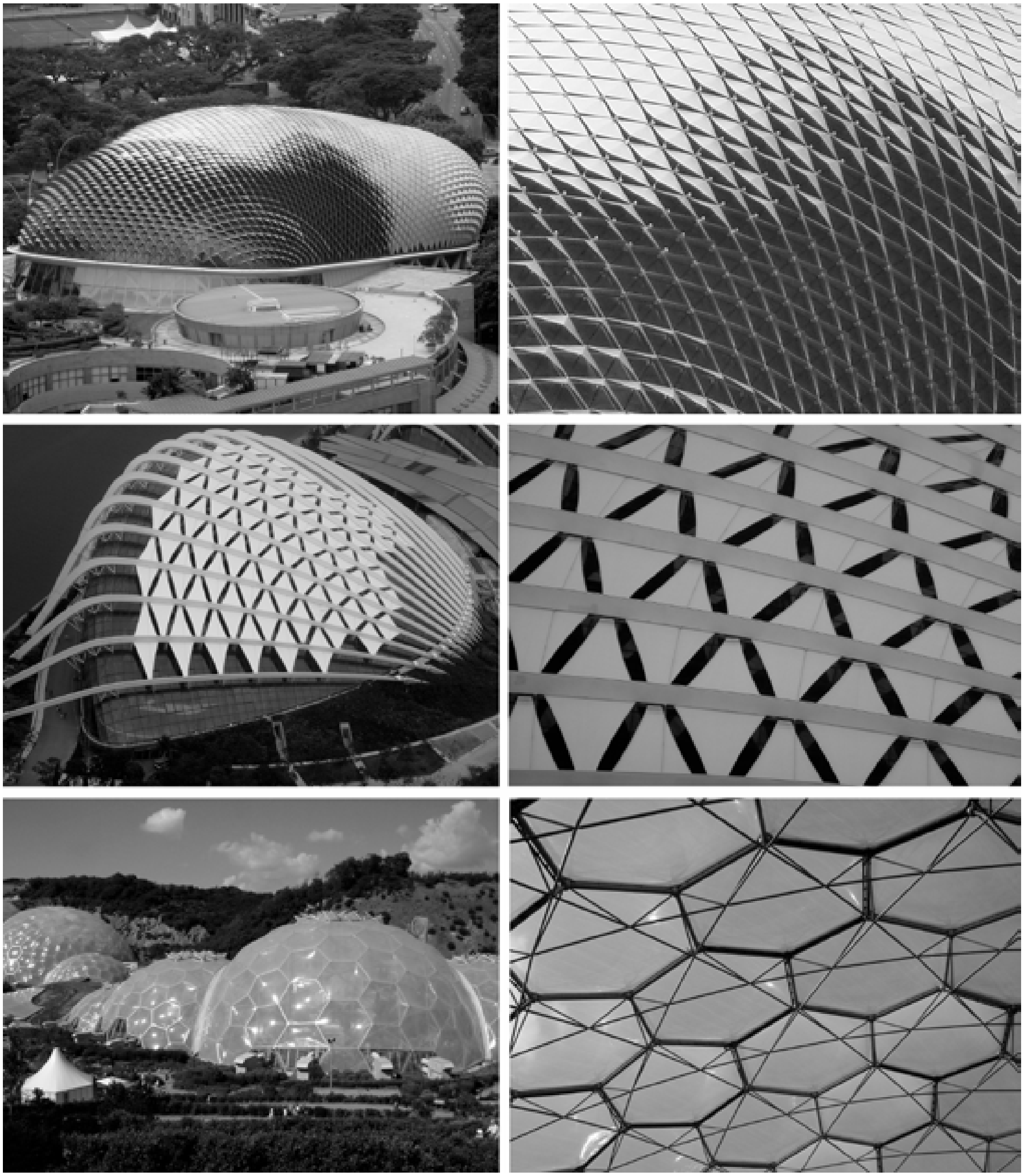

Figure 23
Examples of integrated design of structural systems and cladding and/or shading systems. Top: Esplanade Theatres in Singapore, by DP Architects and Michael Wilford & Partners, with MERO. Middle: Flower Dome (Gardens by the Bay) in Singapore, by Wilkinson Eyre and ARUP. Bottom: Eden Project in Cornwall, by Nicholas Grimshaw, Anthony Hunt and Associates and ARUP, with MERO.

More recently, SOM Architects developed an automatic light modulation system for the Changi International Airport in Singapore to reduce the use of artificial illumination by modulating the natural light coming in through the roof of the terminals. The courtyard of the Prophet´s Mosque in Medina offers an example of thermal control achieved in a passive way supported by adaptive elements. In this case, a set of convertible umbrellas designed by the German architect Bodo Rasch remains open during the day while they close at night and this kinetic behaviour has beneficial influences on the indoor climate of the buildings around the courtyard, protecting their shared surfaces from the diurnal heat as well as allowing night cooling through natural ventilation. A European example of a contemporary well known moveable membrane roof for a courtyard has been designed for the City Hall in Vienna by joining the architectural work of Silja Tillner and the engineering work of Schlaich Bergermann und Partner. Using courtyards or atria in order to passively improve the thermal comfort of the surrounding buildings is again an ancient tradition exemplified by vernacular adaptive systems, nowadays variously reviewed. Within contemporary architecture, it is exemplified by the glazed hall designed by Herzog und Partner for the Holzstrasse Housing Development in Linz. The proposed central access hall with a glazed roof plays a fundamental role in the building's energy performance. During the cold months of the year, the solar energy is in fact collected through the glazed enclosure and kept inside, stored within the thermal mass of the walls. This results in a considerable reduction of the heating-energy needs for the adjacent dwellings. While during the summer, the roof opens allowing natural ventilation that cools the indoor thermal mass and helps to reach indoor comfort. A similar principle is applied to the large openable roof of the Merk Serono by Murphy and Jahn and Werner Sobek.

§ 4.5 Conclusions

In this chapter, the domain of large roofs has been introduced. The importance of large roofs in urban settlements and built environment has been discussed; and the relevance of the climate control of the covered spaces, has been tackled. Since passively achieving or improving the climate control is crucial in order to limit the use of imported energies, the topic of performative skins has been presented. These aspects are additional, but not secondary, to other aspects more traditionally emphasized during the conceptual design of large roofs. This is the case, for example, of structural performances, for which a larger tradition of conceptual morphogenesis exists. Despite the importance of this tradition has been fully acknowledged in the chapter, the mono-disciplinarity of most approaches has been also pointed out. Based on these considerations and for the scope of this research, climate comfort has been proposed as main focus for the performance oriented design approach developed in the research; and structural performance as an example of interdisciplinary references.

For both fields, measurable and meaningful indicators have been identified, based on their relevance. In order to bound the field of this specific research into meaningful but feasible limits, a selection has been made. The selection has included three main groups of indicators, respectively for structural performances, thermal comfort and daylight comfort. For each group, specific measurable indicators have been highlighted as summarized here following:

- Numeric indicators for structural performances; among which deflection is crucial, especially in case of large spams.
- Numeric indicators for thermal comfort; among which overall PET or single aspects influencing the heat-balance models of the human body deserve to be mentioned in this summary.
- Numeric indicators for daylight comfort; among which daylight factor and levels of illuminance have been selected.

In the next chapter, a design approach will be presented, which specifically addresses these aspects, toward an integral design approach.

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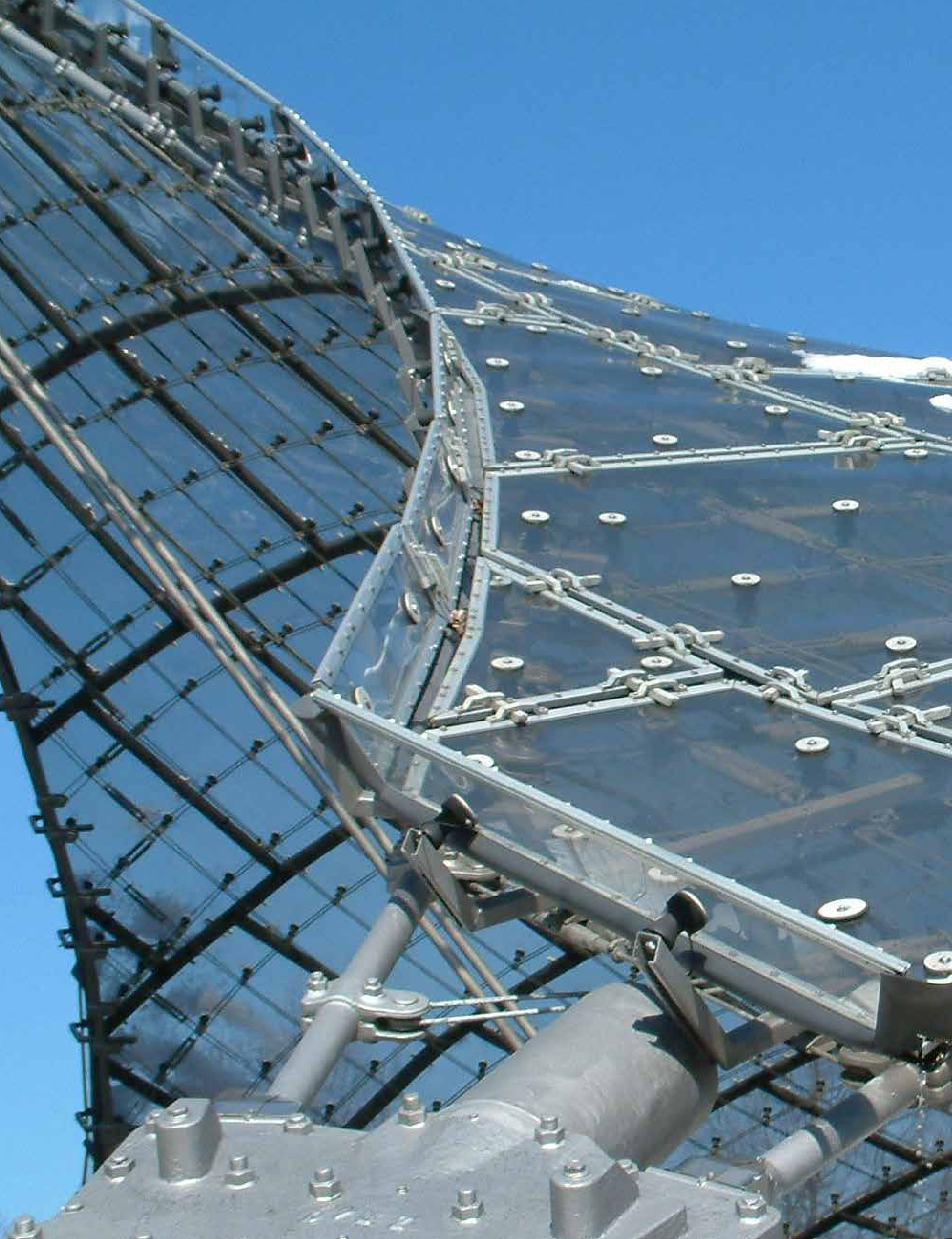


5 PAS: Performance Assessment Strategies

In chapter 2 a set of design approach specifications have been described. In chapter 4 they have been expressed while contextualizing them in the domain of large roof structures. With respect to these aspects, parametric modelling is discussed here for in terms of its potential to overcome current limitations of the conceptual design, and offer possible support in the revelation and comparison of well performing solutions.

While aiming at a performance oriented conceptual design, parametric modelling serves to model the roofs in order to support their design exploration; and it is proposed for the description of the form and its possible variations. The choice for using parametric techniques is based on their capacity for creating design alternatives while managing complex system of relationships. Supporting the exploration of geometric alternatives is addressed with respect to the assessment of measurable performance criteria, while favouring the early integration of different disciplines. With reference to this framework, a performance oriented parametric design method is presented aiming at supporting the design of performative skins.

After introducing the general concepts, parametric design and parametric modelling are discussed and a design method, named PAS, is presented.

§ 5.1 Introduction

PAS stands for Performance Assessment Strategies. Its name also embeds a triple meaning concerning parametric design and passive climatic comfort, by recalling a set of terms used for the performance assessment strategies: Parametric Strategies, Parametric Solutions and Passive Strategies.

PAS is a parametric design approach for the performance assessment of large structures, intended as large performative skins, with focus on passive climatic comfort. The approach is structured in a framework including guidelines and recommendations in combination with an extensible library of procedures and scripts for parametric modelling. The goal of PAS is to support designers in performance driven explorations during the conceptual phase. It is meant to be applicable from the overall geometry of the design to the smaller scale, also when dealing with complex geometries. It is also meant to support the design and integration of adaptive architectural solutions and reconfigurable structures (introduced in chapter 3), when considered suitable. PAS has been developed aiming at meeting the design approach specifications discussed in chapter 2 (recalled here below), by tailoring them for the specific case of large roofs described in chapter 4.

In chapter 2, geometry has been emphasized as a core aspect of architectural performance, leading to the importance of exploring different geometric design alternatives by searching for performance driven solutions. Specifically, in section 2.5.1, the need of structuring the geometry in relation to information on various performances has been discussed with respect to the dynamic nature of a conceptual model. Procedural and parametric geometry has been mentioned as a possible support for flexibly structuring geometries by either embedding or being guided by information related to performance criteria. Following this line, in this chapter the use of parametric modelling is more closely discussed based on its potential to offer support in the revelation and comparison of well performing solutions. These potentials as well as challenges are presented first in a general manner; only from section 5.2.4 on they are directly related to PAS and to the context of large roofs. The reason for this is that potentials and challenges of parametric modelling are independent from the field of application. Based on what discussed in chapter 2, the proposed description is meant to be of possible utility also for other fields than large roofs only. From section 5.2.4 on, PAS is specifically described. It aims at assisting the designer in properly structuring the parametric process in the field of large roofs, based on the aspects presented in chapter 4.

PAS is structured in three parts: pre-PAS, model-PAS and explore-PAS. These are three distinct parts; the three of them together form PAS; they are sequential (from pre-PAS to explore-PAS), though they might be looped into iterative sequences and they might have reciprocal influence. Pre-PAS aims at guiding the preliminary parameterization strategies; this occurs before building the geometric model. Model-PAS aims at supporting the parametric modelling process, while building the geometric model. Explore-PAS aims at supporting the exploration of the design alternatives, once the geometric model has been built.

More specifically, referring to the analysis presented in chapter 2:

- The use of parametric modelling is generally discussed in supporting the generation of design alternatives (see section 2.3.2.1);
- pre-PAS and the parameterization process are discussed in supporting the management of complexity by means of decomposition (see section 2.5.3) and the interdisciplinarity integrating architectural and engineering aspects by means of data and information exchange (see section 2.5.2).

- model-PAS and the use of parametric models are discussed also based on their potential to overcome some of the current limitations of CACD methods, such as the ones concerning the visual approach that is needed during the conceptual phase of the design. With this respect, parametric modelling is proposed for the description of the form and its possible variations considering the potentials of this modelling technique in visual communication by means of 3D models, whose importance has been introduced (in section 2.4.2.1).
- Finally, in explore-PAS, the use of 3D models is related to the performance-based exploration of design alternatives, which includes the direct coupling of the parametric model with performance simulation software, such as FEM software for structural performance and software for climatic simulations, in accordance to the scenario presented in chapter 4. This aspect is discussed in supporting the integration of measurable criteria by means of BTSTs (see sections 2.3.2.4 and 2.5.4).

PAS has been developed based on the theory described in chapters 2, 3 and 4, but as importantly also based on the experience developed during a number of the case studies, the most relevant of which are described in chapter 6 from architectural practice and in chapter 7 from teaching and academic activities. Both with respect to the theory and the case studies, PAS has been formulated based on an iterative process. As in accordance to the action research process (Archer, 1995; Kemmis and McTaggart, 2000) such iterative process passes through states of applications and evaluations by informing the research process, allowing redefining and enriching PAS by grounding it to its application context. Such an iterative process is still open to further developments and PAS is conceived as a flexible system to allow future implementations.

As part of the grounded iterative process, various investigations involved several parameterization processes, some of which are presented in this chapter and constitute the basis of the script library. These are described in the section 5.4; and concern various aspects of the structural geometry and cladding, from the overall shape of the roof to its structural and cladding tessellation. The script library is meant to offer a flexible set of reusable coded processes, ready to use as well as customizable.

The chapter is structured in seven sections. After the introduction of the general concepts, parametric design and PAS are shortly introduced in section 5.2. Sections 5.3, 5.4 and 5.5 present respectively the three modules in which PAS is structured; this includes various levels of the parameterization process; an overview of the guidelines; the structure of the parameters with related script libraries; and the performance evaluation process, together with the exploration of the solution space of the parametric models. Section 5.6 presents and discusses the use of PAS for adaptive architecture. Section 5.7 presents a set of conclusive considerations.

§ 5.2 Parametric design

Parametric design is a design process relevantly based on parametric modelling (for whose definitions, see section 5.2.1). In this section, parametric design is discussed as modelling paradigm to capture the design process.

Some of the potentials of parametric design have been widely recognized. According to Motta (1999), using parametric design as an exploration and search tool allows the process to become "one of navigating a design space efficiently". Motta also illustrates a series of search based parametric models and identifies generic problem solving actions for parametric design toward reusability of knowledge modelling. In addition to knowledge-based approaches, parametric design has also been largely developed for the so-called numerical and constructive approaches. These use respectively a set of constraints converted into a system of simultaneous equations and the construction sequence of a design process (locating geometric entities through a sequence of operations, stored for further execution when parameter values are modified) (Lee and Kim, 1996). The latter approach is at the basis of tools such as the one presented in Roller (1991), automatically storing geometric constraints during the design input; a relevant early example of application for architectural design is illustrated in Martini (1995), using a hierarchical structure of geometric associations. The potentials of parametric design have years of well-established application in engineering and product design (Myung and Han, 2001). While parametric design initially lacked applications in architectural design, recently its potentials are being explored; a number of tools have been made available also in the architectural design field; and its applications are increasing (Hudson, 2008; Gane and Haymaker, 2010), also in the design of large roofs (Peters, 2007; Shepherd and Hudson, 2007).

Among the many potentials of parametric design, focus is given here to the possibility to use parameters and geometric associations for modelling a design logic. Specifically, in accordance to the role of the geometry described in chapters 2 and 4, the focus is on parametric geometry where variations of parameters mainly result in geometric variations, which are meaningful for performance exploration and embed performance data. The goal emphasized here is toward performance-oriented architecture, with emphasis on reusable models and library of features.

The section is structured in four parts. A definition of parametric modelling is provided first. Its potentials in generating design alternatives are then discussed in section 2.2 with reference to the relations among geometric entities as well as to the tridimensional outputs. The challenges of parametric modelling are described in section 2.3. As response to these challenges, PAS is introduced in section 2.4.

§ 5.2.1 Definition of parametric design and parametric modelling

According to Barrios (2005), parametric design is the process of designing with parametric models or in a parametric modelling setting. Parametric modelling is the process of making a geometric representation of a design with components and attributes that have been parameterized. For definition, parametric modelling has in fact the capability to represent both geometric entities and their relationships, based on the so-called associative geometry. This means that through the digital model a network of dependencies is described among geometric entities. Geometric entities can be single entities or features, intended as objects in which various entities are already assembled. The relationships among entities or features are structured in a hierarchical chain of dependencies. Some attributes are described by independent values and others by values that vary in relation to other attributes. When varying these, the independent values act like inputs to the model and the dependent attributes are processed by receiving data from their related attributes. This flow of data keeps the network of dependencies consistent, which itself remains constant, but processes the input values by generating variations of the output. These variations are produced as different solutions of the model. In a large majority of parametric modelers, among which the ones used in this research, the way in which data flows from the inputs to generate the outputs is based on single-directional graph parsing, which means that a graph of geometric entities and relations is parsed entity by entity from the independent parameters to the geometric outputs (Coenders, 2011). Most of the software available for parametric design allows the visualization of such graph next to the visualization of the geometry, which means that, besides the outputs, both inputs and data flow through the network of dependencies are also kept explicit. While systems with this potential are well known in the engineering field, they have become only recently commonly used in the architectural field. Examples are Revit (Autodesk), Catia (Dassault Systèmes), SolidWorks (Dassault Systèmes), Generative Components, named GC, in Microstation (Bentley) and Grasshopper, named GH, which is a plug-in for Rhinoceros (McNeel & Associates). Figure 24 illustrates some examples.

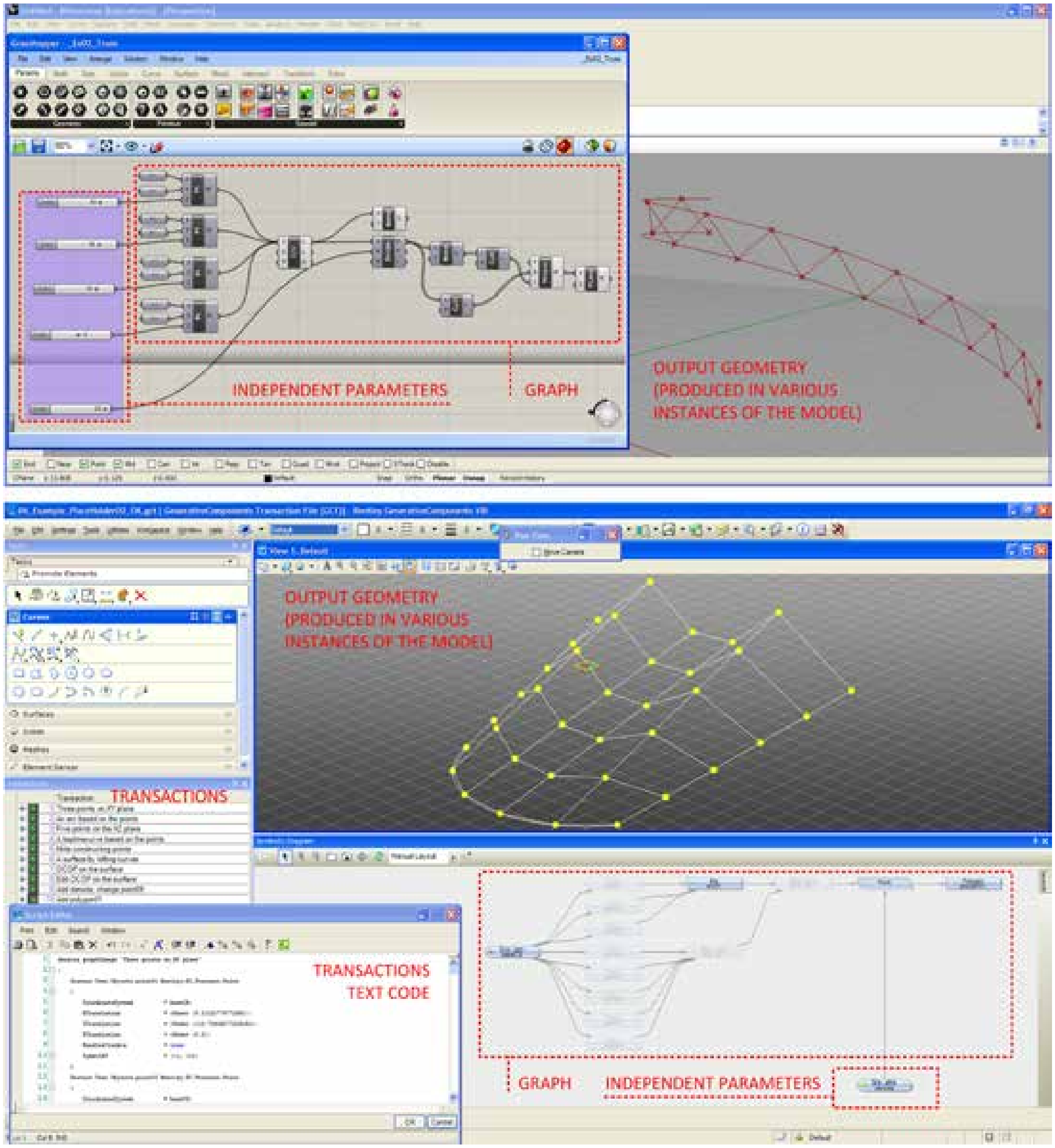


Figure 24
Example of parametric software and their interface. Top: Grasshopper in Rhino (McNeel). Bottom: Generative Components in Microstation (Bentley).

The specific concepts of parameterization process and solution space of the model are introduced in the next sections.

§ 5.2.1.1 Parameterization process

The parameterization process defines which components of the model vary and how the variation occurs. In other words, the parameterization process determines the attributes subject to parametric transformations and the rules following which they vary. It consists of the selection and definition of the interrelations during the earlier structuring of the model. Usually the result of the parameterization process is a hierarchical structure, which describes the dependency chain used in the model, starting from the independent parameters.

§ 5.2.1.2 Solution space

The solution space of the parametric model is constituted by the ensemble of all the possible design alternatives generated by varying the values of the independent parameters of the models. Each design alternative is called an instance of the model. As Barrios (2005) points out, each instance represents a unique set of transformations based on the values assigned to the parameters, allowing design variations and yielding different configurations. Each combination of values for the independent parameters identifies one instance of the solutions space. Differently, different independent parameters and hierarchical associations (in other words, different outputs of the parameterization process) identify different solution spaces.

Figure 25 illustrates the solutions space and the typical hierarchical structure in which the parameterization process results.

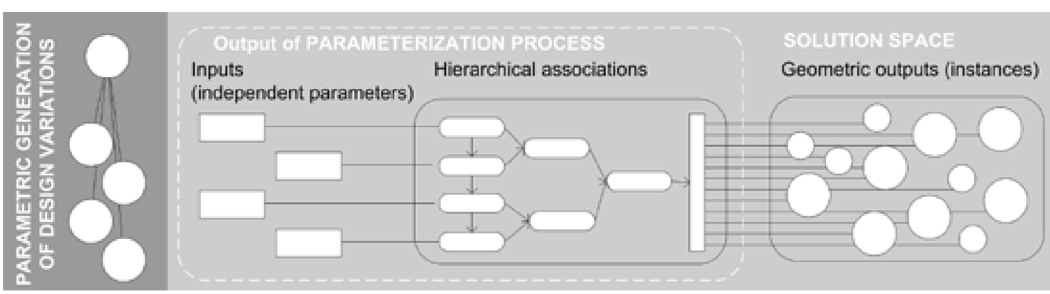


Figure 25
The parameterization process results in a set of independent parameters (inputs) and in a hierarchical structure (describing the dependency chain of associations in the model). The ensemble of the instances of the parametric model constitutes its solution space.

Fully explaining the parametric modelling techniques is out of the scope of this section, and further details on the subject can be found in other publications (e.g. Aish and Woodbury, 2007; Coenders, 2011). Attention is given instead to the potentials of such techniques in supporting performance oriented design, where the generation of design alternatives is meant for performance driven exploration.

§ 5.2.2 Automatic generation of large sets of design alternatives

In this section specific attention is given to the advantages performing transformations that result in different configurations of the same geometric components, which is in fact one of the principal potentials of a parametric model.

As described by Aish and Woodbury (2007), performing such transformations "amplifies the effort of building a representation by providing an interpretation of a model as a typically infinite set of instances, each determined by a particular selection of values for the model's independent variables". "The resulting ability to make rapid changes along a limited range of variation is the primary argument for parameterization" (Woodbury and Burrow, 2006), and the relevance of this has been appreciated in practice. But this capability offers also the great potential to automatically support the generation of a larger set of design variations, providing a broader range of alternative design solutions for exploration. This facilitates the divergent steps of the conceptual design, which are beneficial to the design process but lacking in traditional approaches (as discussed in section 2.3.2.1). When referring to lateral and vertical transformations (as discussed in section 2.3.2.2), the benefits appear evident especially for vertical design transformations, in which parametric variations are produced for each primary generator. However, it can be argued that also lateral transformations can benefit from parametric design, since the generation of new concepts can be favoured based on revelation. Figure 26 illustrates this principle.

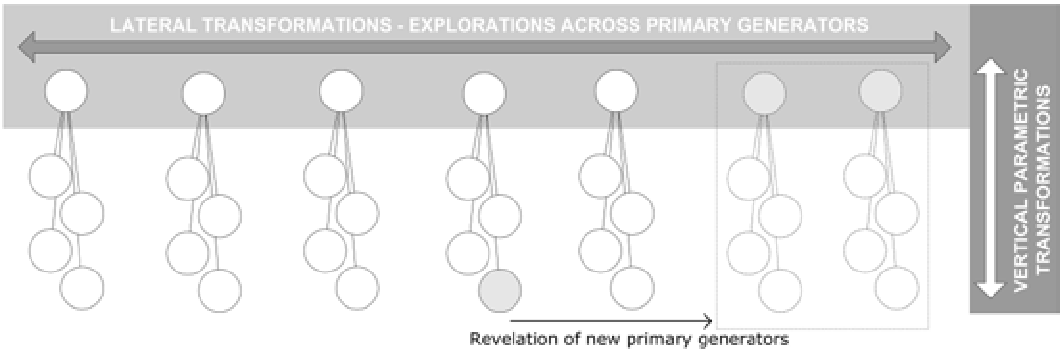


Figure 26
When looking at the double directionality of the explorations of design alternatives, parametric design supports vertical design transformations of primary generators, but may also reveal different design concepts to be included in transversal explorations of lateral transformations.

Moreover, in addition to this general consideration, specific advantages can be foreseen in relation to the use of 3D geometric modellers. With this respect, the potentials of parametrically generating design alternatives are strengthened by the fact that most of the parametric modellers allow working with 3D models. In fact, systematically generating design alternatives in a 3D modeller allows both a quick visualization of different alternatives and the emergence of un-conceived geometric configurations often based on the high number of possible combinations of the variables; both of which favour the revealing of new design directions, and the disclosing of previously un-expressed design aspects. This potential has great utility for the designer to evaluate visual aspects and explore the variations for aesthetic criteria. Focusing on engineering performance criteria, the analysis of available geometric instances based on simulation software and other performance evaluation processes allows exploring and comparing the instances contained in the solution space of the parametric model with respect to a given set of more sharply defined and measurable design criteria.

§ 5.2.3 Challenges of parametric modelling

The section above has introduced the potential of parametric techniques in using computation for generating geometric alternatives within a described structure of relationships by varying the independent parameters of the model. This potential amplifies the geometric representation by providing a model of the design, which is actually a large set of possible configurations, but presents also difficulties. While working with such a system, the effort is moved from the direct definition of design states to other levels of the design (Aish and Woodbury, 2007). Three are here emphasized:

- The first one regards the parameterization process;
- The second one the parametric model making;
- The third one the exploration of the parametric solution space.

Figure 27 schematizes these three challenges within the parametric design process.

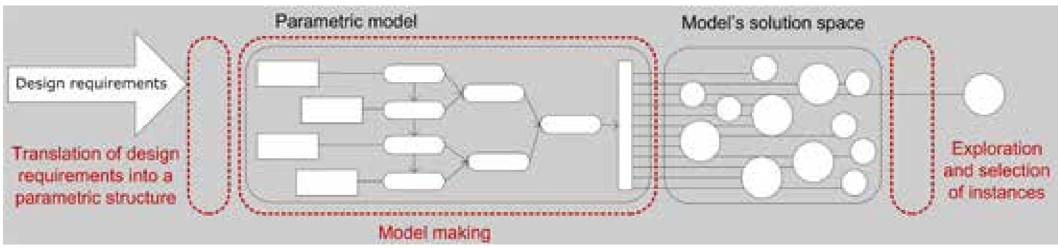


Figure 27
While the parametric model allows the automatic generation of design alternatives, the effort of the designer is moved to the parameterization process and to the exploration of the design alternatives.

The first challenge regards the parameterization process, here intended as inseparable from the rationalization and translation of design requirements into the parametric structure (Gane and Haymaker, 2010). The need of a definition of the hierarchical associations among the geometric entities of the model requires the explicit representation of a design strategy to which the association structured for the geometry responds. In order to understand this aspect, it must be considered that a parametric model is quite goal oriented. There is no meaning in building a parametric model unless the exploration goal is targeted. The identification and analysis of the exploration goal is a crucial starting point for the modelling process and must be prioritized with attention. This has to occur before the parameterization process starts.

The second challenge is intuitively clear and emerges from the required logic of the modelling process.

The third challenge is the exploration of the solution space and the selection process among the large set of generated instances. It concerns the evaluation process of different design solutions. Searching for meaningful instances among the ones embedded in the parametric model is actually an effort. In order to understand this aspect, the breath of the solution space needs to be considered, which is usually too deep to allow a systematic exploration. A parametric model can in fact be seen as a family of models as big as the possible combinations of independent values, therefore sometime even infinite, like in the case described. Being able to generate an infinite number of alternative design solutions is quite a potential, but becomes senseless if it is not associated to a meaningful selection process.

§ 5.2.4 PAS: a tripartite system

In order to support design explorations by means of parametric modelling, PAS aims at taking advantage of generating design alternatives and at overcoming the challenges of the parametric process. Specifically, it offers guidance in translating the design requirements into a parametric structure by means of:

- Preliminary parameterization strategies (pre-PAS);
- Parametric modelling method and related script library (model-PAS);
- Guidance and the possibility to integrate a tool for exploring the design alternatives (explore-PAS; in possible combination with ParaGen as presented in chapter 8).

Figure 28 illustrates the support given by three parts of PAS within the parametric design process.

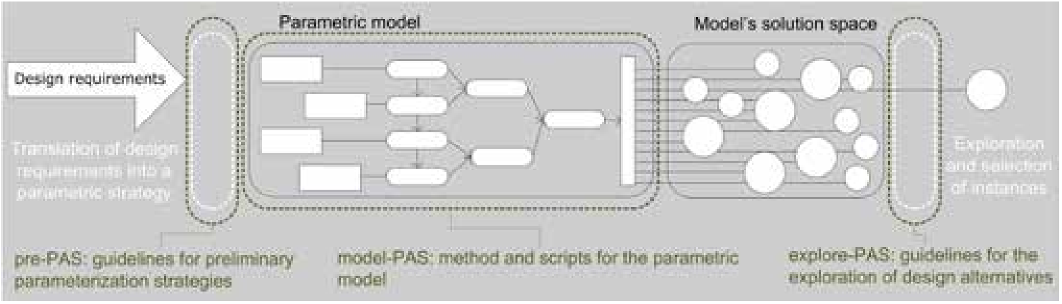


Figure 28
PAS is composed by three parts, supporting the preliminary parameterization strategies, the parametric model making and the exploration of the design alternatives.

The next section (section 5.3) focuses on the first one by tackling the pre-established approach for the parameterization process; model-PAS is presented in section 5.4; explore-PAS is introduced in section 5.5, but will be more deeply discussed in chapter 8.

§ 5.3 pre-PAS: approach and guidelines for preliminary parameterization strategies

In this section, pre-PAS is presented, which is a set of guidelines for preliminary parameterization strategies. First, the importance of determining a pre-established approach for the parameterization process is specifically addressed; secondly, the guidelines in order to establish the approach based on which the parameterization process can be set and the design alternatives can be explored are provided. Thirdly, a set of general recommendations in using pre-PAS are discussed, concerning the definition of the solution space, the decomposition of the design complexity, the use of interdisciplinary collaborations; finally specific warnings are discussed.

§ 5.3.1 Need of a pre-established approach for the parameterization

From the previous sections, the need of defining a pre-established approach, preliminarily to the parameterization process, has become clear. The specific reasons for which defining a pre-established approach is of fundamental importance include different aspects, which are relevant to understand pre-PAS, and are here following discussed.

First of all, one of the key reasons depends on a general aspect: the entire solution space of the model depends on the way the parameterization is set and therefore the parameterization is the fundamental step required to exploit the potential and advantages offered by parametric modelling. The conceptual structure defined during the parameterization process is the one that guides and determines the variation of the geometric output. In other words, the parameterization process defines the solution space of the model. This is what makes the earlier choice of the model focus so important and, for this reason, the definition of a pre-established approach for exploring design alternatives is necessary. When establishing the approach for the parameterization process, one needs to consider that having a solution space meaningful with respect to the design requirements that are being analysed is the only possible way to successfully explore the solution space of the model according to the set of selected criteria. This is especially true when focusing on performance oriented design where instances are expected to express a meaningful range of variations on key aspects affecting the analysed performance criteria or on aspects that are meant to be investigated in relationship to performance variations. As a consequence, also achieving this condition, or not, mainly depends on the parameterization process and on the preliminary description of the model structure.

Moreover, other reasons concern the time and effort management during the design process. In fact, the parametric model making can be time consuming. Being able to build a model of which the solution space corresponds to the desired exploration space cannot be based on a trial process. The same can be affirmed concerning the parameterization process, which is a time consuming process of abstract elaboration. It cannot be based purely on trial processes and instead needs to be addressed through relevant criteria that must be properly pre-selected. These considerations are especially valid when we recognize that the hierarchical nature of the abstract structure has little flexibility in changes once a model has been created (Kilian, 2006). This means that an un-proper parametric model rarely can be corrected without major changes in the structure of its graph. As a consequence of these time and effort-related aspects, the choice of the pre-established approach for exploring the different design configurations is even more of evident importance.

The approach based on which the parameterization will occur must be chosen carefully in the initial phase from possible ways to describe any design state; and its choice strongly conditions the overall design process that follows. Its definition is preliminary to the parameterization and the parametric model making, in which the pre-established geometric dependencies are described, and to the subsequent computational generation of alternative solutions.

§ 5.3.2 pre-PAS guidelines

For the reasons above, before making a parametric model, a pre-established approach is needed for the parameterization. The definition of a pre-established approach can be achieved through analytical investigation of the design requirements. With this respect, design requirements need to be properly captured and rationalized with respect to the geometric properties that affect the satisfactions of the requirements and on which the parameterization will have to focus. As discussed in chapter 2, previous researches have defined a variety of methods providing frameworks for identifying, capturing and managing design requirements. In principle, any of them could be used in the phase preliminary to the parameterization process. A discussion of advantages and disadvantages of the key methods can be found in Gane and Haymaker (2010), where, however, the inadequacy of all methods is also pointed out. The approach proposed in pre-PAS does not aim at solving any general case, even though in principle the approach can be extended and generalized. Currently, pre-PAS focuses on climatic requirements, for which a decomposition is proposed:

- **Phase 1:** given a primary generator and design requirements describing the expected performances (such as thermal and daylight comfort performances), preliminary numeric analysis can be run on a reference geometry that represents the concept. This helps identifying as well briefly quantifying the eventual level of missed satisfaction of the design requirements (such as levels of thermal and daylight discomfort).
- **Phase 2**: based on the preliminary performance analysis results, specific sub-goals can be established. When focusing on climatic comfort, they can be sub-goals such as the reduction of summer overheating or the increment of winter heating or of diffuse daylight or others. Mainly, concerning thermal comfort the heating can be expected either higher or lower, either in certain hours or throughout the day, during the whole year or only in specific periods, either in all spaces under the roof or only in certain areas. Concerning daylight, either direct or diffuse daylight or both can be expected higher or lower in certain hours or throughout the day, during the whole year or only in specific periods, either in all spaces under the roof or only in certain areas.
- **Phase 3:** once the sub-goals have been identified, specific strategies can be set. Focusing on climatic comfort, means from passive strategies can be used to define the design strategy to reach the goals; preliminary calculations can be run in order to briefly quantify the benefits, if any. In principle, all factors would provide a benefit; however, other design requirements may constrain the factors to conditions that make them not effective for thermal and daylight improvements. Such constraints need to be considered. If the factor, within the constraints, does not allow for improvements, its further investigations are mostly not necessary. If the factor, within the constraints, does allow for improvements, then its further investigation is important.
- **Phase 4:** For the factors that do allow improvements, the specific geometric properties of the design that affect each factor and its effectiveness should be extracted, made explicit as geometric aspects to be parametrically explored. This mostly means they are the key aspects for the parameterization process and the independent parameters should allow their investigation. Additional numeric analyses may be necessary in order to identify relevant geometric sub-factors to be parameterized.

Figure 29 illustrates a flow chart of pre-PAS.

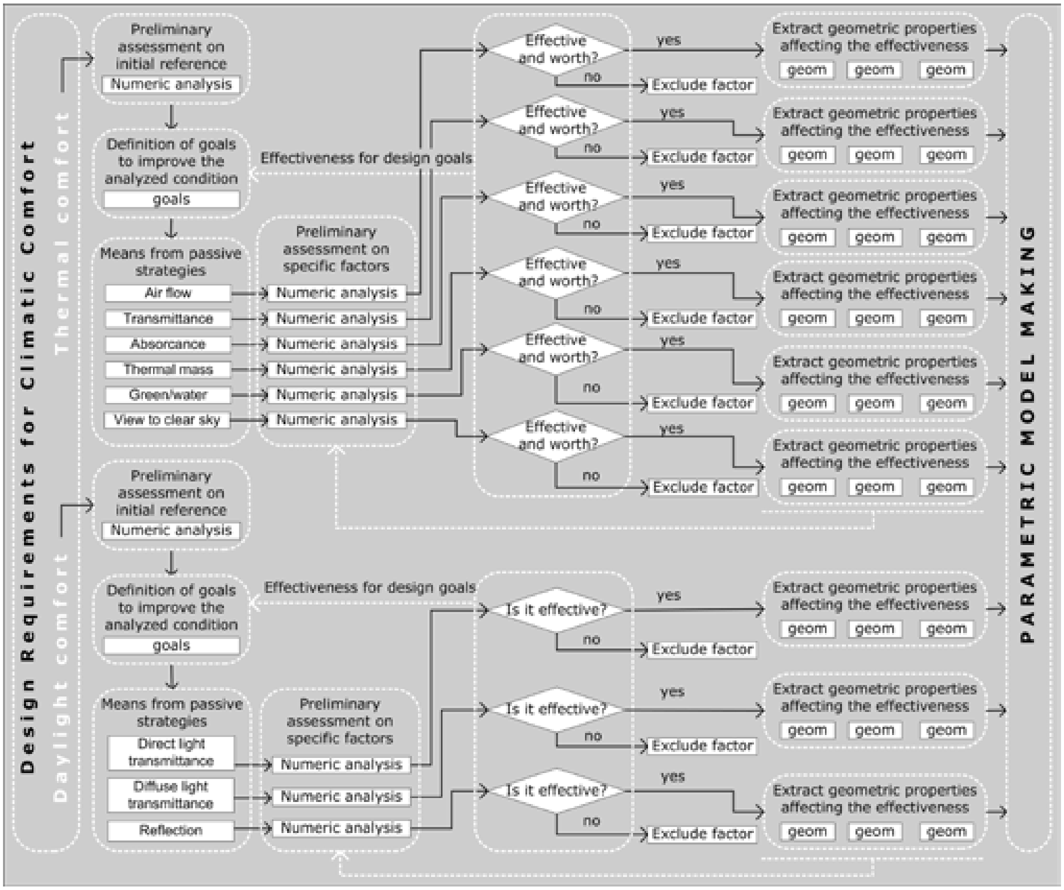


Figure 29
The flow chart illustrates the process for defining the pre-established approach for the parameterization process, concerning the use of passive means both for thermal and daylight comfort.

The pre-PAS flowchart in figure 29 guides the design team in defining the approach for the parameterization process to set the model, by allowing to identify the meaningful geometric aspects to be parametrically explored for the performances considered in pre-PAS. The selected geometric aspects need to be checked as compared to other design requirements as well, in order to detect eventual relevant interrelations that have to be considered from other disciplines (as a relevant example, structural design). This aspect is discussed in section 5.3.3.

Once the goals on which the design investigation focuses have been established, and once the geometric factors affecting them have been identified, then the parameterization process can be finalized and the parametric model making can take place.

§ 5.3.3 Recommendations for using pre-PAS

This section deals with two levels of considerations for the use of pre-PAS: on one hand the need to address a number of issues while applying pre-PAS, on the other hand the advantages that can be derived from pre-PAS already during its application.

The issues to be faced mainly regard the early orderliness that the approach requires. In fact, as it clearly emerges from the previous sections, working parametrically requires a general way of thinking different than traditional approaches, and so pre-PAS does. Specifically, while following a parametric approach, the design aspects involved in the project need to be analysed early and described using an orderliness uncommon in the conceptual design phase. As evident from what is presented in section 5.3.1, formulating the approach for the parameterization process requires a high level of abstraction and the process is a challenge that necessitates effort on the part of the design team. In order to make this process a worthwhile investment, pre-PAS aims at supporting the designer to properly execute the process based on a preliminary consistent modelling of the design criteria. Still, in order to achieve this, the designer must have a certain level of awareness, without which the potentials of pre-PAS would not be entirely exploited. Such awareness regards:

- The necessity of limiting the entities to be represented in a parametric model;
- The mono-directionality of the geometric associations in a parametric model;
- The potentials of favouring the explicit definition of strategies and subtasks;
- The potentials of opening cross-disciplinary boundaries earlier in the process.

In fact, similar to every representation, a parametric model needs to be partial and so it is pre-PAS, as any approach for parameterization processes. In a parametric model, its lack of exhaustiveness indicates on one hand the necessity of limiting the entities to be represented and on the other hand the mono-directionality of the geometric associations.

The need of limiting the represented entities is common in every representation; but it is particularly important in parametric modelling where a complete parametric representation of the design would require too high a level of computation in generating design alternatives, resulting in a reduction of one of the major potentials of the model.

The mono-directionality of the geometric associations concerns the goal oriented nature of the parametric model. Due to the hierarchical structure of the associations, data flowing along a predefined partial direction as well as its reverse direction is usually not possible. This unilateral directionality implies that each model can consistently represent its components according to the predefined strategy, but would mostly not fit other strategies.

This could appear as a limitation and lack of flexibility (and sometime it is), but it is in fact one of the major aspects for which externalizing explicit strategies for the design criteria is needed. While this effort might look discouraging, it actually reveals key advantages also other than the ultimate generation and exploration of design alternatives; and it offers advantages also already during the definition of the parameterization approach. Specifically, the need for coupling the associative geometry to a design approach in which the designer beforehand explicitly externalizes the conceptual and constructive structure by the construction of the digital model is beneficial for a performance oriented design due to two main aspects. First of all, it favours the explicit definition of strategies and subtasks. Secondly, it opens cross-disciplinary boundaries earlier in the process. These two advantages are here identified as the cross-decomposition process.

The cross-decomposition process is presented in the section 5.3.3.1; some specific recommendation is also discussed in order to take full advantage of the cross-decomposition process. These are mainly focused on design tasks. Despite that the recommendations are specifically tailored for pre-PAS and focus on the guidelines described in section 5.3.2 for passive climatic aspects, they mostly have a general value that overcome the specificities of this approach. Moreover, in section 5.3.3.2 considerations and additional recommendations on the resulting solution space are discussed with specific reference to the limited entities and mono-directionality constraints. These are mainly focused on design geometry.

§ 5.3.3.1 Design tasks: cross-decomposition process

A key advantage of pre-PAS consists in the early systematic analysis and decomposition of the design criteria and related geometric factors. First of all, following pre-PAS in response to the need of a preliminary approach for the parameterization process forces the design team to make explicit a particular search strategy early on, to be followed during the design exploration. Secondly, in pre-PAS, the need of goal oriented sub-tasks is specifically addressed. Pre-PAS forces the definition of the preliminary approach to be clearly subdivided into sub-strategies of design exploration by early identifying single goals and objectives of the design, by forcing to break down the design complexity by means of decomposition. Both these rarely occur in the current practice; despite the fact they are of vital relevance.

On one hand, the importance that explicit strategies have on the success of the explorations has been discussed in detail in a number of publications (Krishnamurti, 2006; Woodbury and Burrow, 2006; Kilian, 2006; Gane and Haymaker, 2010). On the other hand, when looking at the design process as progression from requirements toward goals, where requirements usually comprise several and possibly conflicting constraints (Krishnamurti, 2006), the identification and definition of subtasks offers a step toward the decomposition and the understanding of the design complexity. The importance of decomposing the design complexity has been introduced in section 2.5.3. With this respect, being forced of acting in these directions emerges as already beneficial in its-self.

However, while following pre-PAS, awareness of the designer is required on two different levels, the interrelations within and outside pre-PAS. Moreover, the parametric model making should be preliminarily considered already.

Interrelations within pre-PAS: Firstly, awareness of the designer is required concerning on one hand the implications and interrelations among the identified sub-tasks; on the other hand, the implications and interrelations between the identified sub-tasks and the various geometric factors. This means the designer must avoid focusing on single tasks only, but should take into account the overall picture of the design strategy. This includes not only the decomposed sub-tasks and sub-strategies, but also their interconnections as integral parts of the network of design interrelations.

With this respect, an important notice regards the possible iterative application of pre-PAS as a support in identifying such interrelations. This aspect is directly related to the knowledge required during the process. The knowledge on the basis of which parametric strategies should be defined is in fact not necessarily entirely left to the designer's previous knowledge, but can also be extracted during the pre-PAS phase, from possible iterations in which pre-PAS is applied. This aspect is specifically presented in chapter 7, based on case studies. Here it is relevant to emphasize that the benefits offered by pre-PAS are not always straight and linear gains in every pre-PAS process. Differently, iterative applications can be sometime suitable since (besides forcing the design team to set explicit strategies in their subtasks and interdisciplinary interrelations) they have the capacity of making the designer extract and reuse knowledge.

Interrelations outside pre-PAS: Secondly, awareness of the designer is required concerning the nature of interconnections between tasks and sub-tasks, which is highly interdisciplinary. A first level of interdisciplinarity can already be identified within pre-PAS. However it becomes even more explicit when referring to interdisciplinarity toward fields that include performances different than the ones considered in pre-PAS. Defining a proper preliminary approach and structure of the parametric model requires, therefore, a knowledge and expertise based approach during the definition of the parameterization approach, and this needs to be mainly based on interdisciplinary collaboration and early brainstorming which crosses traditional boundaries of expertise. This is even more needed when design explorations are meant to include engineering aspects. In this respect, parameterizing the geometry requires early interdisciplinary collaborations, and this must be mentioned as having a positive influence on the process, as the case studies in chapter 6 show.

Pre-PAS and the model making: Finally, a conclusive consideration regards the relation between the cross-decomposition and the parametric model making. Such a process of decomposition and grouping of design requirements and sub-tasks and related geometric key factors to be parametrically explored, must take into account the relations among different design requirements as well as among related geometric factors. This relates to the choice of exploring the design requirements and related subtasks in either one or more parametric models. Figure 30 illustrates the process for a number of primary generators.

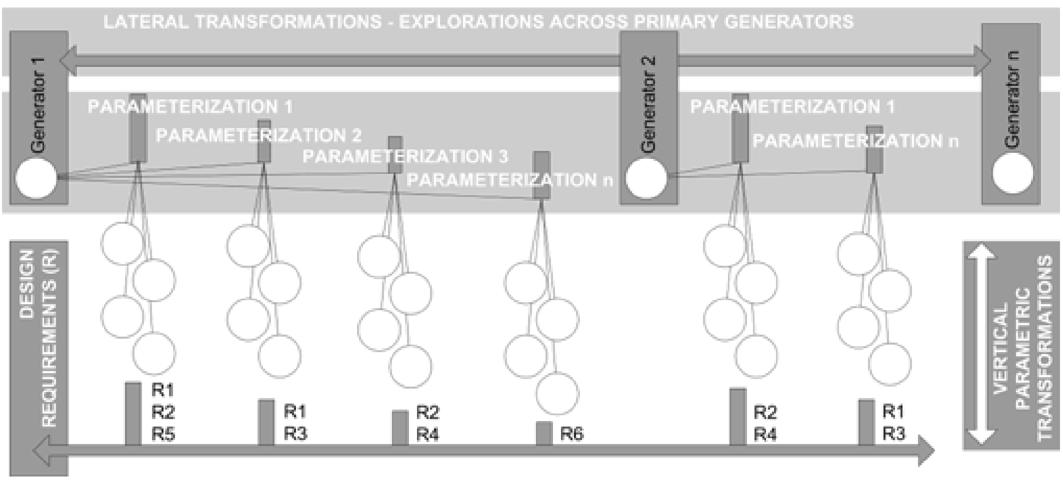


Figure 30
Different parameterization processes and models corresponding to goal-oriented parametric models for exploring various sub-tasks in which the design requirements are subdivided by means of decomposition.

An analogous consideration is extended to the required knowledge and knowledge extraction based on eventually iterated processes. Figure 31 illustrates the process for a number of primary generators.

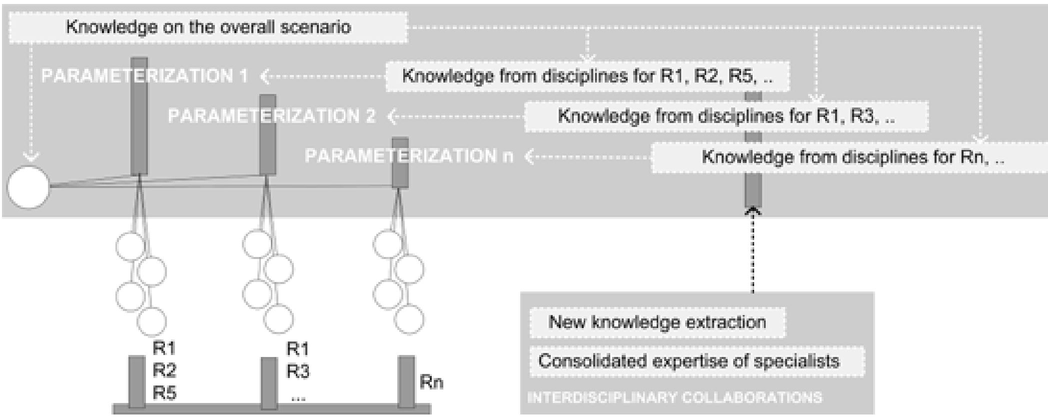


Figure 31
During the definition of the parameterization approach, a knowledge and expertise based approach is needed. This includes interdisciplinary collaboration and early brainstorming toward use of specialist expertise and/or extraction of knowledge.

As a conclusion, it can be summarized that, while following pre-PAS, the designer must:

- Attribute importance to the interrelations among the sub-tasks as well as between the sub-tasks and the various geometric factors. The awareness of such interrelations can be pre-existent or gained during the exploratory parametric process (the issue of gained awareness is specifically addressed in chapter 7, based on case studies).
- Attribute importance to the mentioned interrelations not only within the field of passive climatic comfort, but also concerning other key disciplines (such as structural behaviour, according to what discussed in chapter 3).
- Choose consequently how to group the sub-tasks and related geometric key factors by representing them either in one or more parametric explorations.

Each of these aspects will be addressed and more specifically presented in chapters 6 and 7, based on case studies. Also, the last point specifically introduces the topic of the following section.

§ 5.3.3.2 Design geometry: meaningfulness and completeness of solution spaces

While the previous section focused on the cross-decomposition by privileging the point of view of the design task, this section approaches the topic by privileging the focus on the geometric outputs. With this respect, pre-PAS considers that, once the parametric model has been set, instances of the model can be automatically generated leading to a large range of design alternatives, the exploration of which is the ultimate goal. In order to properly support a performance oriented design process, the solution space of a parametric model must be meaningful and focused. By following the above described pre-PAS phases and flow-chart, the designer is expected to be facilitated in obtaining a proper solution space. Still, also from this point of view, in order to achieve this, the designer must have a certain level of awareness. By focusing on the generated instances, this section points out some aspects that require careful attention and awareness from the designer.

Among the aspects to be considered while using pre-PAS, a first aspect concerns the possible and, mostly, probable missing coincidence between the parametric solution space and the whole design solution space. In fact, it must be pointed out that in most cases there will be an intersection but no coincidence between the project solution space and the set of instances that can be generated from a parametric model in general and, even more specifically, from a model defined using pre-PAS. The missing coincidence is illustrated in figure 32.

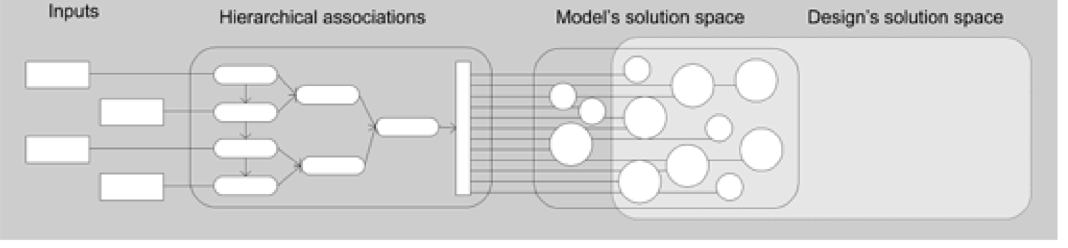


Figure 32
Diagrammatic representation of the structure of a parametric model. The parametric solution space mostly does not coincide with the design solution space.

The missing coincidence between the parametric solution space and the design solution space might not be a problem during the exploration, but needs to be considered explicitly during the parameterization process, starting from the pre-established approach. This is because, contrarily, formulating a parameterization assuming it leads to an inexistent coincidence between the two spaces would lead to design mistakes.

The missing coincidence derives from a double reason based on which the two solution spaces can both be larger than their intersection. On one hand, the project solution space can be larger than the parametric model solution space based on the goal oriented nature of this latter. Usually in fact, facing limits of computational power and time, the parameterization process regards only a part of the design exploration and only the aspects of the project concerned by the investigation are parameterized. More broadly, this regards the missing exhaustiveness of a parametric model, as described in the previous section. On the other hand, the parametric model solution space can be larger than the project solution space due to project constraints that are not embedded in the parametric model. Having a limited intersection between the project solution space and the set of parametric instances is therefore a common situation due to the need to limit the focus of the parametric model not only while choosing the exploration focus but also while choosing the factors to parameterize and define their hierarchy. While the first cause is usually explicit, the second cause can be easily underestimated, misleading the consideration of constraints coming not only from the analysed aspects, but also from other aspects of the project. Chapter 6 will present an example in which, even when limiting the focus to the early structural design, not all the instances belonging to the solution space of the parametric model also belong to the solution space of the real project due to factors and constraints that are not included in the parameterization process and that can range from structural constraints to other interdisciplinary aspects.

On one hand, as a general recommendation, aiming at defining the model solution space as sub-domain of the design solution space is usually suitable, at least with respect to boundaries already known. This allows limiting the exploration feasible solutions or at least avoiding the inclusion of drastically unfeasible solutions. During the formulation of the pre-established approach, this can be mostly achieved by properly considering the geometric factors selected based on the flowchart. In the following parameterization process, the independent parameters have to be then set accordingly and their ranges of variability need to be constrained by considering the feasible variation of the considered factors.

On the other hand, the specific dimensions of the parametric solution space as compared to the design solution space can be decided based on the way the complexity of the design is being decomposed. This is directly related to the cross-decomposition process described in the previous section; the related recommendations are further addressed in section 5.3 and will be also more specifically discussed in chapter 7, based on a set of case studies. Instead, some general considerations are discussed here.

With respect to the respective dimensions and intersections between the parametric solution space and the design solution space, the use of pre-PAS reveals two levels of interaction, within and outside pre-PAS.

Interrelations within pre-PAS: The first level of interaction regards the decomposition of the geometric factors while identifying the ones meaningful for the performances considered in pre-PAS. Once the meaningful geometric factors have been identified, still they need to be properly interrelated before structuring the dependency chain of the geometric entities in the parametric model. Interrelations are intended both among different geometric factors and among parts composing each geometric factor.

If improperly treated, both may still be misleading the properties of the solutions space. The preliminary understanding of such geometric interrelations is therefore necessary in order to finalize the parameterization before setting the model and describing them onto the parametric dependency chain. In this sense, the designer needs to critically approach the pre-PAS phase and especially the transition from pre-PAS to model-PAS (section 5.4).

Interrelations outside pre-PAS: The second level of interaction regards the interdisciplinary relations. With this respect, a first aspect to be considered when using pre-PAS, is the difficult balance between the need to generate a solution space meaningful as well as focused. This results on one hand in preventing the exclusion of solutions relevant for the design, on the other hand in meaningfully focusing the process. In simple words, this regards the dimensions of the solution space, which should not be too broad or too narrow in respect to performances considered in pre-PAS, but also to the general broader set of design requirements. While the overall meaningfulness of the solution space with respect to the considered performances is a main contribution expected by the application of the pre-PAS phases itself, the interrelations with interdisciplinary aspects need to be structured. This is recommended to happen by integrating interdisciplinary knowledge in the pre-PAS phase and especially in the transition from pre-PAS to model-PAS (section 5.4).

As a conclusion, it can be summarized that, while following pre-PAS, the designer should:

- Properly dimension the model solution space for exploring the selected performances by making use of pre-PAS to identify and critically consider possible interrelations among geometric factors affecting the considered performances;
- Aim at a meaningful as well as focused model solution space by making use of pre-PAS to identify and critically consider possible interrelations among geometric factors affecting the other relevant performances.

§ 5.3.4 Time investment in pre-PAS

This section tackles the design team management and time investment in pre-PAS. With this respect, a first consideration concerns the general acceptance of using an early orderliness. A second consideration concerns the time and effort management in the design team when working in the pre-PAS phase as well as moving from pre-PAS to model-PAS.

Concerning the general acceptance of an early orderliness, a resistance needs to be pointed out. While in fact this aspect embeds the advantages of an early systematic evaluation, on the other hand it can encounter the resistance by the design team due to both the difficulties of a different thinking process and the feeling of a loss of creative freedom and intuition. This is an important aspect to recognize, as any approach using the potentials of parametric geometry in bridging different disciplines toward a more integral design approach in the conceptual stage needs to take this into account. Further improving the currently proposed approaches toward higher flexibility in the directionality of the chain of dependencies may be a direction to proceed (Coenders, 2011). However, in order to make use of the current state of parametric software, it is recommended to look at the analysis and decomposition of design criteria and goal in pre-PAS still as a design inspiration step, in which the orderliness of constraints and requirements may generate design ideas.

Concerning the time and effort management in the design team, various aspects should be considered. In the previous sections, it has been mentioned that parameterization is a time consuming process. In fact, parametric design facilitates the generation of design alternatives; however it moves the effort from creating instances to defining the parameterization approach and consequent relational graphs in order to defer the decision on precise values. It has also been mentioned that, in this decision making process, including performance criteria early on in the process is a fundamental issue challenging the design. In fact, the convergence of different disciplines into the first elaboration of the project leads to a more integral design but also increases the system of relationships on which the conceptual design is based. With respect to these issues, the pre-PAS phase and the ability of properly selecting and structuring the factors involved in the parameterization is fundamental, but can be a time consuming process that still does not guarantee always a return on time-investment. Additionally, as discussed, on one hand the hierarchical structure of the model cannot be exhaustive because it cannot include all the design aspects nor all the factors affecting the chosen aspects. On the other hand it cannot allow explorations other than the ones following the stated dependency chain. This latter limit directly relates to the mentioned lack of flexibility, which requires a new parametric description when the exploration focus changes and therefore requires an evaluation of the time-investment when setting a parametric model. Based on all these aspects, the issue of time investment is a key consideration that needs to be taken into account during the design process.

- In teaching, this may usually not be a problem and actually is expected to force students to structure their thoughts and design expectations.
- In practice this can constitute a limit. The time-pressure which is common in practice does not allow such uncertainties and relies on the experience of the designers more than on a systematic exploration of alternatives to produce in time a sensible solution.

From a time and effort investment point of view, the limitations of parameterized aspects and factors can be approached from two directions: either reducing the chosen aspects and factors toward a simplification of the model or choosing them with respect to possible generalizations, avoiding a specificity that is too highly contextual. This second direction is especially feasible when dealing with aspects that can refer to general rules. In other words, this limitation is partially solved when generalization can be used in the process. In fact, time investment assumes a different perspective when the parameterization refers to parametric procedures for design aspects that overcome the specificities of the single design case. This leads to the definition of reusable models, which can enrich pre-PAS by means of reusable information. Moreover, this aspect introduces the importance of using and developing reusable libraries of features and scripts in parallel, as model-PAS also proposes. In this respect, the investment both in defining the pre-established approaches and in developing the related libraries becomes worthwhile, particularly in light of further applications. Structuring both approaches and the libraries by considering and abstracting design problems that overcome the pure specificity of one case makes the effort worthwhile; and it helps in consolidating and framing the design knowledge toward reusability. Moreover, if it is acknowledged that, in common practice, developing approaches, scripts and libraries can be challenging in time and skills, then reusability can be beneficial also for architectural offices that have such limits.

The case of tessellation for structural geometry and cladding offer an example of a recurrent design problem. Once the scripts have been finalized within a generic logic, they can be intuitively reused or even called up through a graphic interface. The case of the space frame offers a clear example of this and is expected to provide a good support within a reasonable spectrum of shape variability in the conceptual stage. Such concepts are presented in the next section.

§ 5.4 model-PAS: method and scripts for parametric modelling

Once the guidelines provided in pre-PAS have been followed, the parameterization approach is defined and the relevant geometric factors to be parameterized have been identified. At this stage, the definition of the relational graph and parametric model making can start. In order to support this phase, model-PAS has been developed, which supports the definition of the development of the hierarchical structure of associated geometric entities. It is a parametric modelling method and related script library, to be used in combination with pre-PAS.

In accordance to the recommendations given in pre-PAS and in order to investigate geometric alternatives that impact aspects of climatic and structural performance in large structures, the parametric design method model-PAS concerns the parameterization of the geometry as definition of the specific hierarchical structure of associations; as well as the parametric model making as modelling process. Specifically, model-PAS is organized on the basis of three levels of parameterization, using a set of pre-selected variables. In order to build models able to generate an array of parametric designs, which describe meaningful alternative solutions to the desired performance criteria, the set of design variables has been selected based on the ones affecting structural and climatic performance. The selected variables and related levels of parameterizations define an infrastructure, which is open to embed the specific geometric factors selected based on pre-PAS and to eventual customization. They have been selected based on a simplified approach which supports a very early stage of the design process.

The general infrastructure proposed for the parameterization focuses on geometric factors defining the overall shape of the large structure, the pattern and the density of its modular structural system and cladding. The proposed design strategy for the exploration of these aspects is articulated on various closely interrelated levels. Each level is meant to allow parametric explorations of, respectively, each of the various aspects. Technically, a set of points is used as a key element to describe the geometry throughout the various levels. In this way, model-PAS is based on overall geometric variation as well as the interchangeability of structural patterns and cladding systems, each of which is also parametric. Specifically, various levels of parameterization that the design strategy develops can be schematized in three main groups. The first group corresponds to the primary parameterization, and refers to the general geometric properties of the roof. The other two groups refer respectively to the cladding and the structure, and contain parameters describing specific properties of their modules. These assume the geometric output of the primary parameterization as reference geometry. This includes an approach to the structural morphology (section 5.5) and the parametric exploration of the cladding systems (sections 5.6). The overall infrastructure of model-PAS in relation to pre-PAS is illustrated in figure 33.

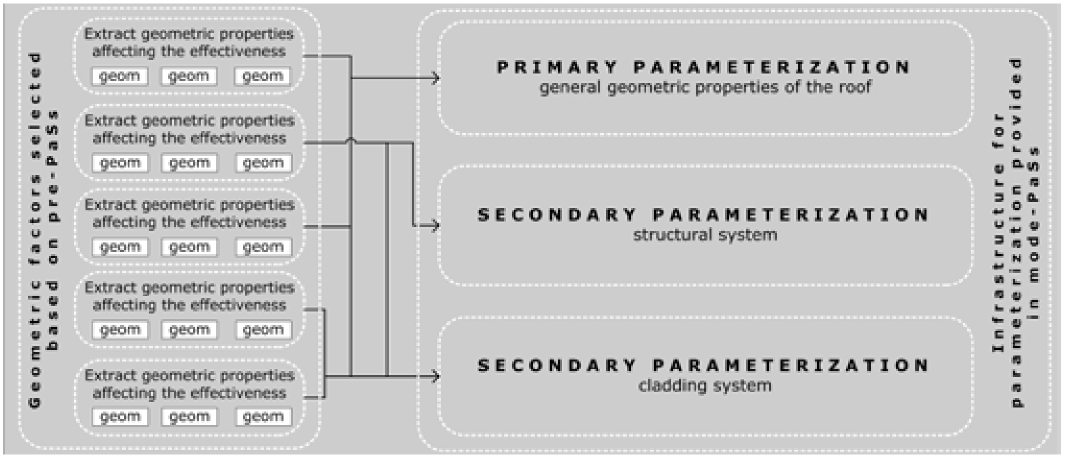


Figure 33

Model-PAS offers an infrastructure consisting in a preliminary structured parameterization in which the geometric factor emerging from the analysis in pre-PAS can be embedded.

For both structure and cladding, various aspects have been considered during the parameterization process. As emphasized in the previous section, in a performance oriented process, the hierarchical structure of the model can be defined to allow the generation of alternatives in a way which is meaningful with respect to the performances to be evaluated; therefore the parameterization must be goal oriented. However, to allow a realistic coincidence between the parametric solution space and the design solution space, the parameterization should also consider constraints coming from other aspects of the design. When looking at the overall design process of large roof structures, various aspects need to be considered besides the overall shape of the roof, its structural tessellation and cladding panelization; examples are the size of the members of the roof structure, the fabrication of its components and its construction process, just to mention some of the most relevant. These and other factors have been also considered or are possible to be considered in the proposed approach.

Also, both for structure and cladding different variations have been explored within this approach and each process was based on a set of operations having the potential for reapplication. Making use of the potential of parametric modelling, in fact, the main idea is to offer a set of pre-set operations, which can be both customized and interchanged.

The following sections describe model-PAS at its different parameterization levels.

§ 5.4.1 model-PAS primary parameterization: the reference geometry

The parameterization of the reference overall geometry is structured to allow the automatic generation of geometric alternatives of polygonal patterns. These are meant to be used as a basis for modelling both the structural and the cladding systems. Moreover, the reference geometry is expected to allow geometric variability of the overall shape of the roof as well as of its tessellations, according to the key aspects illustrated in chapter 4. A set of points is used as a key element to parametrically describe the reference geometry. More specifically, an array of points, variable in distribution and density, is used to describe the position of the vertexes of the polygons. Referring to the same points, a variety of polygonal patterns can be generated. The overall shape of the roof can result from, or itself determine, the distribution of the points.

Although certainly any parametric modelling software might be used to implement the method described here, the examples below have been mostly developed using Generative Components (Bentley Systems). One example of application in Grasshopper (plug-in for Rhinoceros, McNeel) is also presented here and will be further discussed in chapter 7.

§ 5.4.1.1 Parametric single layer point grids

The distribution of the points can be based on three possible approaches. The first two approaches position the points by distributing them along a NURBS surface. These two approaches take advantage of the attributes of NURBS, which allow the free representation of large geometric surfaces that include complex configurations. The third one uses mathematical formulations to describe the positions of the points, and the overall shape of the roof follows from the description given by the mathematical function. This approach offers less flexibility and freedom in modelling, but allows the control of the shape through the precision of an explicit mathematical formulation. When working in a parametric environment, all these methods can provide a point grid as output whose distribution in space is variable.

A - By populating a NURBS surface based on UV coordinates

The first method defines two separate levels of parameterization, the first one regarding the NURBS surface, and the second one regarding the distribution of points on the surface.

A1 - Parametric NURBS surface: The first level aims at parametrically controlling the shape of the NURBS. Such control is based on the parameterization of the entities through which the NURBS is defined. In most of the modellers, a NURBS surface can be determined in various ways, such as based on boundary curves, on curves to loft, on a rectangular list of points that the surface will pass through, or other methods. The entities that determine the NURBS are placed at an upper level of the hierarchy of associations; by varying the positions or configurations of such entities, the entire surface changes its shape. Specifying points as poles is shown here as a significant example, in which the shape of the surface is determined through a set of points acting as control points of the surface (figure 34). In this case, different geometric configurations can be generated by varying the positions of the control points. This can be done parametrically, for example by using as independent variables the Cartesian coordinates of the points. Constraints and proportions can also be included, by expressing the Cartesian coordinates of the control points based on appropriate functions. A typical case consists of surfaces described by allowing parametric variations in height of the points above peaks, regulating the curvature of the roof. Other constraints could be expressed even based on additional dependencies from which the control points might be determined. These can include for example points belonging to a curve or other geometric entities.

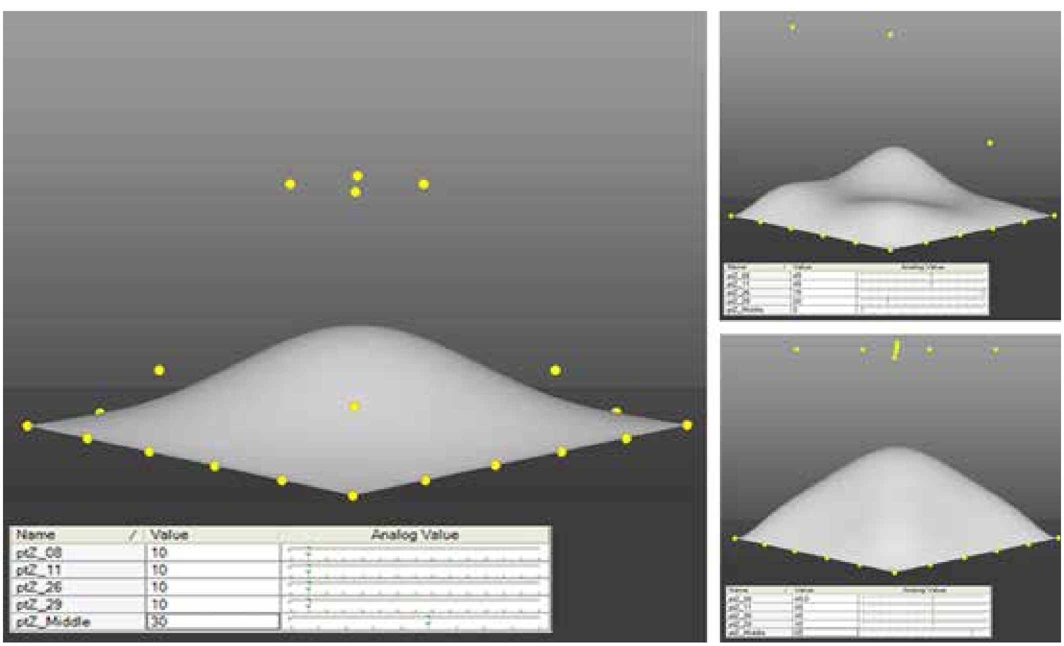


Figure 34
Example of a NURBS surface with parametrically located control points.

A2 – parametric array of points by UV coordinates: Once a NURBS surface is defined, an array of points is distributed onto it in order to describe the position of the structural nodes, cladding vertexes or other. In the context of the present method, this is done based on UV coordinates. UV coordinates are a main property of NURBS surfaces, and are meant to map the surface itself. By expressing the positions of the points based on UV coordinates, the density of the grid and its proportional distribution along the two directions can be regulated by independent parameters included in the equations. Specific proportions might also be desired for the two directions, and can be expressed by setting a dependency between the functions expressing U and V. The equations can be embedded in scripts that can be reused whenever a NURBS surface is used as input to generate an array of points, and that have the flexibility to include additional independent parameters.

Table 10 shows examples of both independently and dependently variable densities in U and V. Figure 35 illustrates examples from the outputs.

Examples	
Independent parameters	**UV functions**
density1 density2	Replication = ReplicationOption.AllCombinations; U = Series(0, 1, 1/density1); V = Series(0, 1, 1/density2);
density1 factor	Replication = ReplicationOption.AllCombinations; U = Series(0, 1, 1/density1); V = Series(0, 1, ((1/density1)*factor));

Table 10
Examples of functions for the distribution of points based on UV coordinates.

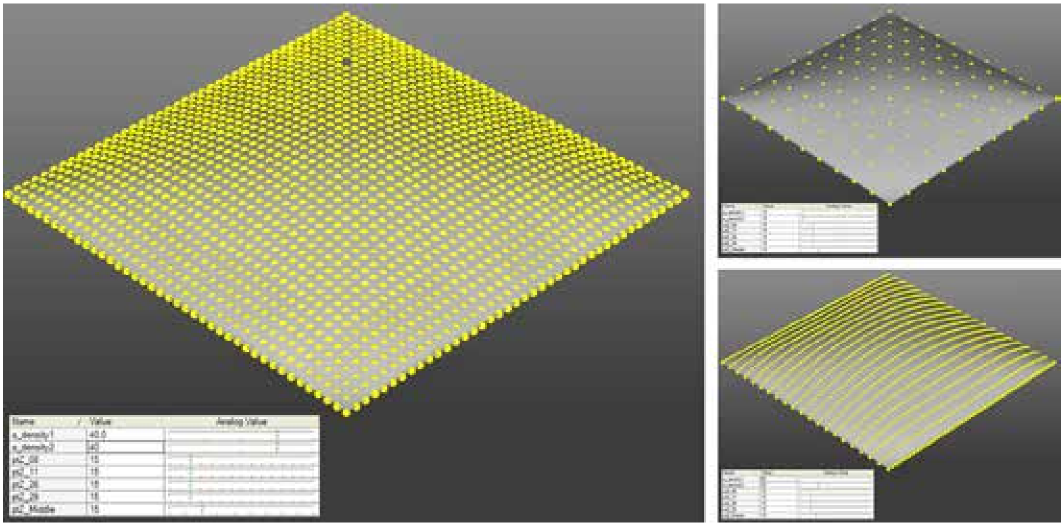


Figure 35

Example of a point grid parametrically distributed based on UV coordinates. Left: Points homogeneously distributed in U and V. Top Right: Points homogeneously distributed in U and V but with decreased density. Bottom Right: Points distributed based on a aFactor that changes the proportion of densities in V with respect to U.

The described method allows for freedom in modelling the surface that is to be transferred into the point distribution. This offers a key advantage especially during the conceptual phase of the design, also in possibly exploring the overall shape according to, not only structural and climatic performance, but also other performance criteria, such as functional, aesthetic, etc.

B - By populating a NURBS surface based on sections

Like the previous one, this method defines two separate levels of parameterization, the first one regarding the NURBS surface, and the second one regarding the distribution of points on the surface. In fact, once a NURBS surface is defined, different methods can be used to distribute the point grid. A second method is presented here based on parallel sections of the surface.

B1 - Parametric NURBS surface: see A1.

B2 – parametric array of points based on sections: Once a NURBS surface is defined, parallel sections of the surface are curves and can be obtained in various ways. A commonly applicable way consists in intersecting a set of planes parallel to the desired directions across the surface. Independent parameters can regulate the distribution of the planes and their reciprocal distances. Points can then be created at relevant points, such as, commonly, at the intersections of the cross section curves (figure 36).

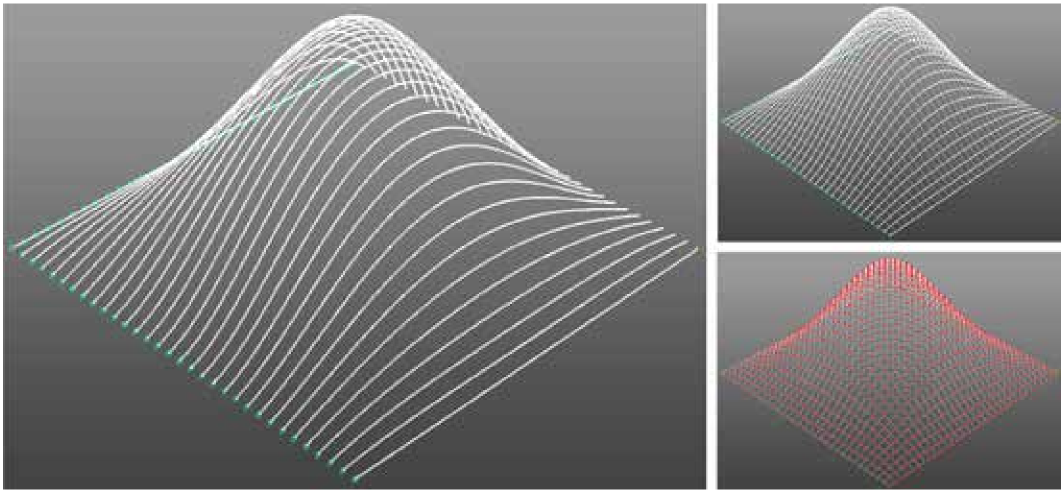


Figure 36
Example of a point grid parametrically distributed based on sections.

C - By using mathematical functions

This method is based on one parameterization level only.

Based on mathematical expressions, arrays of points can be described as functions of variables defining the geometry of the overall configuration as well as the density and proportions of the grid. In this case, both levels of parameterization described above are integrated in the definition of a function or number of arithmetically combined functions. The way this second case can be approached highly depends from the shape to be described. A method that can be commonly applied with flexibility uses functions based on Cartesian coordinates. To explain the principles, an example is taken from one of the case studies (SolSt) deeply discussed in chapter 9. This is also illustrated in figure 37.

In order to integrate eventual geometric constrains, the use of mathematical functions offers major advantages over NURBS surfaces. For instance, different functions can be combined arithmetically to combine different curvature properties. In the example of figure 37 a compound function was used for the special case of the horizontal flat roof boundaries. The two peaks in section were achieved with a sine function. The X and Y values defined the density of the grid, based on an independent parameter n, as well as its overall dimensions. The proportions of the density along the two directions were based on a further independent parameter. The Z value was described using a sine function combined in the X and Y directions to achieve the double curved roof surface with four peaks. The amplitude of the sine function was an independent parameter regulating the height of the peaks. In order to facilitate the integration of regular openable parts in the roof peaks, a horizontal plane intersecting the upper most part of the peak needed to create point symmetry, close to a circular section. To guarantee this condition while still allowing the generation of different design alternatives varying the curvature of the roof, the unaltered sine function in the peak regions was isolated from the boundary by conditional statements. In the boundary areas a zero crossing function was multiplied with the sine function to pull the boundaries down to a zero crossing along the roof edge. A more thorough description of the example can be found in section 9.2.

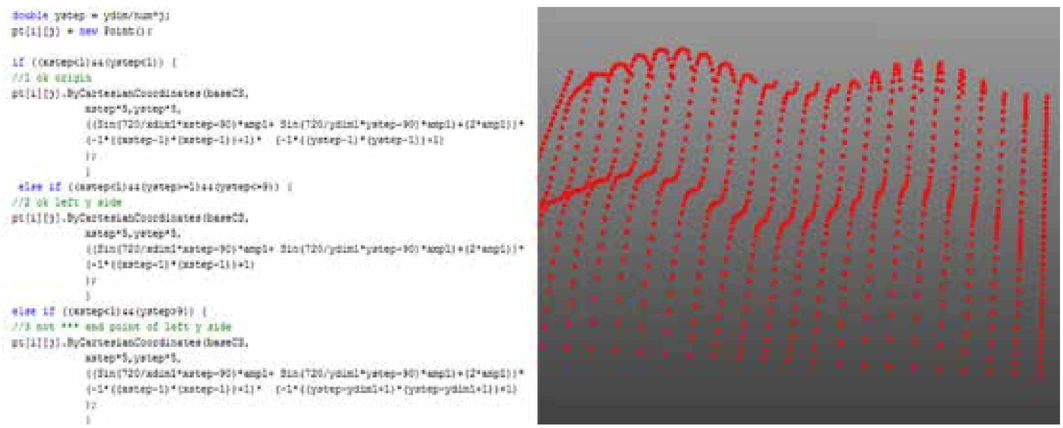


Figure 37
Example of a point grid described based on a number of arithmetically combined functions. The image illustrates the general concept, while a detailed description, including the code, can be seen in section 9.2.

§ 5.4.1.2 Parametric double layer point grids

The above described processes concern a single layer grid point, distributed along the overall shape of the roof. Sometime, in addition to it, a second layer can be needed. This mainly occurs for:

- Describing thickness, and especially variable thickness;
- Describing a second skin (for example in case of double paneling or shading systems);
- Describing the second layer of a structural grid (for example in case of double layer space frames);
- Other.

When this occurs, using the methods defined for the single layer grid, a second layer of points can be added in order to model the needed elements. Even though other methods can also be used, the method based on UV coordinates is here given as illustrative example, considering the advantages it provides.

Having a NURBS surface (A1 or B1) and using its UV coordinates, an initial array of points can be generated as described in the previous section. This can be used as one of the two layers, for example the bottom one. Starting from this condition, a second array of points can be set as the points of the top layer, at a distance d from the bottom layer. The distance can be an independent parameter as well. In case of a double layer space frame, for example, points can be located according to the platonic solids to be defined for the nodes of the space frame. Specifically, each of the nodes can be precisely located based on a local coordinate system positioned at the nodes of the first layer or shifted according to the space frame to be described. Since the local coordinate systems can be oriented according to the normal to the NURBS surface at each node or shifted position, the top layer is generated based on a constant offset of the NURBS surface.

§ 5.4.1.3 Pattern-Generator: generation of parametric tessellations

This step of model-PAS is called Pattern-Generator. It focuses on the generation of geometries by exploring a variety of patterns based on the previously defined point grid. The produced output consists of a set of different parametric tessellations.

Once the point grid is defined (A2, B2, C), a variety of parametric patterns can be generated. Software such as Generative Components already provides a set of precompiled functions by which basic cases of polygonal grids can be generated. This is the case for example with quadrilateral, triangular and diamond grids, which can be used for basic configurations of the structural and cladding elements. In order to generate tessellations corresponding to a larger variety of the geometric (structural and cladding) configurations, a set of scripts has been developed to use the grid of points as input. The output of the scripts consists of various tessellations.

- The scripts have been developed by considering the possibility to reuse and customize them.

In fact, similar to the equations through which the points are defined, these scripts can be reapplied onto different grids of points, and can easily be customized to meet new conditions.

- The scripts have been developed also considering the need of generating the tessellation by means of various geometric entities.

In fact, the tessellations outputted by the scripts are used for modelling both structural and cladding systems, and outline the geometric interface between the two systems. According to the goal for which they are going to be used, the output of the tessellation process can consist of lines or polygons.

Here following, the scripts are briefly presented both in Generative Components and in Grasshopper.

Pattern-Generator in Generative Components: In Generative Components, the Pattern-Generator has been developed as a set of scripts, to be applied and combined according to the design cases. Three major cases are identified: the generation of polygons; the generation of lines as single entities; the generation of lines grouped by polygons.

- Generations of polygons:

The generation of polygons is specifically useful for subsequent generation of cladding elements, in which the polygons are used as a basis for generating the modules.

- Generations of single lines:

The generation of single lines is specifically useful for subsequent structural analysis, in which lines are usually needed as axis of structural members. The generation of single lines instead of grouped lines allows for generation of tessellations that remain open along the edges (possible partial open polygons).

- Generations of grouped lines:

The generation of grouped lines is still specifically useful for subsequent structural analysis, in which lines are usually needed as axis of structural members. The generation of grouped lines instead of single lines prevents open polygons along the edges.

While, as an example, some scripts for grouped lines are presented in table 11.

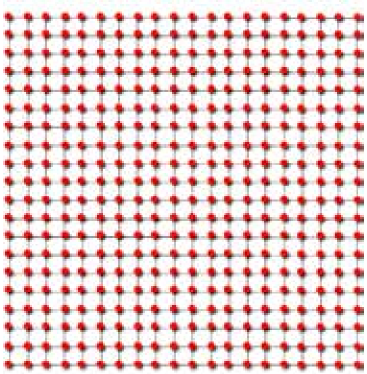
Pattern-Generator in Grasshopper: the scripts developed for Generative components have been adapted and extended, in order to be used in Grasshopper[2] . Additionally, in Grasshopper the proof of concept for a component has been developed, in order to allow users not familiar with scripting with an immediate application. The component is named TurtleShell. Despite the possibility to promptly customize the scripts is decreased, eventual further implementations and variations are fully possible; and the component can be extended and customized. The proposed proof of concept has four inputs and four outputs. The inputs consist of:

- A tree of points (a list of lists corresponding to a two dimensional array).
- An integer, named nTes, acting as independent parameter to select the pattern for the tessellation.
- An integer, acting as independent parameter to select the geometric entities in which the output will be generated.

As an example: in the current state of development of the component, the patterns for the tessellation can be selected among: quadrangular based pattern (nTes = 0); triangular based pattern (nTes = 1); hexagonal based pattern (nTes = 3); and so on for some other patterns. The output can be generated as single or grouped lines and as polylines, in alternative or together.

Examples

Quadrangles — **aFactor = 1**



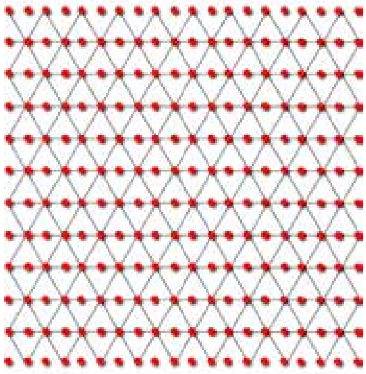
```
for (int i = 0; i < pts.Count-1; i++) {
for (int j = 0; j < pts[i].Count-1; j++) {

Line hex01ln01 = new Line (this);
hex01ln01.ByPoints(pts[i][j], pts[i][j+1]);
Line hex01ln02 = new Line (this);
hex01ln02.ByPoints(pts[i][j+1], pts[i+1][j+1]);
Line hex01ln03 = new Line (this);
hex01ln03.ByPoints(pts[i+1][j+1], pts[i+1][j]);
Line hex01ln04 = new Line (this);
hex01ln04.ByPoints(pts[i+1][j], pts[i][j]);  }}
```

>>>

2 The adaptation of the scripts from Generative components to Rhino, and their further implementation in order to generate a larger variety of patterns have been developed by Michael Winklaar, under the guidance of the author of this thesis, as part of his Building Technology MSc Graduation project at the Chair of Design Informatics at Delft University of Technology. For details, see Winklaar (2012).

Triangles	aFactor = Sqrt(3)

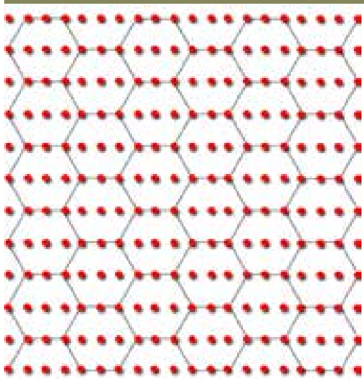


```
for (int i = 0; i < pts.Count-1; i=i+2) {
for (int j = 0; j < pts[i].Count-1; j=j+2) {

Line tr01ln01 = new Line (this);
tr01ln01.ByPoints(pts[i][j], pts[i][j+2]);
Line tr01ln02 = new Line (this);
tr01ln02.ByPoints(pts[i][j+2], pts[i+1][j+1]);
Line tr01ln03 = new Line (this);
tr01ln03.ByPoints(pts[i+1][j+1], pts[i][j]);

Line tr02ln01 = new Line (this);
tr02ln01.ByPoints(pts[i+1][j+1], pts[i+1][j-1]);
Line tr02ln02 = new Line (this);
tr02ln02.ByPoints(pts[i+1][j-1], pts[i+2][j]);
Line tr02ln03 = new Line (this);
tr02ln03.ByPoints(pts[i+2][j], pts[i+1][j+1]);
```

Hexagons	aFactor = Sqrt(3)



```
for (int i = 0; i < pts.Count-1; i=i+2){
for (int j = 0; j < pts[i].Count-1; j=j+6) {

Line hex01ln01 = new Line (this);
hex01ln01.ByPoints(pts[i][j+1], pts[i][j+3]);
Line hex01ln02 = new Line (this);
hex01ln02.ByPoints(pts[i][j+3], pts[i+1][j+4]);
Line hex01ln03 = new Line (this);
hex01ln03.ByPoints(pts[i+1][j+4], pts[i+2][j+3]);
Line hex01ln04 = new Line (this);
hex01ln04.ByPoints(pts[i+2][j+3], pts[i+2][j+1]);
Line hex01ln05 = new Line (this);
hex01ln05.ByPoints(pts[i+2][j+1], pts[i+1][j]);
Line hex01ln06 = new Line (this);
hex01ln06.ByPoints(pts[i+1][j], pts[i][j+1]);

Line hex02ln01 = new Line (this);
hex02ln01.ByPoints(pts[i+1][j-2], pts[i+1][j]);
Line hex02ln02 = new Line (this);
hex02ln02.ByPoints(pts[i+1][j], pts[i+2][j+1]);
Line hex02ln03 = new Line (this);
hex02ln03.ByPoints(pts[i+2][j+1], pts[i+3][j]);
Line hex02ln04 = new Line (this);
hex02ln04.ByPoints(pts[i+3][j], pts[i+3][j-2]);
Line hex02ln05 = new Line (this);
hex02ln05.ByPoints(pts[i+3][j-2], pts[i+2][j-3]);
Line hex02ln06 = new Line (this);
hex02ln06.ByPoints(pts[i+2][j-3], pts[i+1][j-2]); } }
```

>>>

Hexagon + Triangles	aFactor = Sqrt(3)

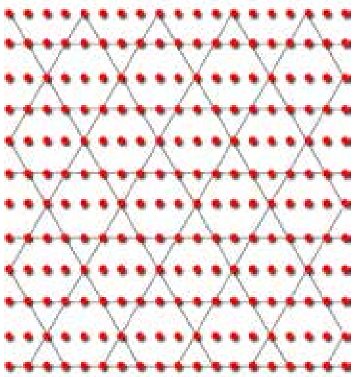
	for (int i = 0; i < pts.Count-1; i=i+4) {
	for (int j = 0; j < pts[i].Count-1; j=j+4) {
	
	Line hex01ln01 = new Line (this);
	hex01ln01.ByPoints(pts[i][j+1], pts[i][j+3]);
	Line hex01ln02 = new Line (this);
	hex01ln02.ByPoints(pts[i][j+3], pts[i+1][j+4]);
	Line hex01ln03 = new Line (this);
	hex01ln03.ByPoints(pts[i+1][j+4], pts[i+2][j+3]);
	Line hex01ln04 = new Line (this);
	hex01ln04.ByPoints(pts[i+2][j+3], pts[i+2][j+1]);
	Line hex01ln05 = new Line (this);
	hex01ln05.ByPoints(pts[i+2][j+1], pts[i+1][j]);
	Line hex01ln06 = new Line (this);
	hex01ln06.ByPoints(pts[i+1][j], pts[i][j+1]);
	Line hex02ln01 = new Line (this);
	
	hex02ln01.ByPoints(pts[i-2][j-1], pts[i-2][j+1]);
	Line hex02ln02 = new Line (this);
	hex02ln02.ByPoints(pts[i-2][j+1], pts[i-1][j+2]);
	Line hex02ln03 = new Line (this);
	hex02ln03.ByPoints(pts[i-1][j+2], pts[i][j+1]);
	Line hex02ln04 = new Line (this);
	hex02ln04.ByPoints(pts[i][j+1], pts[i][j-1]);
	Line hex02ln05 = new Line (this);
	hex02ln05.ByPoints(pts[i][j-1], pts[i-1][j-2]);
	Line hex02ln06 = new Line (this);
	hex02ln06.ByPoints(pts[i-1][j-2], pts[i-2][j-1]);

Table 11
Example of scripts for various patterns.

General specifications: With general value, referring to both cases of Generative Components and Grasshopper, two specific observations should be made. The first observation considers the close relationship between the distribution of the points and the tessellation. This implies that the nature of the polygons might be taken into account while positioning the nodes and recalls what is exemplified in table 10. An example of hexagonal patterns is provided in table 12 where hexagons with regular projections can be obtained by assigning to the parameter ‘factor’ (of table 10) the square root of 3. Obtaining structural tessellations, which include only full polygons that are properly closed along the edges of the roof, depends on the number and distribution of the nodes. Recalling table 10 again, this means that the distribution of the tessellating polygons also needs to be considered when setting the step of variability of the parameter density.

Example
Hexagonal

```
for (int i = 0; i < pts.Count-2; i=i+2)   {
  for (int j = 0; j < pts[i].Count-4; j=j+6)  {
    hex01.ByVertices({pts[i][j+1], pts[i][j+3], pts[i+1][j+4], pts[i+2][j+3], pts[i+2][j+1], pts[i+1][j]});
}}
for (int i = 0; i < pts.Count-3; i=i+2)   {
 for (int j = 0; j < pts[i].Count-5; j=j+6)  {
   hex02.ByVertices({pts[i+1][j+4], pts[i+1][j+6], pts[i+2][j+7], pts[i+3][j+6], pts[i+3][j+4], pts[i+2][j+3]});
}}
```

Table 12
Example of a script for hexagonal patterns.

Finally, it must be noticed that the geometry can still be parametrically modified according to each of the previously described levels of parameterization (figure 38).

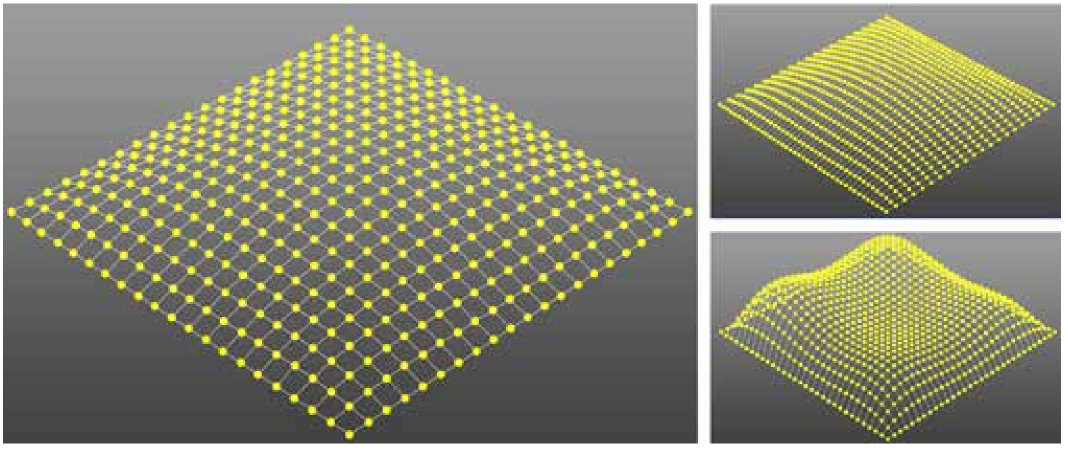


Figure 38
Examples of parametric variations. Left: Example of quadrilateral tessellation. Top Right: variation in proportions. Bottom right: variation of the overall shape.

§ 5.4.2 model-PAS secondary parameterization: structural systems

Concerning the structure and focusing on discrete systems, a wide range of modular structures can be modelled based on the different tessellations. These can be used to propagate the structural elements or can be used directly as structural geometry. Among the many, the example of space frames is quite common as well as illustrative, since single layer grids can be generated directly based on different geometric entities connecting the points. When considering a double layer space frame, a second layer of points can be added at either a fixed or parametric distance from the first layer and used for generating the second layer as well as the diagonals between the layers. The result is a parametric space frame composed of modular cells which vary in density and overall shape.

All these operations have the potential for reapplication. This operation might recall the concepts of formex algebra processing in the Formian programming language (Nooshin and Disney, 1997) and the well-known and extensive, related approach for structural design exploration. However, despite the more basic level of development of the parametric approach presented here, its potentials are noteworthy in several regards:

- an intuitive applicability to complex geometries
- an integration into the design process
- a highly visual interface combined with a library of scripts
- a versatility in being combined with further implementations of the geometric models (such as the integration of the cladding system)
- an interoperability with performance evaluation software from different fields.

This section provides a detailed explanation concerning the example of space frames. Similar approaches can be used in case of other discrete and modular structural systems.

§ 5.4.2.1 Single layer grids

In the case of grids based on single layer grids, the different tessellations achieved through the exemplified scripts can be used directly as structural geometry. By making use of the tessellating process, the structure can be generated based on different geometric entities, usually lines, polylines or polygons, according to what is most suitable for the final use. In many cases, lines are preferable for the structural analysis that follows, or polygons for the propagation of cladding elements.

§ 5.4.2.2 Double layer grids

As in the case of the single layer grids, in the case of double layer grids different tessellations can also be scripted in each of the two layers. A set of diagonals is then introduced by following the space frame requirements. Figure 39 shows both the double layer of points and the combination of bottom layer, top layer and diagonal elements of the structural system.

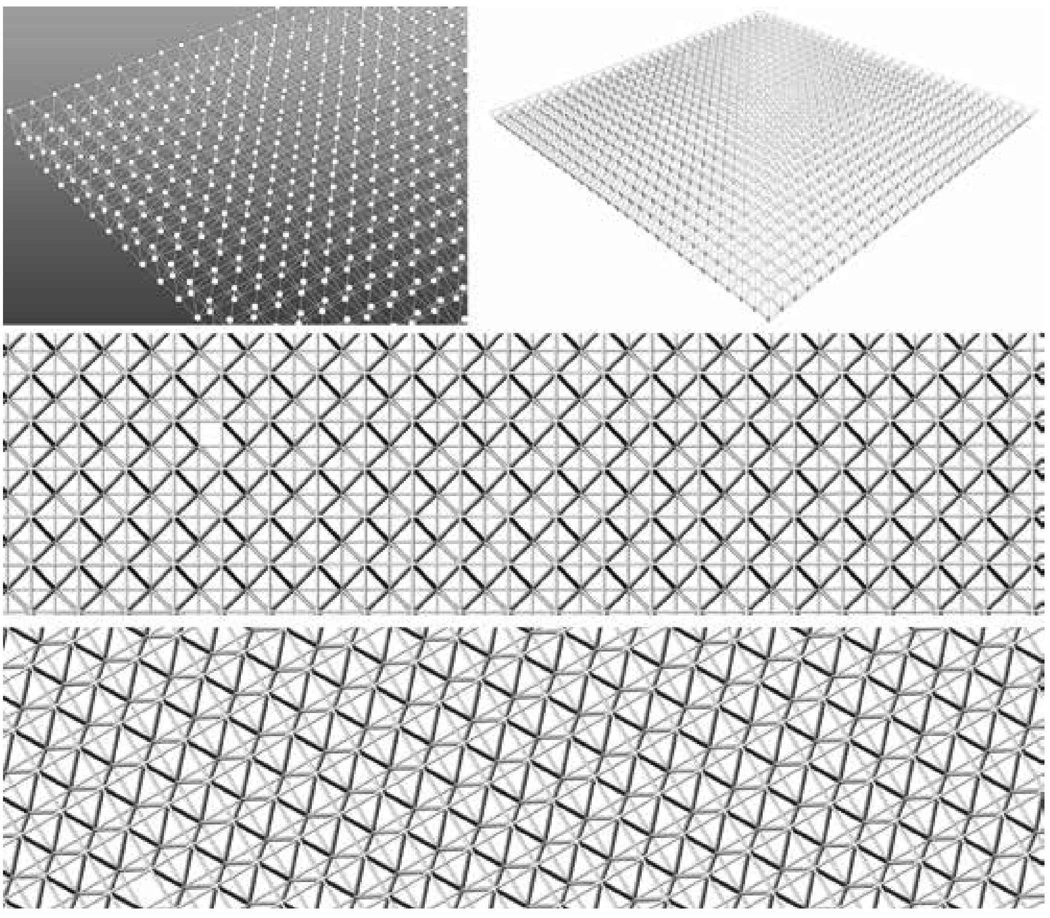


Figure 39
Example of double layer space frame with quadrilateral tessellation.

Different instances of the resulting parametric space frame can be generated by both varying its density and modelling the overall shape, as shown in figure 40

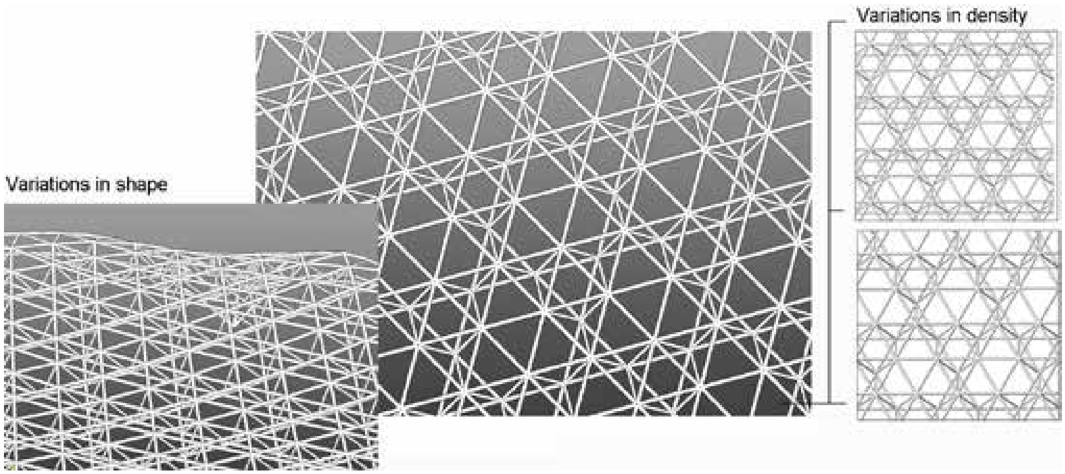


Figure 40
Example of double layer space frame with hexagonal and triangular tessellation, parametrically varied in shape and density.

§ 5.4.3 model-PAS secondary parameterization: cladding systems

Regarding the cladding, various considerations need to be pointed out, especially concerning, on one hand the geometry of the modules, and on the other hand the way the geometry is modelled and propagated.

The geometry is discussed in relation to the performance criteria presented in section 4.3. Specifically, focusing on the control of the solar exposure, the configuration of the cladding modules might aim at various requirements. Common examples are the shading of the spaces beneath the roof (such as in the case of summer overheating) or the capturing of solar radiation (such as in the case of winter need for solar gain). Depending on the aim of each specific design process and on the preliminary approach set for each design process in its pre-PAS phase, various geometric configurations can be investigated based on different principles. Some examples are presented below.

Once the geometric principles are established, the cladding modules can be predefined, modelled, and then propagated across the tessellated surface. For this procedure, polygons are usually preferred as geometric input. Specifically, the modules can be modelled starting with the polygonal tessellation, which is the interface between the cladding and the structure. Each module can be structured for different base polygons to match various tessellations or as single options specifically built for a given polygon. The modelling can be based on a repetitive process of geometric dependencies. Thus, when modelling one module, a routine of operations can be written to express the geometric relations of the module, both among its components (internal associations) and with external references (recalled as inputs). This routine can integrate independent parameters by constituting a parametric model itself. The module can then be saved as a replicable feature. Hence, it can be propagated onto the tessellation by guaranteeing the relationships with the structural geometry as well as with the other references assumed in determining its geometry.

The advantage of creating a module as a component lies in the possibility of replicating the feature not only within the model, but also in other models. This means that, as in the case of the scripts described above, the creation of libraries of predefined modules is also possible for cladding systems. This possibility is discussed in more detail in section 5.4.4.

§ 5.4.3.1 Examples of parametric cladding systems

Two examples of parametric cladding systems are presented here in order to show the flexibility of the method on a variety of design cases for semi-outdoor spaces, dealing with the control of direct solar radiation and daylight. Both examples concern complex geometry and the option of adaptivity. Detailed case studies will be instead presented in chapters 6 and 9.

The first example deals with the option of adaptivity. The cladding is meant to provide shading, with no requirement of rain protection. The primary focus is on the solar exposure and the daylight levels of the spaces underneath, controlled through the geometry. The shading system is based on hexagonal modules with six flat panels fixed to a bar passing through the centre of the hexagonal polygon. It is explored in two different options. One option combines the shading panels with a structural, single layer space frame based on a hexagonal tessellation. The bar is fixed to the frame by a set of cables, forming a triangulated structure. The other option aims at a closer integration of the cladding into the structural system, without the need of a secondary supporting space frame. In this option, a set of cables connects the top and bottom ends of each bar, again forming a triangulated structure (figure 41).

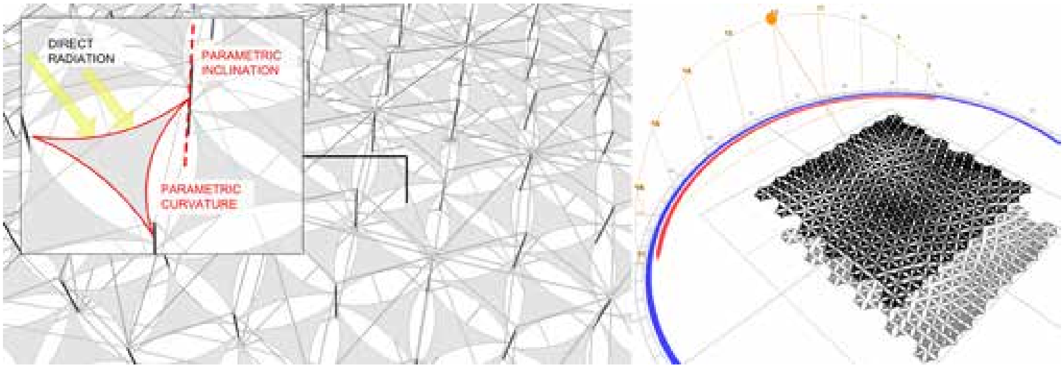


Figure 41
Parametric modelling of the cladding without space frame. Left: Control of direct radiation based on inclined panels, parametrically explored based on various inclinations and curvatures of the edges. Right: Shadows simulation for a configuration with horizontal panels and medium curvature.

For both options, two main parameters are identified. The first one controls the inclination of the bar (and consequently the orientation of the panels). In this respect, the exploration leaves open the option of adjustability of the structure, by regulating the inclination of the bars according to different environmental conditions (such as the position of the sun and the need to increase or decrease the solar gain). The second parameter governs the shape of the panels, by controlling the curvature of their edges, and, consequently, affecting the filtering of the solar radiation. Also in this case, once created, the module for each of the two options has been saved as a replicable feature, and can be propagated onto a tessellation having parametric variability in density, overall shape of the whole structure, and/or other meaningful aspects.

The second example centres on the comparison of different strategies for solar control, given certain cladding principles. The cladding is meant to regulate the solar exposure and the daylight levels based on the geometric alternation of transparent and opaque panels, with different orientations. Two options following different strategies are compared based on their performances. Specifically, in both options each component is based on a hexagonal pattern, defined by a combination of six pyramids with a triangular base, together forming a hexagonal element. Based on an algorithmic pattern, each face of the pyramids can be either an opaque or a transparent panel. In one of the two versions, opaque panels are south-oriented in order to achieve a shading effect and reduce the direct solar radiation (figure 42 top). In the second version, opaque panels are north-oriented and extended over the transparent panels in order to shade them (figure 42 bottom).

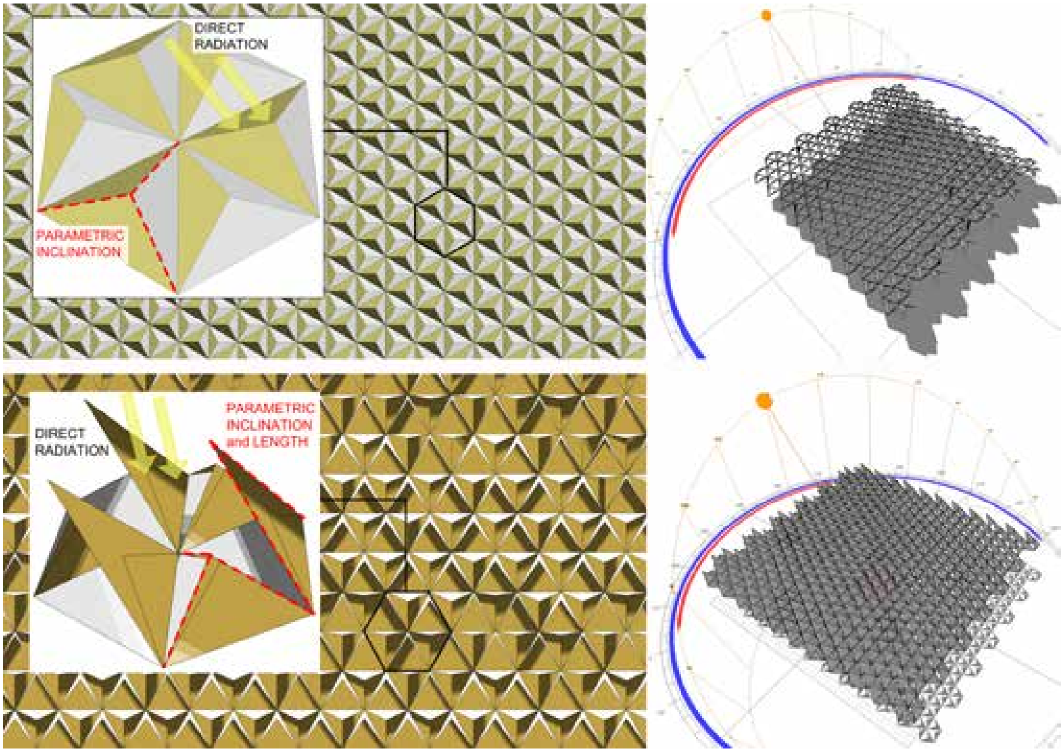


Figure 42

Top: Parametric modelling of the cladding with south facing opaque components; left) control of direct radiation based on inclined panels, parametrically explored based on various inclinations; right) shadow simulation for one of the configurations. Bottom: Parametric modelling of the cladding with north facing opaque components; left) control of direct radiation based on inclined panels, parametrically explored based on various inclinations and elongations; right) shadow simulation for one of the configurations.

In the first one of the two options, independent parameters regulate the inclination of the panels. In the second option, independent parameters regulate the inclination of the panels, but also the length of the shading elongation. Also in this case, the routines through which the geometry was created were saved as replicable features which can also be stored in a library for future applications.

§ 5.4.4 model-PAS and the hierarchy of the parametric model

The process described above allows for the generation of specific parametric models and reusable libraries of scripts and features, which can be reapplied and customized. Each parametric model can be structured in order to allow geometric variations of a given typological solution. This is the case, for example, in the variations in densities and proportions within a chosen tessellation. Moreover, the parametric model can be structured in order to allow parametrically switching from one typological solution to another, and not only from one to another geometric configuration of each single typological solution. This depends on the parameterization process, which can include a set of top parameters regulating the option to be applied. Different options can refer to different tessellations (and in this case variations in parameters imply switching from one to another pattern by recalling for example different scripts); or to different cladding modules (and in this case different parameters would recall for example different precompiled features from the cladding library); and so on. When properly articulated, such a parametric model would still allow the parametric variation of the geometry of each option (such as density, proportion, and so on). In this way the parametric models can contain a large series of alternative geometric solutions, which are widely differentiated also in topology (figure 43).

The advantages offered by this structure mainly consist in an enlarged solution space of the model. Its benefits need to be assessed in relation to the design exploration in balance with the higher complexity of the model and computation required to generate design alternatives.

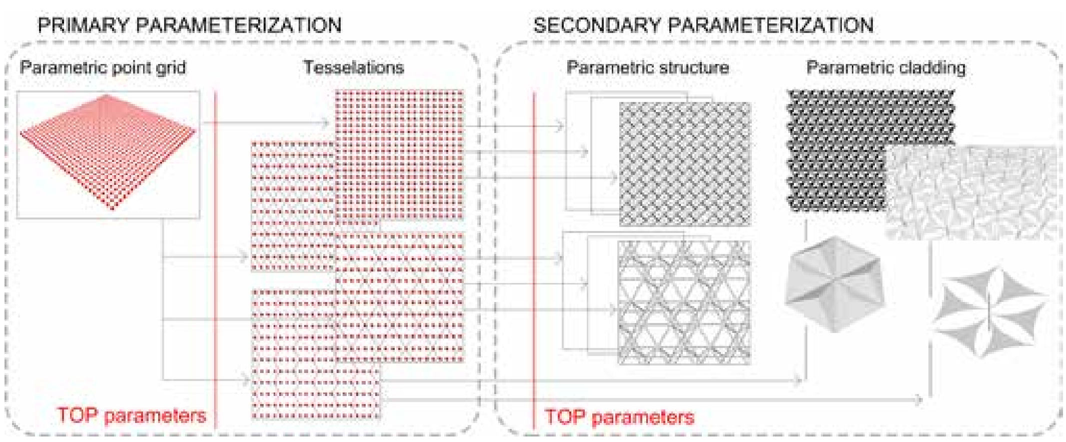


Figure 43
Scheme of parametric process.

§ 5.5 explore-PAS: performance evaluations

Explore-PAS is the last part of the method. It concerns the search for satisfactory design solutions based on the evaluation of the performance, and is based on the combination of parametric modelling with performance evaluation software and computational search techniques. Two aspects are specifically considered. On one hand the way in which the instances of the model are selected in order to be evaluated through performance simulations and on the other hand the way in which the evaluation process is set. The first aspect is presented only in a preliminary discussion, which will be more deeply tackled in the following chapters.

§ 5.5.1 Selection of instances for evaluation

Establishing the parametric models allows for automatically generating large sets of design alternatives. Based on a properly set parameterization process, the alternative solutions can be generated with meaningful reference to the performance to be analysed; and the solution space of the parametric model can be explored based on the various performance criteria. This includes evaluations on climatic comfort related aspects (thermal behaviour, daylight levels, and so forth) and structural performance, based on the relationship between structural morphology and energy related aspects. An increasing number of digital tools for early performance evaluations are being developed while parametric modellers allow for the integration of scripts for numeric evaluations. However, performing analytical evaluations still usually requires the use of specialized software in which the geometric alternatives are imported and their behaviour is simulated. The complexity of such a design exploration and performance assessment process is evident when considering the depth of the solution space, which can already consist of many thousands of solutions for a very limited number of independent parameters. This exploration and evaluation process can be carried out manually, in an iterative way, based on selection, import and evaluation of the design solutions, as illustrated in figure 44.

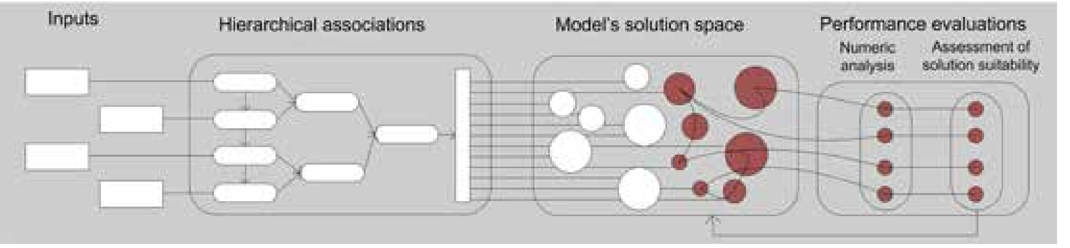


Figure 44
Selection, analysis and assessment of a limited set of design solutions.

Iteration allows extracting information and gaining knowledge from the analysed solutions in order to select the following ones. These can be explored based, for example, on their structural performances and the way they meet specific structural requirements. A manual process implies a manual selection of the alternatives to be analysed, the importation of the correspondent models into an analysis software, such as FEM software, and the simulation and evaluation of their performances. The same occurs for daylight and thermal behaviour.

The solution space of the model needs to be adequately explored in order to identify suitable design solutions among the different alternatives. Due to the breadth of the solution space, its systematic exploration is not possible when left to the intuition of the designer. A knowledge and expertise based approach is required during the exploration process, and is mainly based on interdisciplinary collaboration. For this reason, brainstorming and consultancies transversal to different disciplines are strongly recommended when selecting the design solutions to be analysed by means of performance simulations. Based on knowledge, a limited number of design solutions can be chosen due to good expectations on their performance behaviour. Simulations and analyses might confirm the expectations or not but, in both cases, they inform the process concerning the way to proceed. Based on the results, in fact, design alternatives can be chosen for comparing their performance, and so on, in an iterative process in which the awareness of the designer increases thanks to a better understanding of the relations between design variables and performance behaviour. This aspect will be specifically discussed in section 6.9 based on a case study in chapter 6. However, it must be already mentioned that, despite the indubitable support that the parametric system offers, the difficulties in exploring the solution space are a definite drawback when using parametric techniques. This becomes even more problematic when dealing with broadly interdisciplinary aspects. The integration of other computational techniques, such as search techniques related to the analysis and evaluation of performances, will be discussed in chapter 8.

§ 5.5.2 Evaluation process

The evaluation process is meant to assess the performances and support the identification of suitable design solutions, with respect to the considered performances.

It has to be set by selecting the performances to analyse, the environmental conditions in which the performances are analysed, and the design requirements upon which the performances have to be assessed. All these aspects have to be set in direct relation to the criteria considered during the parameterization process. Other criteria can be included as well, but with the awareness that the solution space of the model may not be fully meaningful with respect to these additional criteria.

Moreover, the changing properties of the context have to be considered. As introduced in chapter 2, architecture is defined in relation to human needs and environmental factors (whose ensemble is here called context); it is expected to interface both and its performances depend on the data describing both. However, both human needs and environmental factors are not constant, but vary in time. In order to take this into consideration, multiple evaluations should be made, both considering changing human needs if of relevance and changing environmental conditions. This aspect is specifically addressed in section 6.5.1.

The first aspect may be of minor relevance in a number of cases, especially when focusing on climatic comfort of semi-outdoor spaces and large enclosed areas, while it would be of fundamental importance for example when focusing on the thermal comfort of indoor areas where activities are expected to relevantly vary or for the illumination of exhibition areas or other examples. As a result, this aspect is sometime neglectable during the analysis and the design requirements might be considered constant. Differently, the second aspect cannot be neglected and is of fundamental relevance for most of the projects based on passive strategies. This appears evident when considering the daily as well seasonal changes in climatic conditions.

§ 5.5.3 Relation between pre-PAS and explore-PAS

It is significant to notice a straight relation between the pre-PAS phase 4 and the explorations that are needed in explore-PAS. The more phase 4 provides for accurate and deep analysis, the less analyses are needed while exploring the solution space of the model. This is because the coincidence between the solution space of the model and the desired design solution space increases. This aspect will be discussed in detail based on the case study presented in section 7.3.

More specifically, this aspect can be brought to extreme consequences, when the analyses lead to a so defined relation between the variation of the geometric factors and the performance trend that the generated instances of the model are all relatively well performing configurations. This aspect becomes of extreme importance when adaptivity is taken into account in the design exploration. This is specifically presented in the following section.

§ 5.6 PAS for adaptivity

This section deals with adaptivity and specifically with form-active architecture (see chapter 3). While large attention has been given to the detailed design of systems that allow for geometric reconfigurability, modest efforts have been invested in supporting the early architectural design toward the integration of reconfigurable systems in buildings. However, following the point of view presented in chapter 3, adaptivity is directly related to performance. Therefore, in contrast to traditional approaches, PAS aims at allowing design explorations also toward adaptivity, by focusing on the early phase of the architectural design process. Also for this, the primary reason lies in the large impact that preliminary design decisions have on the performance of buildings over their life time, in form-active as in static buildings.

With focus on static architecture, the potential of parametric modelling in supporting performance oriented design have been presented in the previous sections and are summarized here as the automatic generation of a large set of alternative design solutions based on a pre-set range of independent parameters; exploring such large design solution spaces based on performance evaluations has been also shown as beneficial; properly selecting the independent parameters and structuring the chain of geometric associations has been emphasized as key points in order to define solution spaces meaningful for the analysed performance.

When focusing on form-active architecture, the potentials and benefits as well as the recommendations discussed above concerning the parametric approach are still influential. However, as compared to the design of static architecture, the approach needs to consider an additional perspective, since the alternative design solutions generated based on the parametric models are not necessarily design alternatives anymore, but can be embedded in a form-active design solution as different configurations of the project. Also, when compared to the design of static architecture, the conceptual design of form-active architecture embeds additional tasks necessary to be confronted while using a parametric approach. Among them, attention is given here to three enterprises corresponding to three levels of design exploration, for which the support given by parametric modelling is discussed and the PAS approach is illustrated. These enterprises are demonstrated in case studies in chapter 7. They consist in identifying respectively:

- The proper geometric means of adaptivity;
- The suitable configurations within predefined geometric properties;
- The proper systems for form-active architecture.

The approach to these three aspects cannot be univocal nor is it within each of them, however for each of them benefits are taken from the parametric approach, as presented in the following sections. Moreover, by reckoning this perspective, three case studies of large structures are presented in the following chapters.

§ 5.6.1 Exploring proper geometric means of adaptivity

The first design exploration for adaptivity deals with the identification of the changes in various geometric properties that positively affect the performance trend of architecture during contextual changes. Particularly, this addresses the trend of a certain performance (in order to satisfy changing requirements in a constant environment or constant requirements in a changing environment or the combination of both) as compared to geometric variations. A first level of exploration deals with the identifications of the various design configurations that are suitable under different environmental conditions and can be generically represented as schematized in figure 45.

Such design exploration is here especially concerned with the explore-PAS phase. In it, the search for geometric changes positively affecting the performance trend can be performed in multiple runs, where the solution space of the parametric model is explored according to different contextual conditions, either referring to different design requirements or different environmental conditions or both. As introduced in section 5.5.2, this is of crucial importance especially considering a set of fixed design requirements to be dealt with in changing environmental conditions, such as climatic aspects for thermal and daylight comfort. With this respect, multiple explorations allow identifying multiple solutions, each of which is well performing under certain environmental conditions.

As presented, PAS supports the identification of multiple design solutions. It must be noticed that additional evaluations and decisions are then required. Once the set of design solutions is identified, further studies are needed in order to evaluate:

- The entity of geometric differences among the selected solutions;
- The feasibility of materializing such changes by means of adaptive design solutions;
- The worthiness of adaptivity as compared to the benefits in performance and eventual disadvantages of adaptive solutions (i.e. increased level of complexity in the design solution).

Figure 45 illustrates the overall proposed process.

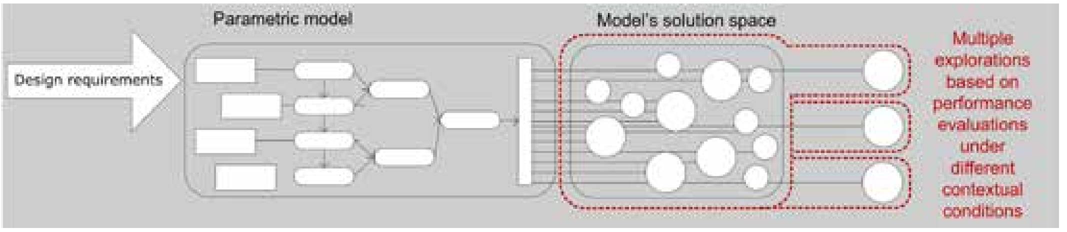


Figure 45
Exploration process of geometric means of adaptivity.

However, such exploration might result too broad and face challenges as described in section 5.5. In order to reduce the complexity of such exploration, specific sub-explorations can be conducted concerning each parameter in a preliminary analysis phase. In such process, the parametric model might be used to specifically address whether the trend of a certain performance implies the analysis of geometric variations of a different nature, some of which can be beneficial, others less. Especially when the geometry is complex and the considered performance is affected by multiple phenomena, identifying the meaningful set of geometric properties to be changed can be challenging. In other words, multiple runs of explorations can be performed by focusing on single independent parameters, in order to explore their capacity and effectiveness in affecting the performance under different environmental conditions.

§ 5.6.2 Exploring suitable configurations within predefined geometric properties

The second aspect deals with identifying the specific configurations that are suitable to achieve the desired performance trend, already knowing the nature of the required geometric changes. This also allows tracking the expected frequency of needed reconfigurations as well as their patterns during the life span of the building. The major difficulties of this consist in relating the pattern of changes in the context with the needed responses by the building.

§ 5.6.3 Exploring proper systems for form-active architecture

Finally, the third aspect deals with the identification of technical means to integrate in the building geometric adaptivity, which can include predefined systems or customized and new reconfigurable systems. While designing new reconfigurable systems is an evident challenge, integrating systems based on well-known reconfigurable structures (such as foldable or deployable units) is also a difficult task, particularly due to the geometric constraints limiting the exploration that is proper for the early phase of the design.

§ 5.7 Conclusions

In this chapter, PAS has been presented, which is a parametric design approach for performance oriented design of modular large roofs. PAS has been iteratively derived from the knowledge and theoretic studies described in the previous chapters and from the experience through the case studies described in the following chapters.

Specifically, in this chapters, potentials and challenges of parametric modelling have been discussed, with reference to the generation of design alternatives. The discussion has been proposed in general terms, for which it is applicable also to fields different than large roofs only. According to the potentials and challenges of parametric modelling, the three parts of PAS (pre-PAS, model-PAS, explore-PAS) have been then described, with direct reference to the field of large roofs. By presenting pre-PAS, a set of specific guidelines and a flowchart summarizing the process have been given; recommendations have been also provided, which aim at raising awareness on various aspects of the use of pre-PAS. In a design process, the pre-PAS phase outputs the parameterization strategies, which are then applied in the model-PAS phase. By presenting model-PAS, procedural geometries and scripts have been described for three levels of parameterization: the overall geometry of the roof, the structural system and the cladding system. Specific scripts have been also provided, which can be further implemented; they have been mostly developed for Generative Components, but their logic can be eventually translated for other software as well. The model-PAS phase allows developing the digital parametric model, whose solutions are then explored in the explore-PAS phase. By presenting explore-PAS, the selection of solutions to be evaluated and the means of evaluation have been discussed. Relations between pre-PAS and explore-PAS have been also introduced, which will be tackled in details in the following chapters. Finally, the whole process has been briefly discussed in respect to adaptive architecture.

Following the sequence above, PAS has been presented. Its potentials and limitations will be further discussed also in the next chapters, where the case studies based on which PAS has been developed and tested are described.

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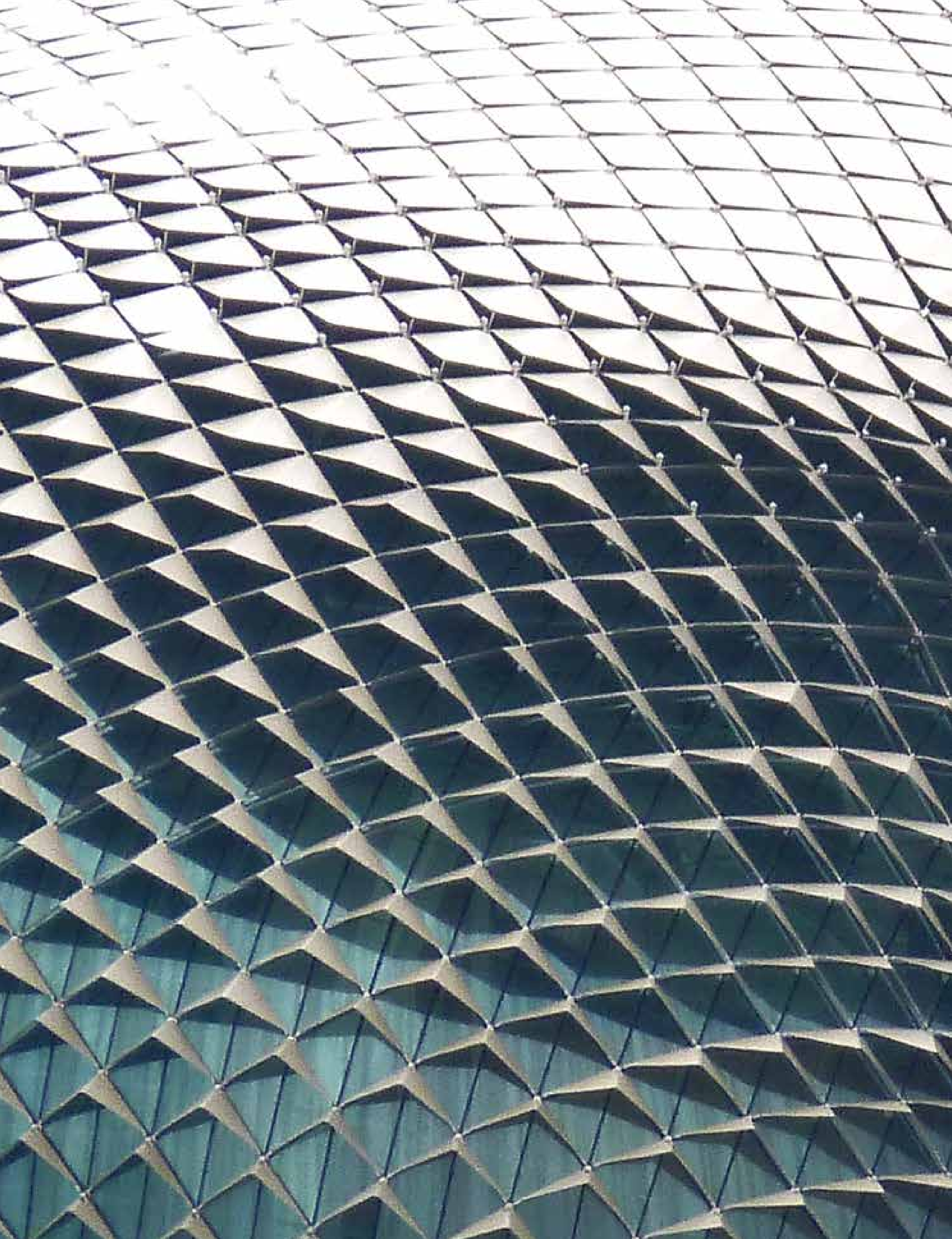
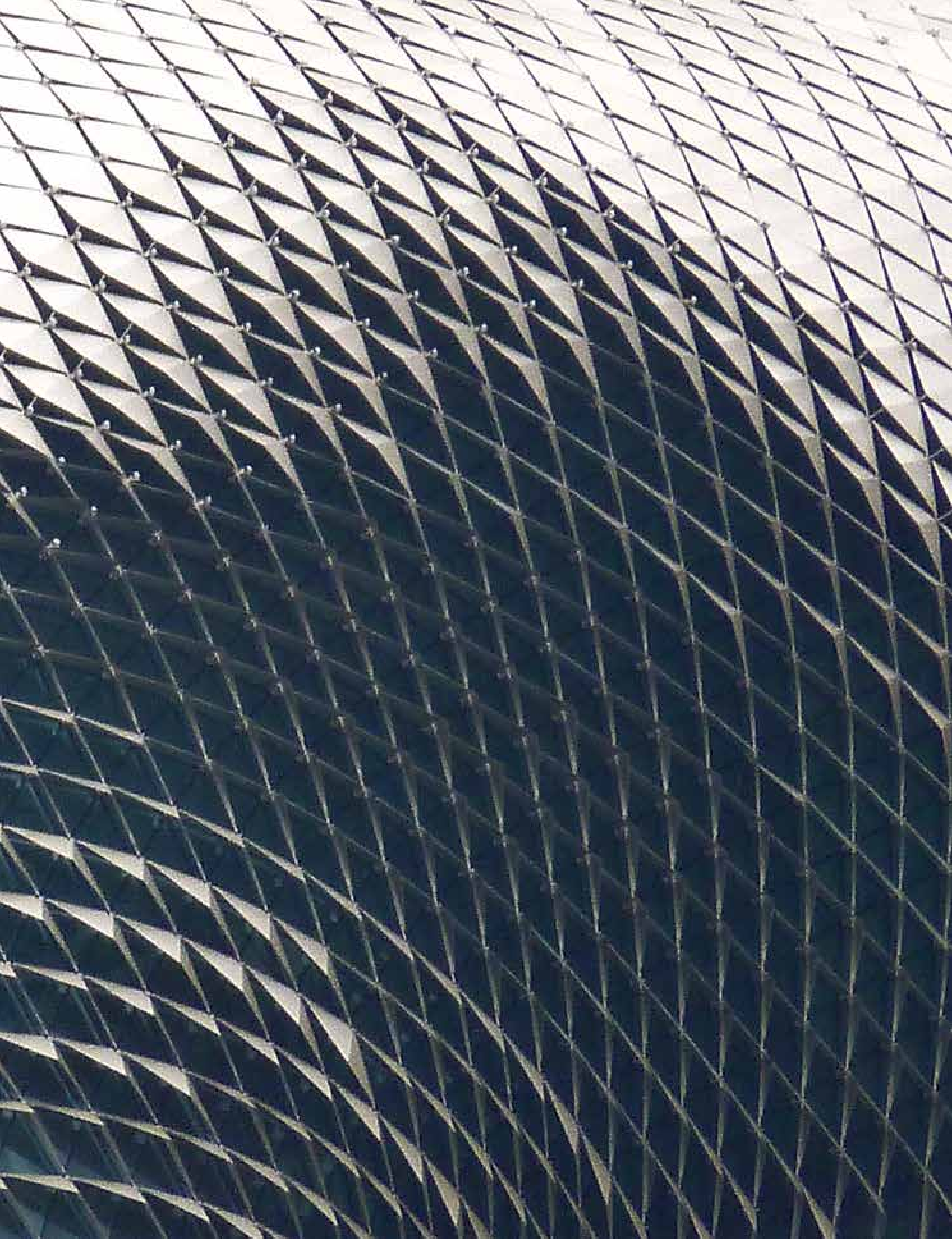




6 The Vela: a case study on the overall process

In the previous chapter, PAS has been described, which is a parametric approach for the performance oriented design of large roofs, intended as performative skins. In this chapter and the following one, a number of case studies are shown in which the parametric design approach is used and which supply feedback to the process described in the previous chapter. The case studies consist of parametric design processes in practice and in teaching.

The case study described in this chapter is from practice. An interdisciplinary team, including the author, worked on the performance oriented design of a long span roof, the Vela roof in Bologna, Italy. During this design process, parametric models were built to investigate different scales of the project, aiming at identifying geometric configurations that would contribute to the passive reduction of summer overheating of the covered spaces. The obtained instances were evaluated based on their performance regarding solar transmittance and daylight, with a combination of manual and software simulated calculations. The process was based on a reciprocal crossed validation of manual and digital tools, which required a close collaboration of the entire interdisciplinary team.

Besides showing the advantages of a performance driven exploration of parametrically generated design alternatives, the limitations of the processes are also discussed. Specific attention is given to the difficulties in exploring the solution space.

§ 6.1 Introduction

With respect to PAS, the work presented here for the Vela project played a key role in a process of action research, in which the interdisciplinary collaborations have been used as iterative fundamental contributions in formulating PAS. According to the principles of action research (Archer, 1995; Kemmis and McTaggart, 2000), the interdisciplinary work was planned, acted and elaborated into progressive feedbacks, then reflected upon the process. The work as presented here is the final result of such elaboration. This also means the explicit subdivision in phases of the building physics analysis toward a parameterization process has been partially based on the output of the research case study, while making explicit and extracting the general values of the process.

This applies to other case studies as well. For this reason, this chapter is closely related to the work of the case studies from teaching, presented in chapter 7. Also, being a collaborative and interdisciplinary process, the work was conducted as part of a team. For this reason, references to various fields of expertise are given, though the process is not presented here in its interdisciplinary completeness.

This chapter is based on a set of reports developed at TUDelft for Open Project Office and owned by the office.

§ 6.2 The Vela project

The case study focuses on a large span roof, referred to as the Vela roof, and was developed by an interdisciplinary academic team, as part of a larger on-going project from the practice. The architectural process was led by Open Project Office, in Bologna, Italy; the structural design was led by Prof. Massimo Majowiecki and his office, also in Bologna. An interdisciplinary group at TU Delft was involved in the design process of the Vela roof.

§ 6.2.1 The UNIPOL project and the Vela roof

The larger project of which the Vela roof is part of is an on-going project in Italy referred to here as the UNIPOL Project. The UNIPOL project is a large intervention on a 45.000 sqm plot located between a city by-pass and a suburban area in the periphery of Bologna (Italy) and it develops an area for services. More specifically, three building blocks enclose a public square: a high-rise office building, a hotel, and a system of lower buildings for shops and services, referred to as the Piastra. The hotel is located on the opposite corner of the plot, facing the South direction, with a floor extension of approximately 6.000 sqm; the Piastra is located between the hotel and the high-rise building, with a surface of 5.000 sqm including shops, restaurants, and a fitness centre with swimming pool. The outdoor space semi-enclosed by these buildings forms a square at the ground floor level. This square has an underground multilevel parking structure underneath and is partially covered by a large roof, the Vela, resulting in a semi-outdoor public space open along the sides. The overall area as well as the Vela roof is illustrated in figure 46, showing the concept developed by the architectural office. The academic team started the development of the case study when the office tower and the building facing it were in an advanced stage of the design and construction process, the low-rise buildings and the public space including the roof were still at a conceptual level. Currently, the office tower is finished; the hotel, the Piastra, the Vela roof, the square and the parking place are in an advanced stage of construction.

Figure 46
Top left: Project site. Top right: Overview of the UNIPOL project. Bottom left and right: The Vela roof and the public spaces underneath. (Images published with permission of Open Project Office, copyright holder).

§ 6.2.2 Design requirements for the Vela roof

The Vela roof is a large span structure covering an area of approximately 65x65 meters. The main criterion for the design of the Vela roof in relation to the buildings surrounding the square was the development of a system that joins the specific architectural, functional and climatic requirements. It was meant to protect some of the outdoor public spaces from climatic factors and at the same time provide an iconic sign within the architectural project. The square is supposed to be a public space protected from bad weather conditions, offering a sheltered area faced by shops, services and offices. At the same time, it should maintain the feeling of an outdoor area, properly illuminated by natural light and with an open view to the outside. As for this latter aspect, one of the architectural requirements concerned the visibility of the office tower from the spaces underneath the roof. Focusing on the technical requirements of the roof, the main performance-related aspects that were dealt with in more depth are its structural behaviour and its influence on the thermal comfort and daylighting of the spaces underneath. The structural performance was tackled by the structural engineers; the details of these studies are outside the scope of this research and the focus is instead given to the geometric aspects of the structural morphology. Furthermore, the roof was expected to have a large influence on the thermal comfort and daylighting of the covered spaces. As for the daylight requirements, sufficient natural light should be guaranteed not only to the covered areas directly, but also to the indoor spaces facing these areas, which are in prevalence shops and services. As for the climatic requirements, although ideally a microclimate could be created by improving the outside climate under all circumstances, realistic expectations for semi outdoor spaces are generally close to the outdoor climatic conditions. This means high improvements on thermal conditions are usually not expected, but higher levels of discomfort are not accepted either. This is in accordance with the principles presented in section 4.2.2. In the case of the Vela, this was supposed to be achieved by means of passive principles, in accordance with the strategies presented in section 4.3. Table 13 summarizes the design requirements on which the work presented in the following sections focused.

Design requirements	
Field	**Requirement**
Visual perception	Visibility to the outside – especially to the tower
Thermal comfort	At any time, thermal comfort not inferior to the outdoor comfort
Daylight comfort	Sufficient daylight for the covered area, with outdoor feeling Sufficient daylight for the indoor spaces facing the covered area

Table 13
The table presents a summary of the design requirements here considered.

§ 6.2.3 The primary generator of the Vela roof

When the interdisciplinary TU Delft team became involved, the geometry of the roof was already under design. Specifically, at that stage a primary generator was preferred, which consisted of a light horizontal element degrading into vertical along a diagonal, to be grounded in the middle of the square, as shown by figure 47. A set of alternative concepts have been discussed by exploring transversally across a number of possible design directions. Some of them are also illustrated in figure 47.

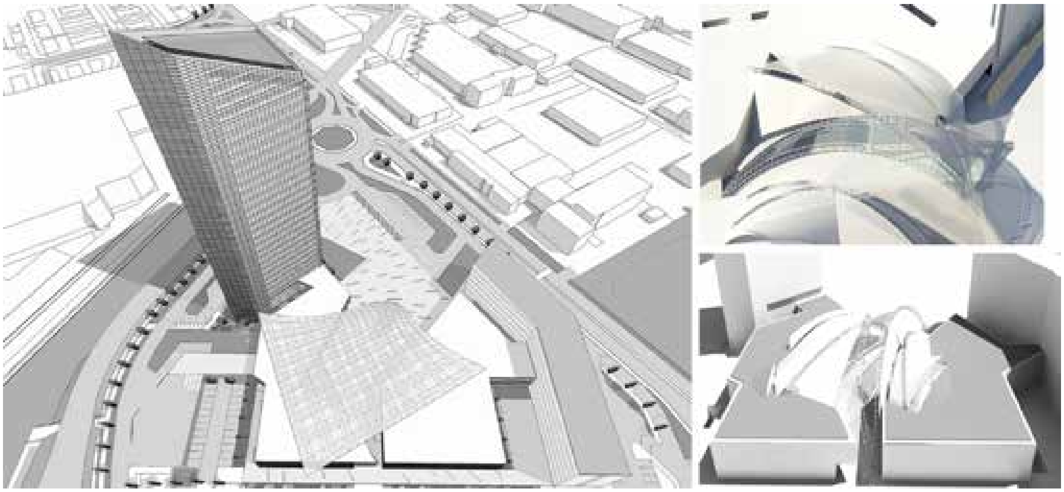


Figure 47
Primary generators. Left: The Vela roof in its initial geometry. This primary generator is the one developed into a final project. (Image courtesy of Open Project Office). Right: one of the other primary generators, among the ones discarded. (Images courtesy of Paul de Ruiter for Open Project Office).

The following sections will focus on the preferred primary generator only. However, in principle the process could be repeated for the other different primary generators too. Moreover, the preliminary considerations on the design requirements have made the ones concerning thermal comfort emerging as the most challenging. This is the reason for which emphasis in the following sections is given to them.

§ 6.3 pre-PAS

In this section, the formulations of the preliminary parameterization strategies are presented and the way in which they were pre-established is discussed, with focus on thermal comfort. The process of the calculations was developed by the building physic engineers. The aspect emphasized in pre-PAS is the extraction of information in order to properly formulate the parameterization strategies.

§ 6.3.1 Phase 1: preliminary calculations

Focusing on thermal comfort, the Vela roof is expected to avoid higher discomfort than the outdoor level of comfort or even mitigate the outdoor climate conditions by means of passive principles. The requirements concerning thermal comfort are directly based on a comparison between outdoor comfort and the comfort of the covered spaces. For this reason, both aspects are analysed in the preliminary assessment.

Starting from the outdoor comfort, deeper insights into the outdoor conditions were given by the climate analysis. The climate aspects were provided by the analyses of the local climate, based on EERE statistics data (EERE, World Wide Web reference). Specifically, the local climate is characterized by high annual thermal excursion (about 22C difference between the coldest month, January, and the warmest, July), limited wind speed and absence of dominant wind direction, high air humidity and little precipitations. In such a condition, possible summer overheating under the roof was identified as the most critical risk. In order to verify the risk of summer overheating, preliminary calculations were made concerning the outside context, based on the EERE data. Specifically, the physical equivalent temperature, PET, (Hoppe, 1999), the predicted mean vote, PMV, (Fanger, 1972; van Hoof, 2008) and the predicted percentage dissatisfied, PPD, (Fanger, 1972; van Hoof, 2008) were calculated for the month of July, without direct solar radiation. The results are shown in figure 48, which visualizes also the outdoor daily average temperature in July. Further calculations show that when direct solar radiation is instead taken into account the PET value rises above 60 degrees C.

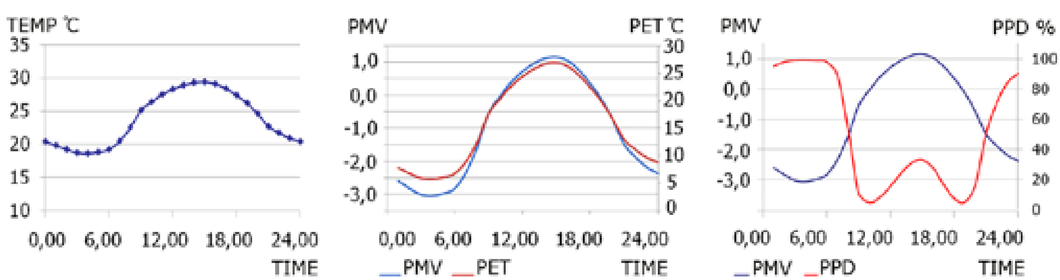
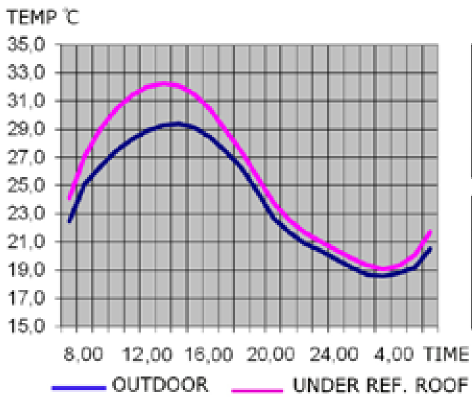


Figure 48
Outdoor temperature, PMV, PET and PPD on an average day in July in Bologna (no direct solar irradiation).

Secondly, in order to understand the conditions under the roof, preliminary calculations were made assuming a reference shape and reference materials. Given the primary generator, preliminary numeric analyses were run on a reference geometry that represented the concept. Specifically, the geometry of the roof was assumed as given by the initial preferred architectural concept, with 50% transparency, and 30% solar absorbance by the opaque elements. These calculations confirmed the risk of highly uncomfortable thermal conditions and showed that in high summer season the climate underneath the Vela roof would be worse than the outside climate, leading to unacceptable conditions. Figure 49 shows the comparison between the air temperature, PMV and PET outside and underneath the reference roof.



OUTDOOR			
	air temp	**PMV**	**PET**
maximum	29,4	1,2	26,9
average	27,8	0,5	23,4

UNDER REFERENCE ROOF			
	air temp	**PMV**	**PET**
maximum	32,3	2,5	35,1
average	30,2	1,7	29,9

Figure 49
Comparison between the outdoor temperature, PMV, PET and the temperature, PMV, PET underneath the Vela roof assumed with 50% transparency, 30% solar absorbance of the opaque elements and an average thermal mass.

§ 6.3.2 Phase 2: definition of sub-goals

Based on the risk of highly uncomfortable thermal conditions emerging from the preliminary calculations on the reference roof's shape and materials, specific sub-goals were set as reduction of summer overheating under the roof. This need was high for the daily hours of the summer period.

§ 6.3.3 Phase 3: design strategy by passive principles

As mentioned in chapter 5, having defined the sub-goals, the means from passive strategies can be used to define the design strategy suitable to reach the goals and preliminary calculations can be run in order to briefly quantify the possible benefits, if any. With this respect, in designing the Vela roof, various strategies were investigated considering both active solar technologies and passive systems for heating and cooling. Reflecting on the expected critical summer overheating, especially the second kind of systems was analysed more deeply.

In order to improve the summer critical situation, a wide range of investigations was made during the design process of the roof. Recalling the principles described in section 4.3, strategies for improving the thermal comfort involve a large set of combined systems for heat gain reduction and passive cooling, among them increasing and controlling the air flow, reducing the direct solar radiation and the mean radial temperature of the roof, using thermal mass and evaporative (adiabatic) cooling for reducing the maximum temperatures. In the following sections, specific attention is given to these principles.

§ 6.3.3.1 Increasing and controlling the air flow

Increasing the airflow was expected to have three different effects on the thermal comfort: getting the air temperature in the space under the Vela roof closer to the outside air temperature; increasing the air speed; decreasing the gradient temperature. Preliminary studies were made concerning these effects under the Vela roof. In order to reduce the summer overheating, getting the air temperature in the space under the Vela roof closer to the outside was obviously advantageous only when the air temperature under the roof exceeded the outside air temperature. Increasing the air speed generally improved the thermal comfort, according to the diagram shown in figure 50. Finally, increasing the air speed was supposed to decrease the expected temperature difference of 3 to 6 degrees between the floor and the roof. This was identified as especially important for the terrace on the 1st level and the fitness area on the 2nd level.

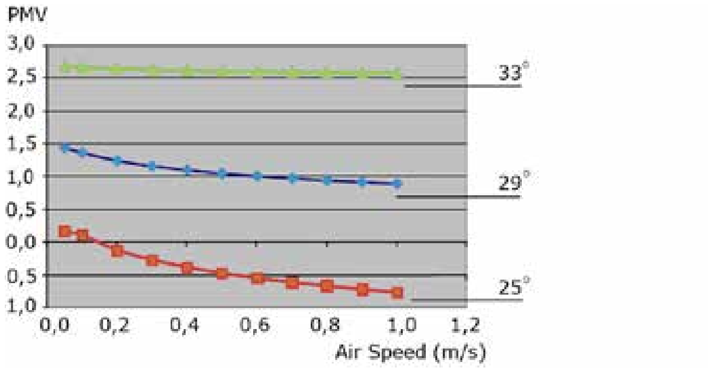


Figure 50
Effect of air speed on PMV.

Each of these three effects was considered for potential benefits. None of these effects were however expected to provide a level of thermal comfort higher than the outside comfort in summer conditions. It was concluded that:

- Increasing and controlling the airflow was a passive principle selected for further investigation.

§ 6.3.3.2 Reducing direct solar radiation transmittance

The total amount of solar energy transmitted through a roof depends on the percentage of transparent and/or translucent elements and the solar energy transmittance (g-value) of these elements. Different levels of transparency of the Vela were preliminarily investigated looking at the effect of the incoming solar energy on the average air temperature in the space under the roof. These are illustrated in figure 51.

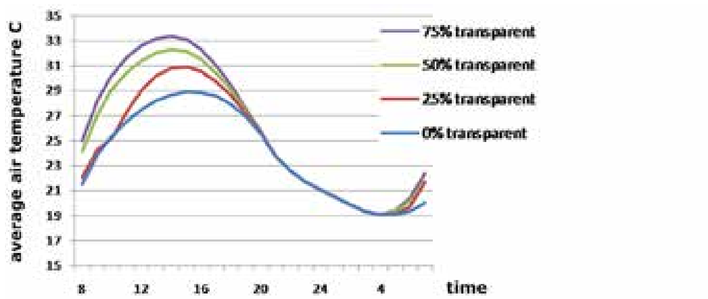


Figure 51
Effect of solar radiation transmittance on air temperature.

The results clearly favoured a solution with high level of opacity. This was potentially conflicting with the architectural wiliness of transparency and the importance attributed to the outside view. It was concluded that:

- Reducing the direct solar radiation transmittance was a passive principle selected for further investigation.

§ 6.3.3.3 Reducing long wave radiation from the roof

As explained in section 4.3.1.2, when a roof is irradiated by the sun the temperature of the inner surface of the roof can rise high above the air temperature; this depends largely on the absorption factor of the roof. A roof temperature higher than the air temperature influences the thermal comfort since it causes a long wave heat radiation. To preliminary investigate this aspect, the inner surface temperature of the Vela roof was calculated during a hot summer day in July for different solar absorption factors, varying from 0% (=100% reflective) to 40%. The results are illustrated in figure 52. it was seen that the air temperature reaches a maximum of 29 C. It was also seen that the roof temperature, i.e. the temperature of the opaque elements in the roof, can easily rise above 40 C when the outer surface of the cladding system has a solar absorption factor of 40% or more.

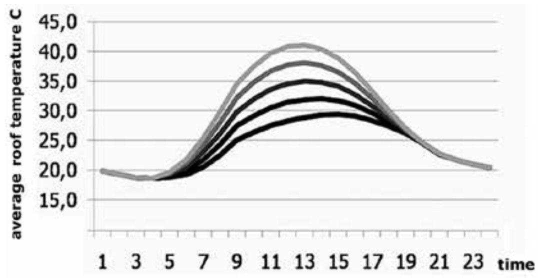


Figure 52
Effect of solar absorption on the roof temperature, for five different levels of absorption (from 0% to 40%).

It was concluded that:

- Reducing the solar absorption factor of the roof in order to lower the average roof temperature was a passive principle selected for further investigation.

In addition to the reduction of the absorbance, also other means for reducing the long wave radiation from the roof were preliminary considered. These were based on accepting some absorbance and consequent radiations, but then limiting the effects of the radiation. Several principles could be applied to reduce the long wave radiation, such as lowering the roof temperature by thermal insulation of the roof; reducing the long wave emissivity of the inner surface of the roof by using a reflective coating; using a screen, between the roof and the space below. When considering the overall framework, using thermal insulation showed the risk of being too expensive; and using inner screens as second skin required attention to the architectural wiliness of transparency. It was concluded that:

- No other means for reducing the long wave radiations were selected for further investigation. Reflective properties should be however considered.

§ 6.3.3.4 Stabilizing the temperature using thermal mass

Having an outdoor temperature difference between day and night of about 10 degrees, the daily temperature fluctuation under the Vela roof could be influenced by activating the heat storage in the thermal mass of the building and thus making use of the colder outside air during the night. Based on the preliminary studies, the maximum temperature was possible be lowered with around 2 degrees by enhancing the thermal mass.

In order to activate the thermal mass, ventilation could be enhanced through the underlying parking spaces and through the ground. Moreover, additional thermal mass could be included by using heavy building materials for the building volumes under the roof and adding extra elements such as walls. However, since most of the buildings facing the covered square needed large glass windows for visibility of the shops and public services and the ventilation through the underneath structures must be limited to comply with the regulations for underground parking areas, this option was included in the strategy, but not considered as a key point. It was concluded that:

- No specific aspects on the thermal mass were selected for further investigation.

§ 6.3.3.5 Reducing maximum temperature using adiabatic cooling

Preliminary studies on adiabatic cooling included water located under the roof, in the form of ponds or fountains; and the use of vegetation, as shown in figure 53. In general, ponds can be used to reduce the maximum temperature in the space under the roof based on two effects. First a pond provides heat storage capacity (per kg water can store five times more energy than concrete), moreover, and more importantly, on the surface of the pond latent cooling through evaporation would occur. Under the Vela roof, the preliminary estimation quantified the cooling capacity of a pond as est. 50 – 200 W/m2. In general, vegetation reduces the maximum temperate by means of evaporative cooling and provides shading. As additional benefit, besides the adiabatic cooling effect, it was considered also that trees or pergolas protect from the long wave radiation from the roof. An example is illustrated in figure 53.

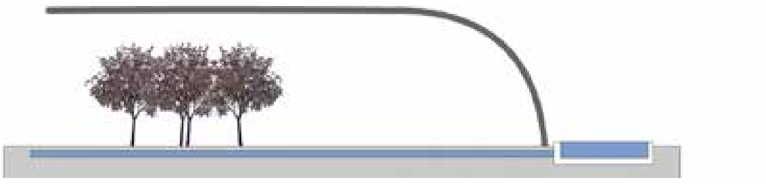


Figure 53
The scheme illustrates a combination of ponds and vegetation for adiabatic cooling.

Based on the preliminary analysis, adiabatic cooling was expected to have high potential in reducing the summer overheating under the Vela roof. It was concluded that:

- Adiabatic cooling by means of water and vegetation was a passive principle selected for further investigation.

§ 6.3.3.6 View factor to the clear sky

A final note is made concerning the view factor to the clear sky along the edge zones and by means of openings in the Vela roof. Increasing the view factor along the edge zones could be achieved by increasing the height of the roof and/or reducing its surface. However this would have had an impact on the functionality of the roof (including protection from rain along the edges) and on the proportions between the structure and its context that were considered unsuitable for architectural and urban purposes. The effect of openings in the roof was instead considered in combination with the need of openings for ventilation. It was concluded that:

- No specific aspects on the view factor to the clear sky were selected for further investigation.

§ 6.3.4 Phase 4: extraction of meaningful geometric properties

For the factors selected during phase 3, the specific geometric properties of the design that affect each factor and its effectiveness were extracted and made explicit, in order to then be used in the parameterization process that followed.

A comparative table for the numeric results of the preliminary analyses can be found in appendix AII. Based on these results, design directions to improve the thermal comfort under the Vela roof included a combination of the following measures concerning material and geometric properties:

1. In order to enhance the air flow under the roof, geometric properties of the roof were to be explored at two levels. At the level of the large scale geometry of the roof, the overall shape was to be investigated. At the level of the medium scale of the roof, the distribution and size of openings were to be explored.
2. In order to reduce the direct solar radiation transmittance, both material and geometric principles were to be considered. Among the material properties, the most relevant was the transparency. Among the geometric properties, the distribution and combination of transparent and opaque elements emerged as the most relevant. Appendix AIII shows several possibilities for this. This mainly affected the small scale geometry of the cladding.
3. The solar energy absorbance of the roof was to be limited. This mainly depended on the material properties; especially solar energy absorbance of the opaque roof elements had to be preferably lower than 20%. Since the integration of screens and other additional means was excluded, no relevant effects were expected form geometric aspects.

4 Trees and ponds were to be integrated in the project to reduce the maximum temperature; however no relevant effects were related to the geometry of the roof. Concerning the geometric properties considered for parameterization, the process is represented in figure 54.

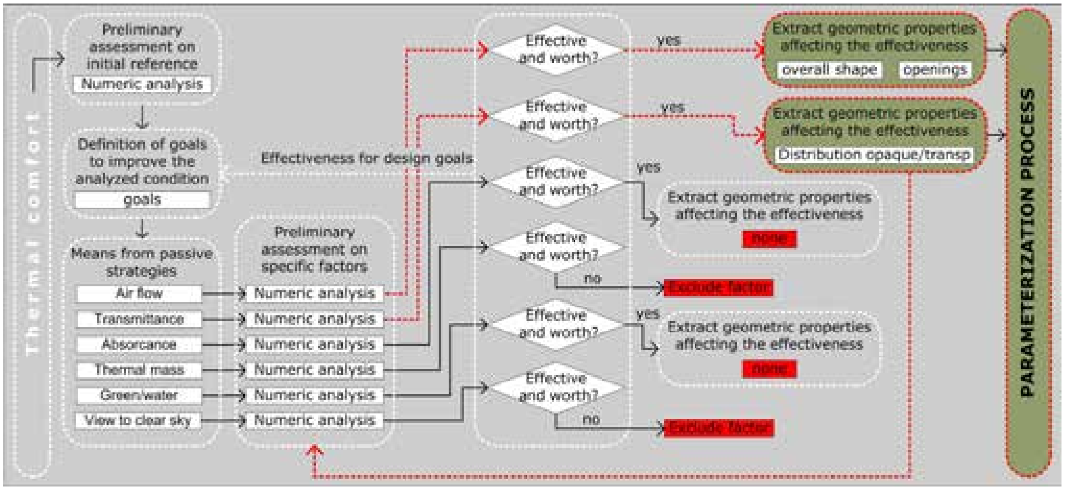


Figure 54
The flowchart shows the process of selection for meaningful geometric properties toward parameterization.

As a result, three main topics of geometric investigation emerged as relevant:

- At the large scale: the overall shape of the roof;
- At the medium scale: the distribution and size of the openings;
- At the small scale: the reciprocal distribution of opaque and transparent cladding elements.

§ 6.4 pre-PAS, model-PAS, explore-PAS: large to small scale geometry

This section introduces the setting and structure of the overall final investigation in pre-PAS and the parameterization in model-PAS phases; and the setting for their performance evaluation in the explore-PAS phases.

§ 6.4.1 Preliminary analysis and parameterization

At each of the three scales, more specific geometric properties were selected based on additional numeric analysis. Also the development of the parametric model (model-PAS) regarded each of the three levels, taken one by one. As such, they are singularly described in the following sections. However, the general framework proposed by model-PAS links the three levels and allows their parametric interconnection through the whole hierarchy of associations. Figure 55 illustrates the process.

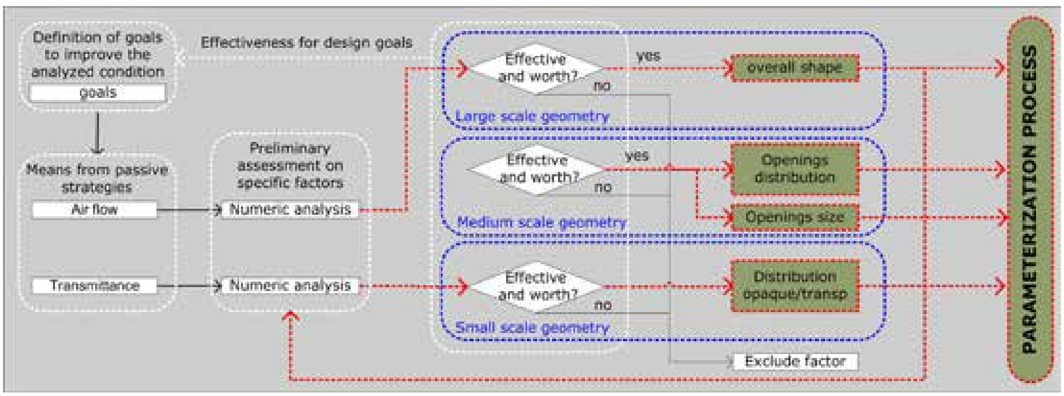


Figure 55
The flowchart shows the process of selection for meaningful geometric properties toward parameterization for the large scale geometry.

§ 6.4.2 Setting for performance evaluations

Generally, before stepping into the parametric model making, brief general considerations on the performance evaluation process are advised, which can be taken from the process the building physics engineers need to perform. This is of key importance in order to build the parametric model by using geometric elements that are appropriate for providing the needed information for performance evaluations or even being imported into the simulation software.

In the Vela case, performance valuations were planned by the building physics engineers concerning both the single factors and their effect on the perceived equivalent temperature, PET (see section 4.3). Various software were used for this, and will be presented in the specific sections later in the chapter. Concerning the single factors, performance simulations were made for the airflow and for the shading. Effects on PET were evaluated for the airflow, the shading and direct solar radiation transmittance, the long wave radiation and adiabatic cooling. Calculations of PET were done with the software CONTAM 2.4. This software is a multizone modelling software that requires the definition of zones in the analysed area. The spaces covered by the roof are divided in 9 zones, each subdivided in 4 subzones at different levels. Here following, results of the calculations are presented for the transversal section D-D' and are shown for the 20 points located along the section. Figure 56 shows the reference scheme for identifying the nine zones, and includes the section D-D' with the 20 points.

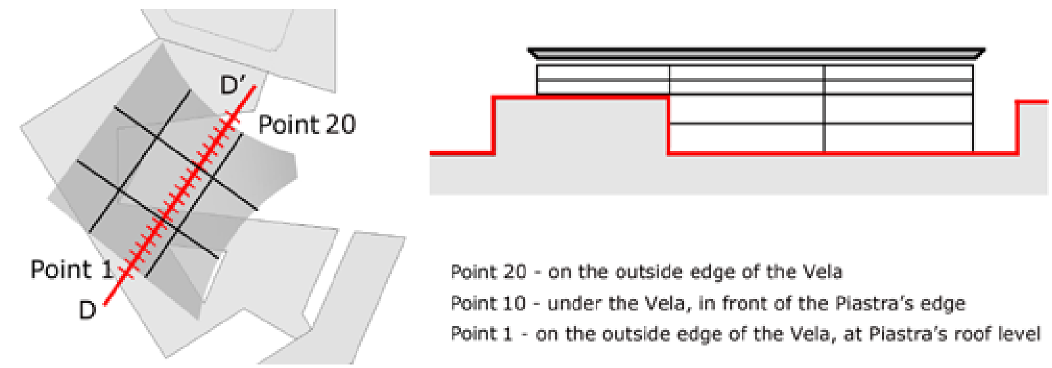


Figure 56
In order to simulate the performance of the Vela, nine zones were defined under the roof and section D-D' was taken as reference section, by visualizing the results for 20 of its points. The right image shows the schematic cross section D-D' with the crossed compartments.

Unless differently specified, all the results regard PET calculations that were performed for the July average conditions; assuming constant clothing and average air speed (clothing = 0,7; average air speed = 0,5 m/s). According to the comfort requirements described in section 6.2.2, all the PET results calculated for the different factors can be compared with the outdoor PET in summer time in order to be assessed.

§ 6.4.2.1 Reference threshold

Being equal and not worse than the outside conditions was taken as the acceptable threshold. For this, the outdoor PET is illustrated in figure 57.

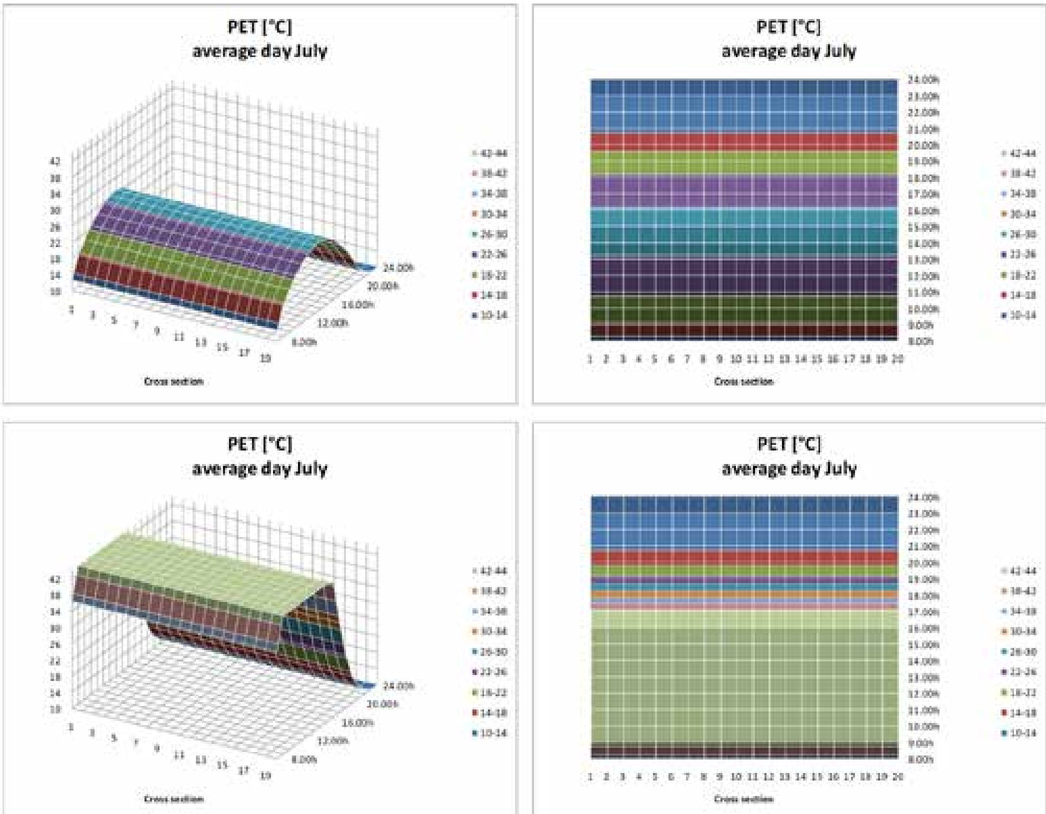


Figure 57

The diagrams show the PET in July of the reference outside situation: shaded (top diagram) and un-shaded, under direct solar irradiation (bottom diagram).

§ 6.5 pre-PAS, model-PAS and explore-PAS on large scale geometry

At the large scale geometry, increasing and controlling the air flow was investigated with respect to two possible air-flow drivers: wind and stack effect, which are both directly affected by the large scale geometry of the roof. Cooling through wind-driven ventilation typically uses the on-site air draughts, while the heat extraction through stack effect driven ventilation typically uses the differences in the height of the structure.

§ 6.5.1 pre-PAS design strategy: wind-driven ventilation for cooling

In genial, cooling through wind-driven ventilation is based on the use of the local wind behaviour. In order to investigate the use of wind-driven ventilation for cooling in the case of the Vela, CFD simulations were performed to analyse the air flow on site. Based on their results, alternative roof configurations were considered to enhance the underneath air flow.

§ 6.5.1.1 Local wind analysis and CFD simulations on the site

In general, Bologna is a challenging context with respect to wind due to the low speeds and the fact that the local wind rose shows almost no dominant wind direction. The wind is weak and almost equally coming from all sides. However some differentiations are identifiable. The process for the Vela is presented here following.

From the data below and from the Relazione di VAL S.I.A. della Variante al Piano Particolareggiato del Comparto R3-28 via Larga Bologna, it was read that two conditions were the most relevant situations regarding the local wind behaviour: the summer condition and the winter condition. In winter time, calm wind periods equalled around 70% of the measured conditions; in case of wind, there was a 30% predominance of West Winds. In summer time, calm wind periods decreased to 35% of measured conditions; the dominant direction was more variable and less identifiable, even if some predominance from East had to be acknowledged especially in daily hours. While in night hours calm winds were more frequent and there was a predominance of West Winds. During May, July and August no relevant amount of wind was coming from North-West. Although the location had little wind and no single dominant wind direction, the simulations showed that the built environment created some enhanced wind speeds (figure 58).

Month	I DWind %	II DWind %
Jan	NE 15%	SE,SW 14%
Feb	S 16%	SW,N 14%
Mar	SW 15%	E,S,NW 13%
Apr	SW,W 14%	N,NE,SE 13%
May	SW 15%	N,NE,S,W 13%
Jun	S 16%	SW 14%
Jul	SW 15%	NE,SE 14%
Aug	SE 15%	S 14%
Sept	S,W,NW 14%	N,NE 13%
Oct	SE 15%	W 14%
Nov	S,W 14%	NE,SE,SW 13%
Dec	S 17%	SW 14%

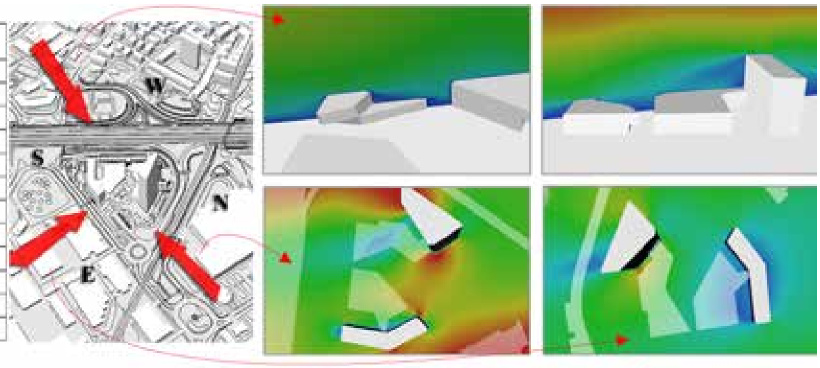


Figure 58
Dominant wind directions and related wind analysis on the project site.

Since the short time did not allow digitally simulating all the wind directions, a choice was made to evaluate both the dominant summer directions (East in daily hours; West during night hours, with more frequent calm wind periods) and the built environment configuration. In this early phase, three main directions were then chosen and analysed: South-west; South-east; North-east. Referring to these wind directions, two main general aspects emerged for the square design. On one hand, not only did the average wind never reach an uncomfortable speed, but also it resulted so slow that it needed to be captured in order to provide the desired cooling effect. On the other hand, natural wind was almost absent due to the configuration of the built environment, but some useful draughts were created by the high-rise building. Within this general context, some aspects were selected for further consideration.

Concerning winds from South-East, due to the Hotel the whole square was within the wind shadow. Trying to redirect the wind from the Hotel's roof did not seem effective in respect to the aim of making the wind enter the spaces covered by the Vela and, thus, the wind shadow had to be assumed as it was. However, when the South-East wind blows, a relevant draught resulted to be brought into the square by the high-rise building. This meant that when the South-East wind blows the only wind affecting the square resulted to be the one coming from the North-East. Wind from the South-West resulted to be stopped by the highway at the levels of the Pistra, but up to the top level of the Piastra it could blow without interferences. This meant that wind from the South-West could be caught by the roof and driven within the enclosed spaces of the square. A note about the South-West direction has to be made with reference to the Restaurant Terrace. That area in fact highly needed cooling winds but was totally in the shadow wind of the top level of the Piastra. In order to make some cooling draughts blowing on the terrace, wind had to be driven there. It was shown that wind from the North-East converge on the square under effect of the build environment with specific influences given by the high-rise building and the Hotel. Since these latter drive the wind within the square, in their proximity higher wind velocity was evident. The same behaviour was highly expected also by East wind.

§ 6.5.1.2 **Design strategy**

Referring to the previously described local wind behaviour, with respect to the analysed wind directions, it was known that the South-West wind comes in the square from the high-rise, that North-East and supposedly East winds converge in the square by brushing the high-rise building and the Hotel, and that the South-West wind blows up to the roof of the Piastra. By combining the thermal considerations presented in the previous sections with the local wind factors, two main design directions were considered. The first one aimed at catching the wind draughts; the second one at speeding them up underneath the Vela roof in order to make effective use of these draughts. Regarding both aspects, among the boundary conditions given by the architectural concept, the curvature of the roof was identified as the key factor.

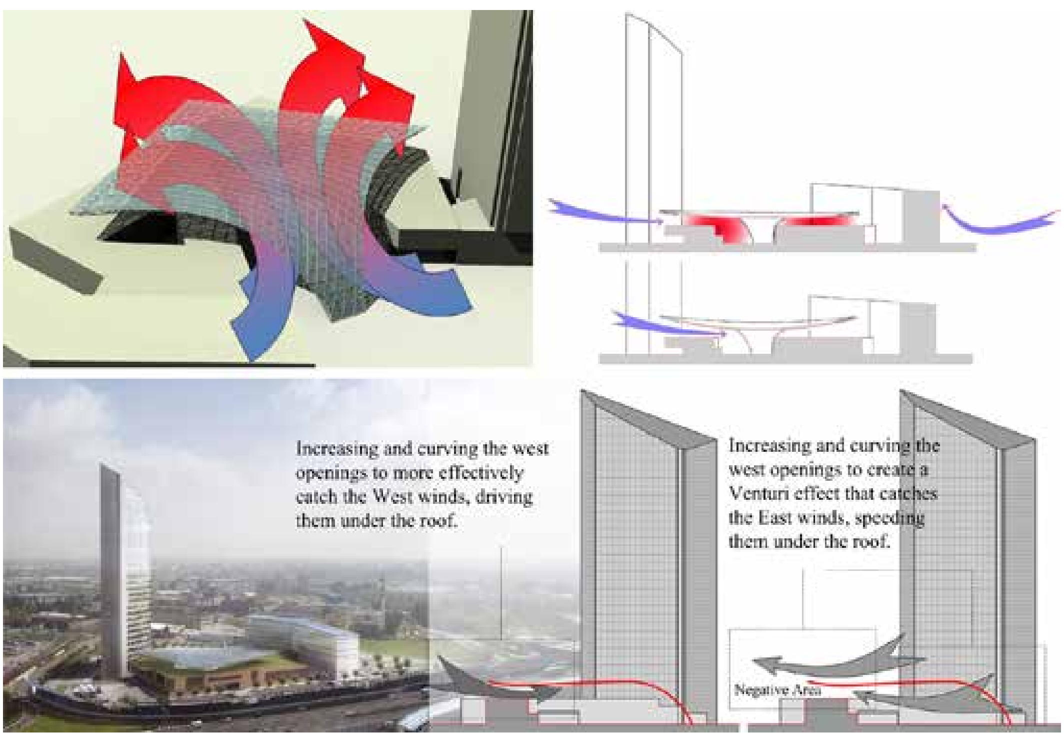


Figure 59
Strategies for increasing the air flow for cooling by driving the wind drafts through the curvature of the roof (Bottom left: image courtesy of Open Project Office).

Regarding the first one, opening the roof close to the Hotel on the East side and, even more, close to the high-rise building was quite important. This was to allow catching the South-West, East and North East winds. Figure 59 top-left illustrates both the wind caught from East and North East; figure 59 top-right the wind caught from South-West, for which properly shaping the openings was crucial.

Regarding the second one, shape variations were searched to induce local Venturi-effects that would have resulted in increasing the air speed in the direction of the created negative-pressure areas (figure 59 bottom). A Venturi effect on the West side was expected to increase the incoming wind from the east directions; and bigger openings were expected to increase the incoming west wind. Figure 59 bottom-right illustrates this double positive effect, reached by curving the west edges of the Vela.

Adaptivity: Adaptivity in the large-scale was expected to contribute to an adaptive control of various factors, including an eventual wing effect. The use of a reconfigurable geometry (see section 3.4.2.2) truss system was considered for allowing the roof to assume different curvatures. However, the level of complexity of this design direction was estimated too high as compared to the benefits. This was especially true when considering the combination with the cladding in addition to the adaptive structural system.

§ 6.5.2 pre-PAS design strategy: stack effect driven ventilation

Cooling through thermal driven air flow is a principle based on the thermal stack effect. The thermal stack effect is driven by buoyancy, which increases when increasing the height difference between the air inlet and air outlet. In the case of the Vela, this required to focus on the height of the extraction point. More specifically, the thermal stack effect is based on the natural Delta temperature between the bottom and the top air enclosed by the roof. As result of the consequent convection air drafts, extracting warmer air through a hole properly shaped and located in correspondence to the top point of the Vela was an option. Assuring a high top point for locating the openings was expected to favour the warm air flow extraction and avoid annoying air draughts at the height of the ground floor surface in the covered area. For this, the investigation with respect to the overall shape was crucial, for which various curvatures were considered. Figure 60 illustrates the principle, according to which the effect was improved if the overall shape was designed by making higher the location of the openings to favour warm air flow extraction and to avoid annoying air draughts at the height of the ground floor surface in the covered area. Integrating in the investigation also the configuration of the opening was important, for example including a small wing located on the top hole to further improve the air extraction.

Adaptivity: Regarding the adaptivity of the wing, an adjustable orientation was expected to improve the air pressure control.

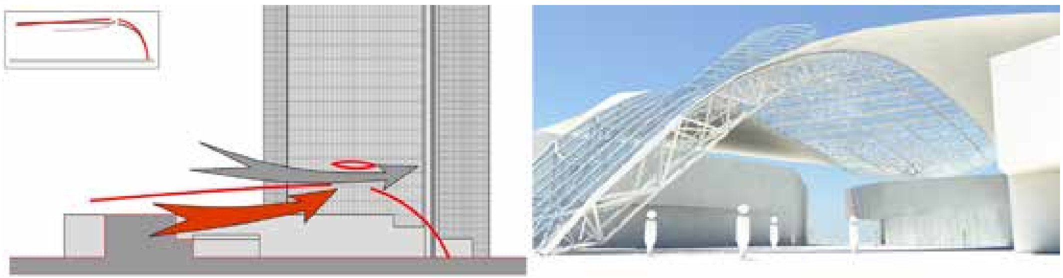


Figure 60
Strategies for increasing the air flow for cooling by thermal driven air flow.

§ 6.5.3 model-PAS: large scale parametric geometry

As presented in the above sections, both in the case of wind-driven and thermal driven air flow the geometry of the Vela roof played a key role; and in both cases the curvature of the roof emerged as the most relevant geometric property. This was crucial for the primary parameterization (see section 5.4.4).

Moreover, investigating alternative configurations of the overall shape of the Vela required attention to the structural consequences, besides other aspects such as, for example, the rainwater discharge and run-off. Considering the strong preference expressed by the architects and structural engineers for a double layer space frame structure, options for this structural typology were included in the investigations. This was crucial for the secondary parameterization (see section 5.4.4).

The following sections describe the parametric model and the detailed parameterization process, according to the process presented in chapter 5.

§ 6.5.3.1 Primary parameterization: the overall shape of the roof

In order to investigate the geometry of the roof at its large scale, its overall shape was described through a NURBS surface. Independent parameters were set in order to model the surface. They corresponded to the Cartesian Coordinates of the NURBS Control Points. For the early modelling of the roof, sixteen Control Points allowed modelling the surface with a reasonable degree of precision with respect to the free-form shape proposed by the architects and engineers. Therefore a set of forty-eight independent parameters was specified to parameterize the overall shape of the roof (figure 61).

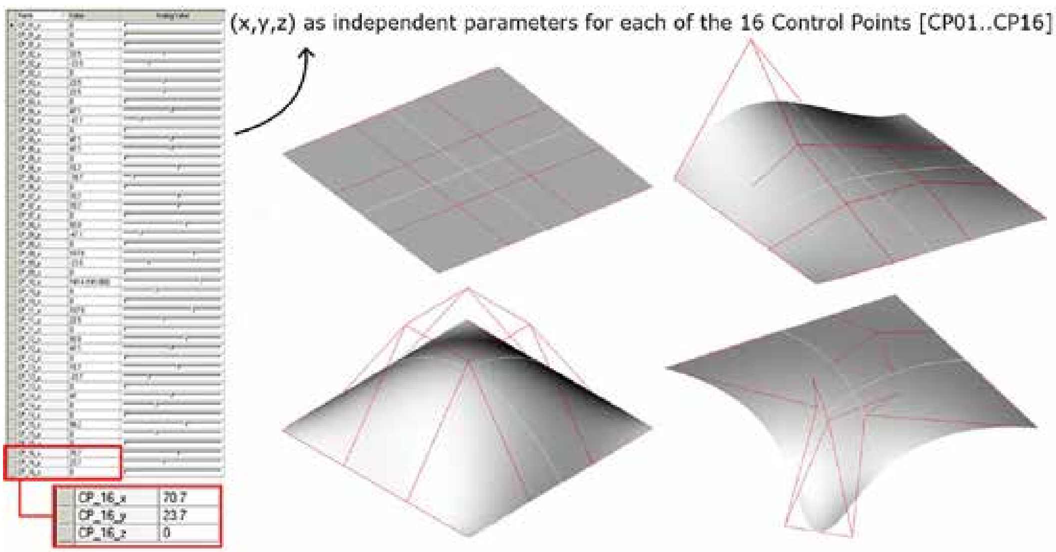


Figure 61
NURBS surface and its independent parameters (Cartesian Coordinates).

While exploring different curvature options, the structural morphology was also taken into account. A starting configuration was modelled as a square flat surface on which the parameterization of the structural geometry was applied.

§ 6.5.3.2 Secondary parameterization: the structural morphology

The model assumed as conditions the preliminary studies conducted by the engineers, favouring the selection of a double-layered space grid. Among the various possible patterns described in chapter 5, an external triangular-based layer and an internal triangular and hexagonal-based layer were preferred by the architects and engineers at this stage for the high level of transparency allowed by this configuration. A starting instance was modelled as a square flat surface on which the structural geometry was parameterized based on a dependency chain describing the position of the top layer's nodes on the surface, using UV coordinates. However the grid was not wanted parallel to the sides of the roof, but following diagonal directions. Therefore, with respect to the general approach described in chapter 5, the scripts were customized in order to meet the diagonal orientation of the pattern. The problem was reduced to a two dimensional array set on Pythagoras relationships (figure 62), and including the factor square root of 3 according to the proportions for hexagons. The number of rows is defined as an independent parameter, n, to regulate the density of the grid (table 14).

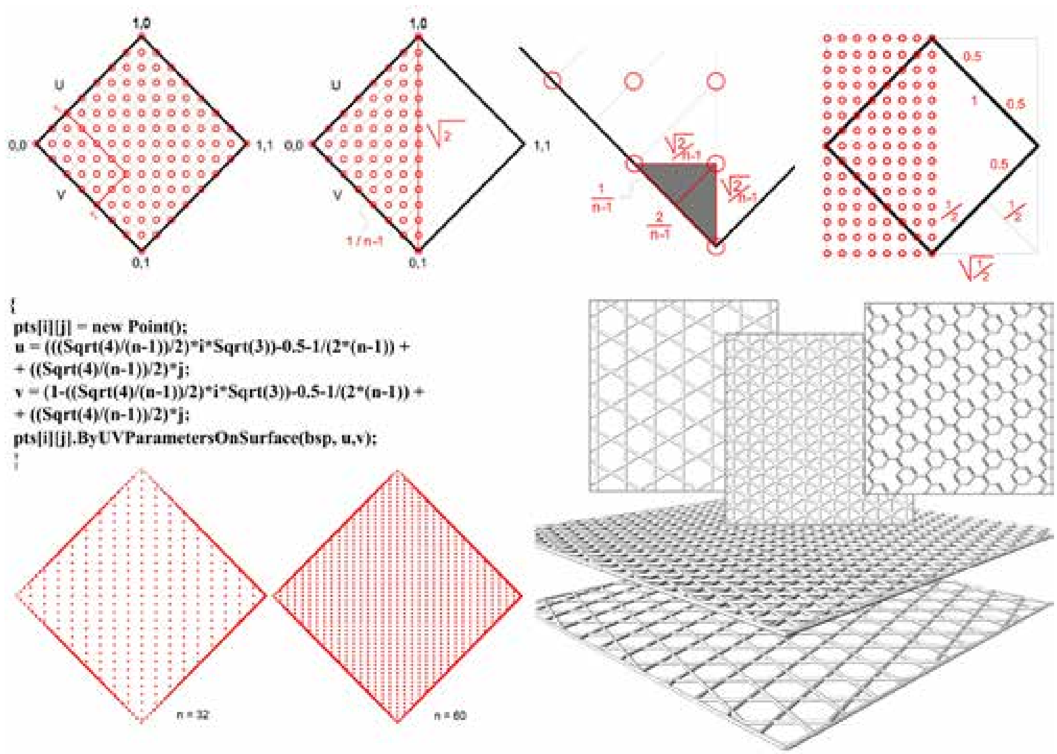


Figure 62

Parameterization of the diagonally oriented grid of point based on UV coordinates; and the diagonally oriented point grid and the pattern for the top, bottom and diagonal bars of the space frame.

Examples	
Independent parameters	**UV functions**
n (density)	In a for Loop with counters i and j: u = (((Sqrt(4)/(n-1))/2)*i*Sqrt(3))-0.5-1/(2*(n-1)) + + ((Sqrt(4)/(n-1))/2)*j; v = (1-((Sqrt(4)/(n-1))/2)*i*Sqrt(3))-0.5-1/(2*(n-1)) + + ((Sqrt(4)/(n-1))/2)*j;
n (density) sh (shift)	u = Sqrt(0.5)*(Sqrt(2)/(n-1)*i)*(Sqrt(3))-0.50-(0.5/n) + + Sqrt(0.5)*Sqrt(2)/(row-1)*j; v = sh-(Sqrt(0.5)*(Sqrt(2)/(row-1)*i*(Sqrt(3))))- -(row*0.5)/(row -1) + Sqrt(0.5)*Sqrt(2)/(row-1)*j;

Table 14
Examples of scripts for generating diagonally oriented point grids based on UV coordinates.

The obtained point grid was used to model the structural elements, combining hexagonal and triangular configurations for the bottom layer, and using only a triangular configuration for the top one. The second layer was set to a distance d from the bottom layer, an independent parameter as well. A set of diagonals was then introduced following the space frame requirements. Different instances of the resulting parametric space frame were possible to be generated both by varying its density as shown in figure 63. This still remains consistent when modelling the NURBS surface for the shapes of different roofs.

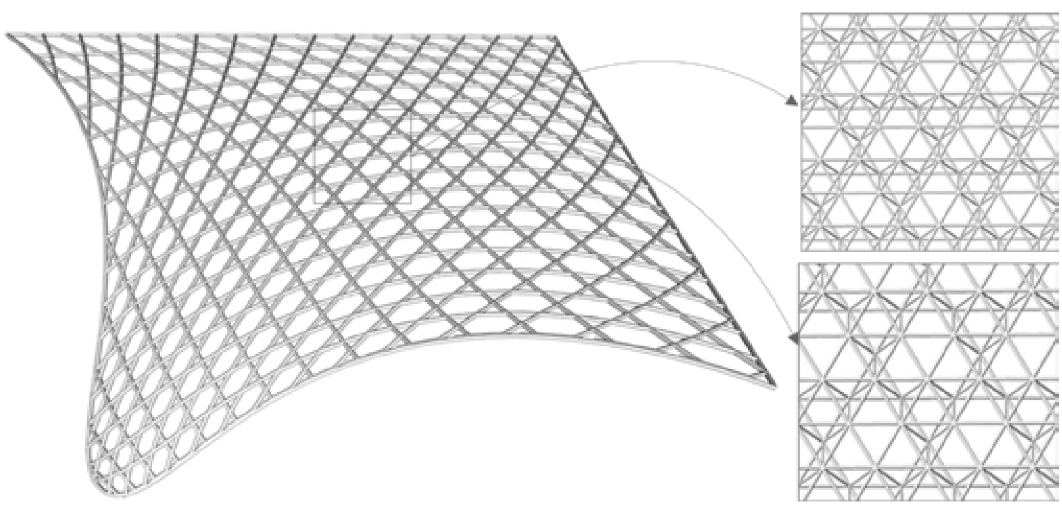


Figure 63
An example of an instance of the top layer and two different densities of the double layer grid.

Changing the roof curvature influenced the convergence angle of the bars in the nodes. This was a critical point, which was approached by adding a parametric factor, a, to stretch the tessellation in either one or both of its main axes. Including such a parametric factor in the description of the two dimensional array allows acting on the position of the points, distorting the regular tessellation (stretching or squeezing the regular figures). Furthermore, a second parametric factor, b, was introduced to allow sliding the tessellation on the surface in order to search for suitable edge configurations. Examples of different alignments are shown in figure 64 for the bottom layer of the space frame.

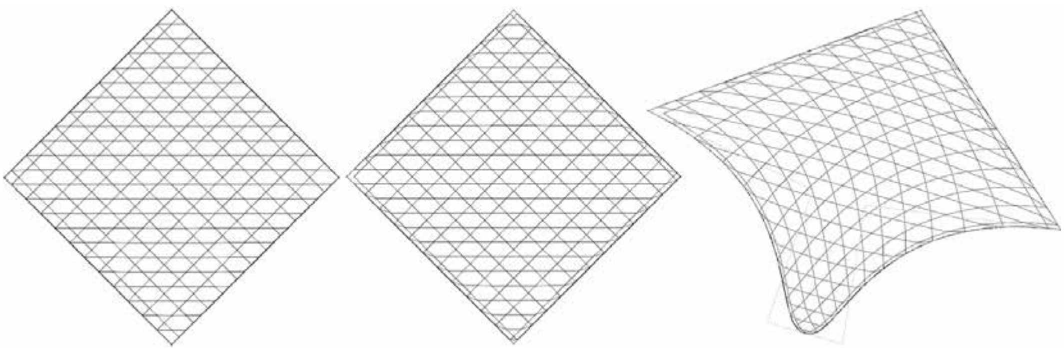


Figure 64
Left: Example of instance generated by varying a to stretch the tessellation pattern. Middle: Example of instance generated by varying b to slide the tessellation on the surface. Right: Variation of the overall shape.

§ 6.5.4 Outputs for large scale

The outputs concerning large geometry explorations are discussed concerning both the parametric approach and the design of the Vela.

§ 6.5.4.1 Reflections on the parametric design

This section presented the parametric model of the Vela roof, with parameterization of the overall shape and its structural morphology. Figure 65 illustrates the potential of the overall process in generating alternatives at both levels of the parameterization.

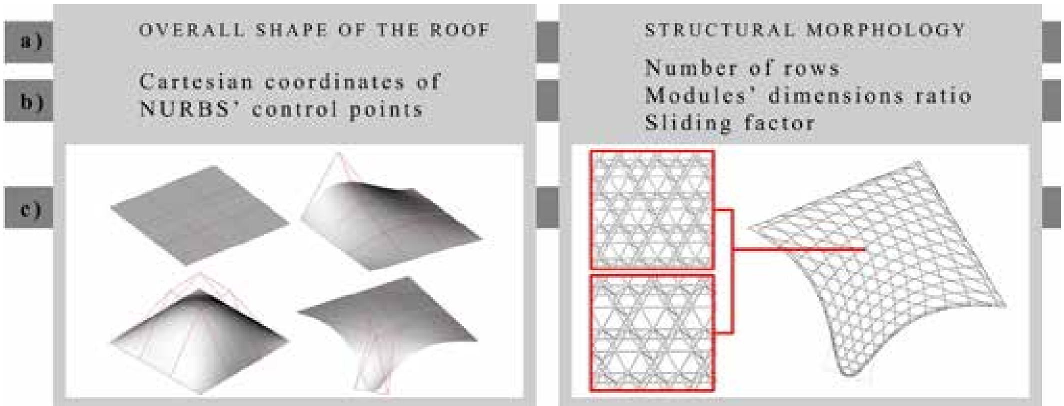


Figure 65
Matrix of the parametric process: a) design exploration tasks; b) independent parameters; c) examples of instances.

The so defined parametric model allowed the generation of different geometric configurations of the roof with respect to the curvatures and the structural geometry. The roof configurations expected to be suitable for cooling air-flows were identified and the process should have continued toward the more detailed performance evaluation and design exploration of the options. However, both in the case of wind driven and thermal driven air flow, the roof configurations resulted in conflicts with other design requirements, such as structural stability in case of wind storm and proportions of the roof height to its surrounding. These latter criteria led the decision making process for the final shape of the roof.

Although the model was therefore not further explored for the design of the overall geometry of the Vela, relevant conclusions were drawn based on the use of it. Besides confirming the advantages discussed in chapter 5, some critical aspects were faced and require discussion.

The first one concerns the shown flexibility of the approach, which allows customizing the scripts in order to meet additional conditions, in comparison with the consequences of the customization. The possibility of customizing the scripts presents a great opportunity. It was in the case of the diagonal orientation. As a negative effect, customization requires high attention at the additional consequences, especially concerning aspects already potentially problematic. An example is provided in this case looking at the conditions at the edges, which is in general a critical aspect of the design exploration for space frames. With this respect, the approach showed good potentials for a conceptual and preliminary investigation, but would need further implementation if used for exploring the detailed configuration at the edges providing a more robust design support in non-standard cases.

A second aspect that needs to be discussed concerns the amount of computation that is required to process the generation of design alternatives. In the case of the Vela, this was faced while generating shape variations of the entire roof including dense spaces frames. This aspect will be further discussed later in this chapter, but setting the script in a way that allows subdividing the model in subtopics can already be mentioned here as important.

§ 6.5.4.2 Outputs for the Vela design

During the parametric modelling, considerations emerged that led to a decision before performing the evaluation process. Due to requirements different than the climatic aspects, the geometry of the roof was defined with a relatively flat configuration, as the initial concept was (figure 66). Still, the air flow for cooling was considered for the further design steps, by means of openings distributed on the roof. Design alternatives were considered and their performance assessed, when investigating the medium scale geometry of the project, as presented in the following section.

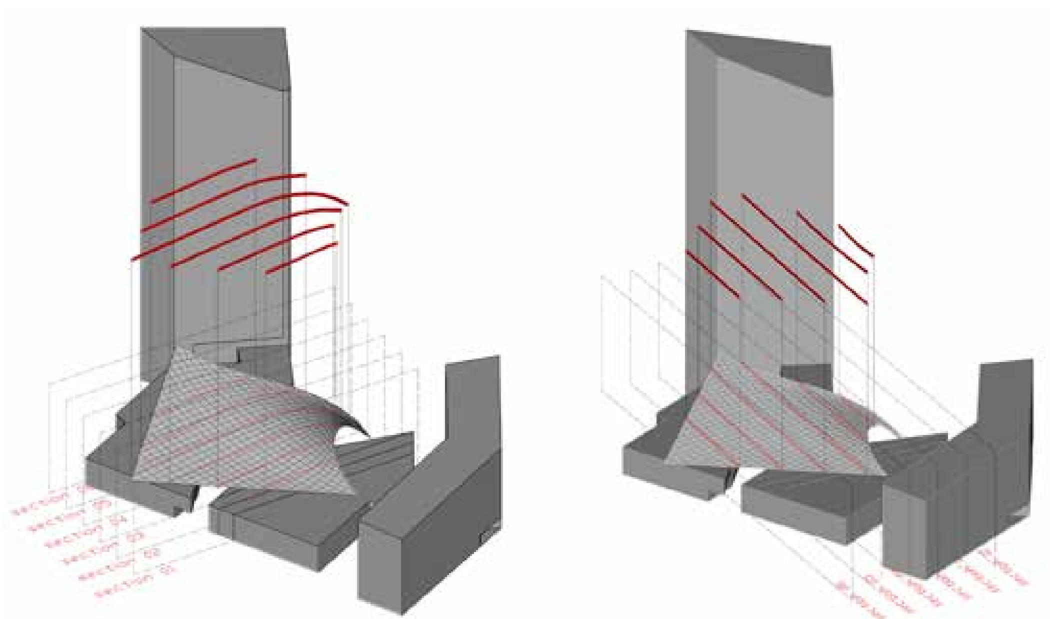


Figure 66
Sections of the Vela illustrating the little curvature of the final overall shape of the roof.

§ 6.6 pre-PAS, model-PAS and explore-PAS at medium scale geometry

Assuming the overall roof's shape, the expected performance of the reference geometry with no openings was initially evaluated. Based on it, further investigations were made for the air permeability of the roof and analysed with respect to passive cooling. Specifically, the air flow regulation required switching the roof between a closed (barrier like) and an open (filter like) condition. Various systems were investigated that allow the opening of some parts of the roof in order to make it permeable to airflows, with different openable modules integrated in the roof structure and an investigation of the effect on thermal comfort.

While the performance evaluations were conducted on the chosen roof configuration only, the parametric model still included the potential of generating design alternatives also by means of the primary parameterization. For completeness concerning this potential, the parametric model is still presented in its overall hierarchy.

§ 6.6.1 Performance of the initial reference geometry

Preliminary performance evaluations of the airflow were run on a flat configuration of the roof with no openings. The calculations were done with the software CONTAM 2.4, according to the setting presented in section 6.4.2. The simulations were run to obtain a reference situation for comparing the effects of different openings' dimensions and distributions. With this respect, two major factors affected the airflow behaviour: the wind, which would interfere with the airflow generated by the stack effect, and the g-value of the roof, which affect the thermal driven air flow. Calculations were made for wind-still condition and for a roof with an average g-value of around 0,35. Results of the calculations are presented by describing the airflow behaviour and the air temperature in the transversal section D-D'. The PET trend was calculated for each of the 20 points on the section D-D'. Calculations were done for the daily hours from h.9.00 to h.24.00 of an average day of July. The properties of the roof assumes a g-value of 0.35; the clothing was assumed at 0,7; and the average air speed at 0,5 m/s. Figure 67 illustrates the results for both air flow and the PET behaviour in daily hours for the 20 points located along the section.

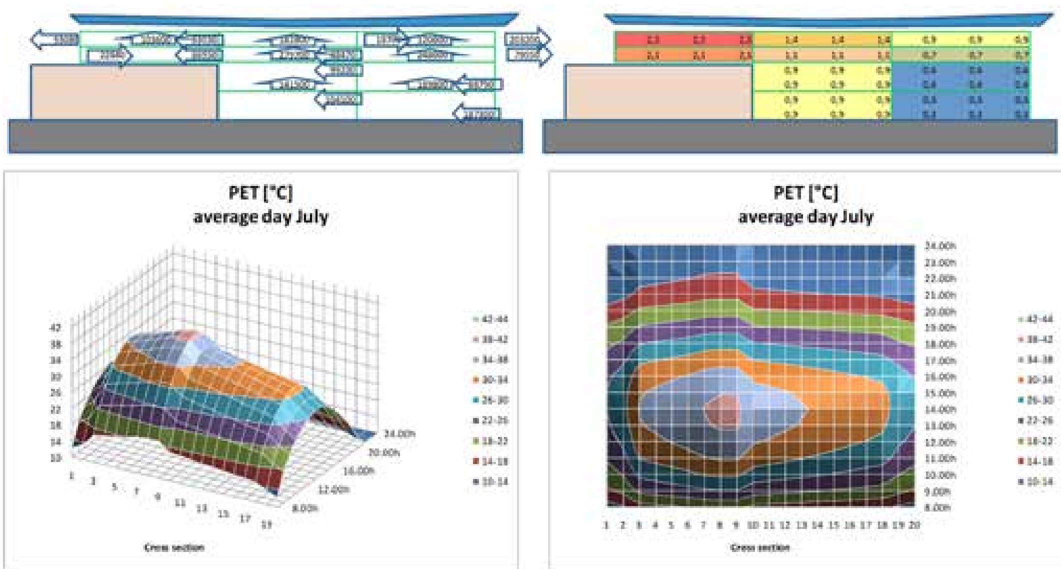


Figure 67

Preliminary calculations for the roof with no openings. Top: Preliminary calculations on air flow [m3/h] and raise of air temperature [K]. Simulations of airflow and air temperature distribution have been performed for summer conditions without wind. Bottom: PET in section D-D', by assuming 70% of opaque cladding (g-value = 0,35).

§ 6.6.2 pre-PAS design strategy: increasing air flow by means of air rate exchanges

Based on the preliminary performance evaluations for a relatively flat roof configuration, the needed openings were expected to have a larger total area than what an opening for heat extraction at the top point would require. This was to be achieved by either concentrating or distributing the needed open surface. Moreover, the needed open surface might have been openable and closable in order to be able to regulate the extraction of heated air with respect to the indoor comfort (i.e. winter time / summer time). These options were investigated and are presented in the following sections.

Adaptivity: Focusing on the eventual adaptivity of the roof, an additional note must be added concerning a design option that was not investigated into details, but that has general interest. The regulation capacity of the roof was expected further improved by making closable also the openings along the sides of the roof in order to regulate both incoming air flows and the extraction of air. Such options were to allow controlling the semi-outdoor nature of the area by getting closer to the indoor condition, when desired. However, this also implied additional costs to the project, which needed to be balanced with the benefits in satisfying the comfort needed according to the functional and architectural requirements. Based on this, the option was excluded in the case of the Vela.

§ 6.6.3 model-PAS: medium scale parametric geometry

In order to explore the openings in the Vela, additional parameterization levels were added to the primary and secondary ones. A first additional level concerned the distribution and size of openings; a second one the morphology and adaptivity of the openable modules.

§ 6.6.3.1 Parametric geometry: distribution and size of openings

Various locations and dimensions of openings were evaluated, using the modular structure of the reference geometry as a basis. The parametric model was used in a preliminary phase both to investigate the distribution, location and size of different openings and for the first conceptual design of their possible geometric options. Specifically, using the modular structural, the parametric model allowed generating a surface including hollow modules with variable distribution and dimensions. An important note concerns the potentials for investigating various distributions of the openings also in case different shapes of the overall roof would be generated.

§ 6.6.3.2 Parametric geometry: openable modules

Preliminary explorations were done concerning the morphology of the openable modules. Various typologies are considered, such as sliding or inched cladding elements. Some of the options are represented in figure 68 and include both large openings and more numerous and distributed small openings.

Not for all the different options of openings the parametric model were developed. The example shown here following regards an option selected because of interest for the overall process. This example is developed as part of the overall hierarchy of the model, including the primary parameterization. This means it still makes use of the potentials for generating also alternative overall shapes of the roof, if desired. Specifically, the example shows the integration of openable parts in the modular structure of the roof by focusing on the possibility of adding complexity to the model while collapsing sets of repeated relationships into new objects that can be propagated in the model. This allowed also investigating them at a different hierarchical level than the general morphology to which they are related.

The parameterization process was based on the idea of symmetrically shaping the roof along its diagonal by defining a central line where the airflow is driven to the top point. Considering this, only a relevant subset of instances generable by the overall parametric model described in section 5 was considered. More specifically, the instances forming the large solution space of the overall model can be grouped in subsets defined on the basis of particular properties, some of which emerged as relevant for the design option explored here. Based on this, the solution space of the model was limited to a sub-domain of the overall solution space. One such subset was defined by the following two conditions: first the hypothesis of symmetry was introduced at the level of the overall shape constraining the 16 control points to assume positions symmetrical to a central axis; second only the values generating symmetrical tessellation patterns were assigned to *n*.

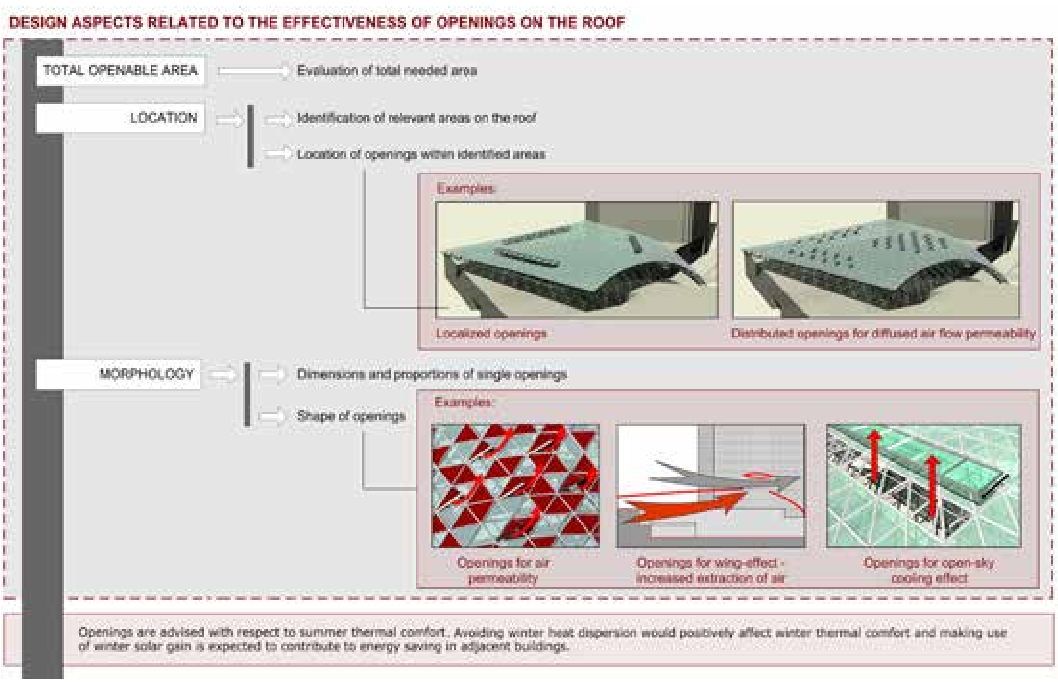


Figure 68
Examples of the options considered for both the large openings and more numerous and distributed small openings.

The openable modules were investigated as pantographic deployable modules. With reference to pantographic structures, the deployability constraint, presented in appendix AI, assumed therefore a key importance. Also the use of symmetry to describe a relevant sub-family of deployable pantographic modules was previously presented in appendix AI. This is considered here with specific reference to the semi-symmetry principles. Because of symmetrical relationships, conditions for some deployable modules were matched by the generated set of instances, which is a relevant but not exhaustive family of solutions. The same principle can be repeated for other relevant sets of instances; the one presented here is considered only as an example.

The deployable module was parametrically built as an entity separate from the general model, based on a set of relationships to this general model. The structure of the dependencies guaranteed that its morphology fitted the selected structural modules of the roof and, as a consequence of their properties of symmetry, respected the deployability constraint. Additionally, an independent parameter k was introduced to visualize the kinematic behaviour of the module (figure 69).

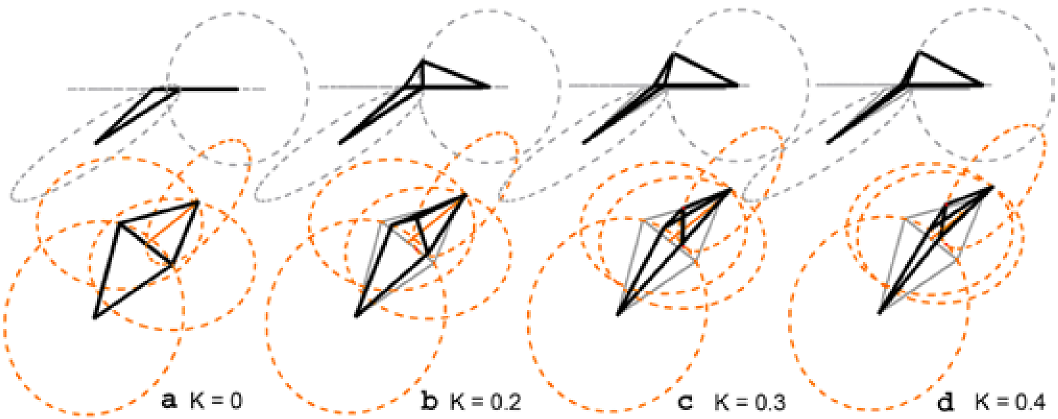


Figure 69
Deployable module: deployed configuration (a) and three steps (b,c,d)

The parametric entity defined in this way was propagated along the roof structure by selecting its bars as input to properly configure and allocate the feature. In the graph structure of the parametric model the deployable module therefore became a new node which included the whole set of dependencies involved. In other words, it was treated as a sub-graph of the roof structure and was automatically updated when generating new instances of the roof. Particularly, figure 70 shows the generation of instances, which required changes of the morphology of the deployable modules. These changes were automatically obtained while still guarantying the deployable behaviour.

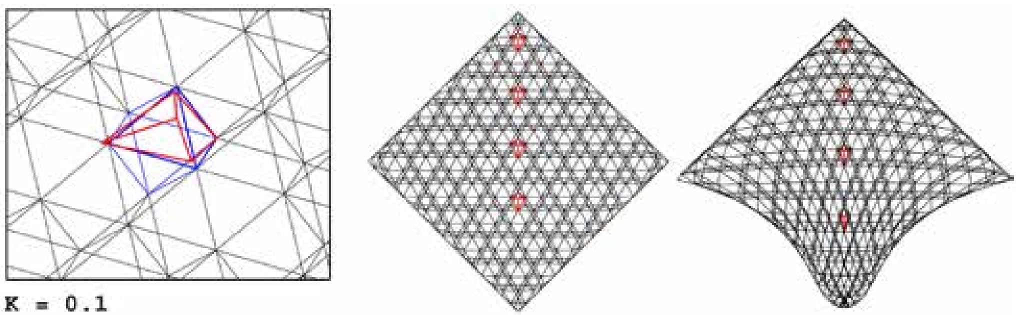


Figure 70
Propagation of the deployable modules on the model; different instances.

§ 6.6.4 explore-PAS: digital air flow analysis

The simulations were done aiming at comparing different openings' dimensions and distributions. Both for air flow and temperature and for PET, the calculations were made for the same conditions presented in section 6.5.1. A first comparison was made concerning the dimensions of the openings. Figure 71 shows the air flow and air temperature in Section D-D' in case of 200 m2 of openings located in the centre; and the PET behaviour.

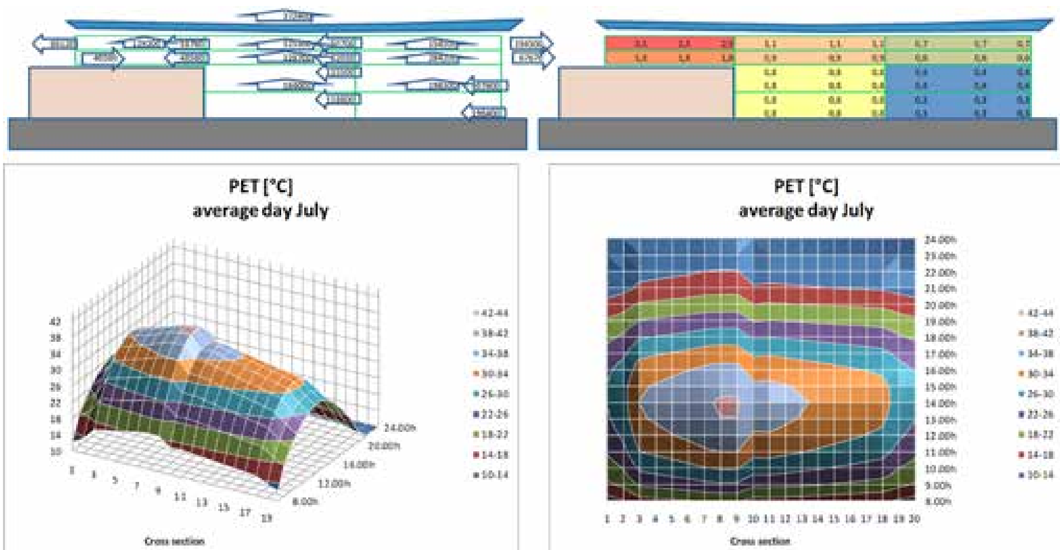


Figure 71
Calculations for the Vela with 200smq opening in the centre of the roof. Preliminary calculations on air flow [m3/h] and raise of air temperature [K]. Simulations of airflow and air temperature distribution have been performed for summer conditions without wind. Bottom: PET in section D-D', by assuming 70% of opaque cladding (g-value = 0,35).

The results were compared to the conditions in case of no openings, previously illustrated in figure 67. In the case of no openings, it was shown that outdoor air enters the covered spaces from bottom sides: from the square 187.300 + 88.790 m3/h; from the Piastra's roof 22.840 m3/h. Air rises to the top spaces both laterally and in the centre and gets out from the covered spaces through the top sides: 203.200 + 79.550 m3/h to the square; 93080 m3/h to the Piastra's roof. It was also shown that the most critical area for air temperature was the spaces between the Piastra's roof and the Vela roof. In case of 200 m2 of openings located in the centre, it was shown that outdoor air enters the covered spaces from the bottom sides with slightly increased volumes: from the square 196.400 + 107.600 m3/h; 40.580 m3/h from the Piastra's roof. Air still rises to the top spaces both laterally and in the centre but also in this case with slightly increased volumes; it then exits from the covered spaces both through the top openings and the sides, where volumes are slightly decreased. As a result, the total exchange of air volumes per hour did not result relevantly increased if compared with the one in absence of top openings. It was also shown that the most critical area for air temperature gets some minor benefits. It was therefore possible to conclude that even large roof openings of 200 m2 have a relative small effect on the maximum temperature.

Similar considerations were made when comparing the PET. By comparing the PET with and without openings, it appeared that no relevant improvements were provided by the opening. Also, it was significant to notice that in both cases, by comparing the results with the outside situation (figure 57) it appeared that PET under the roof was less comfortable than outside PET. In both cases, the points close to the roof's edges were less critical; the points on the Piastra's roof level were the most critical, with a top problem in the areas far from the roof's edge. Numbering the 20 section's points from 1 to 20, points on the Piastra's roof level were from n.2 to n.10; the most critical area was around points n.7 to n.9 from h.13.00 to h.15.00, where a PET of 38-42 °C was reached. Uncomfortable PET of 34-38 °C applied to larger areas from h.11.00 to h.16.30/17.30.

A second comparison was made also including the distribution of the openings. Specifically, a comparison between spread and concentrated openings of different sizes was made concerning the effect of the openings on the exchange of air volumes with the outside. It was shown that in case of no openings around 16 volumes/h are exchanged; 19-20 in case of 200 m2 openings; 21-22 in case of 400 m2 openings. The results are illustrated in figure 72. It was possible to conclude that there is a slight difference in the performance of spread and concentrated roof openings.

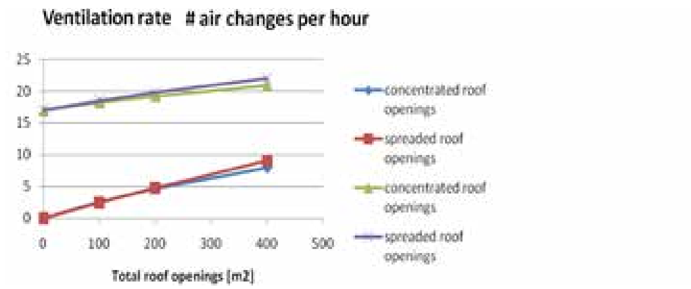


Figure 72
Effect of roof openings on ventilation.

§ 6.6.5 Outputs for medium scale

The conclusions concerning large geometry explorations are discussed here concerning both the parametric approach and the design of the Vela.

§ 6.6.5.1 Reflections on the parametric design

The parametric process developed for exploring the medium scale geometry of the Vela with respect to the air flow surely provided relevant benefits, among which the easy extraction of schematic cross sections for different dimensions and distributions of the openings along the roof and the visualization of design alternatives to be discussed with the architects. The availability of 3D models was beneficial also for measuring the effective opening area of different openable modules. However, it must be noticed that the performance evaluation process could not make full use of the potentials of 3D parametric modelling. This was because air flow analysis still required either simplified approaches (like in the case of CONTAM) or high manual intervention and computational capacity (reason for which CFD analysis was not performed at this stage).

At last, parametrically working on deployable modules highlighted the relevance of having an abstract model to refer to during the parameterization process. Particularly, previous systematic representations of rules and extrapolation of parameters to support the exploration of deployable structures were used to support the process. On the other hand, also the difficulty of having theoretical models general enough to embed the complexity of design cases has to be highlighted. Both in relation to morphological variability and deployable behaviour, the theoretical structure used here was based on symmetry. This allowed supporting relevant subsets, among which an example has been provided, but would not allow for an exhaustive exploration. Further investigations concerning non-symmetrical modules are a potential area for future work.

§ 6.6.5.2 Outputs for the Vela design

Numerical analyses showed that the ventilation rate air exchange underneath the roof was not relevantly affected by an open roof area smaller than 200sqm. More precisely, it was concluded only large openings (> 200 m2) have a measurable effect on thermal comfort but the effect was not large enough to justify the extra costs; there was no relevant difference in performance of concentrated or spread roof openings. As a consequence, the option of including openings specifically for increasing the thermal comfort was not further investigated and the openings' morphology was not developed. Instead, a proper location of the openings in any case needed for exhaust of smoke and polluted air was addressed; these openings were to be concentrated at the highest level of the roof, and in the area along the edge of the 2nd level. Figure 73 shows the recommended location of these openings by also providing an approximate quantification of the effective opening area according to the example of triangular cladding modules. The example shows the case of 20smq of effective openings based on a triangular module with an average area of 2,5-3,5 m2.

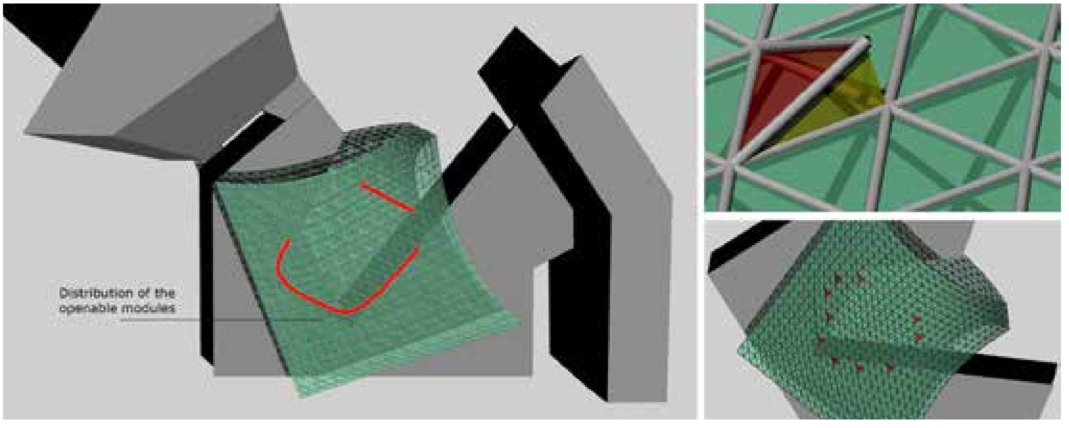


Figure 73
Recommended location of openings for smoke-out and schematic minimum quantifications and recommended locations of openings for smoke-out.

§ 6.7 pre-PAS, model-PAS and explore-PAS at small scale geometry

Assuming the overall roof's shape and the resulting openings, focus was given to the direct solar radiation transmittance of the roof and its solar energy absorption when investigating the small scale of the roof, which mainly refers to the cladding system. Both direct transmittance and absorption affect the total solar energy transmittance factor (g-value) of the cladding. The solar energy transmittance consists in fact of two parts: the direct transmittance itself and the secondary transmittance by convection and long wave radiation, caused by the heating up of the cladding system and mainly related to its solar energy absorption. With respect to both aspects, the investigations closely considered various design alternatives that differ from each other both for geometry and for the properties of their materials. This section gives emphasis to the geometric investigations in order to discuss the support of parametric modeling. As a consequence, most of the numerous performance evaluations based on different material properties are not included in the chapter. However some information are given concerning a selection of the investigated material properties, when these are useful to understand the design strategies and the geometric explorations.

Like in the case of the medium scale geometry, also for the small scale geometry the performance evaluations were conducted on the chosen overall roof configuration only. However the parametric model would still include the potential of generating design alternatives also by means of the primary parameterization.

§ 6.7.1 Performance of the initial reference geometry

Several preliminary investigations were performed in order to explore cladding alternatives. The most significant are presented below.

§ 6.7.1.1 Preliminary investigations

A first group refered to the general evaluations needed at this stage in order to define the overall design strategy for the cladding concerning thermal comfort. It included investigations performed previously in the process. According to these, summer thermal comfort under the roof was critical due to the risk of high temperatures, reason why the cladding system was required to have low total solar energy transmittance factor (g-value). In order to mitigate the summer thermal discomfort, the preliminary calculations presented in sections 4.2 and 4.3 showed the importance of both reducing the direct solar radiation transmittance of the roof and its solar energy absorption. Specifically, the transparent elements of the roof, their energy transmittance, and the solar energy absorbance of the opaque elements should be limited as much as possible. In general, the total solar energy transmittance factor was required not to be higher than 35%. Based on these considerations, figures 67 and 71 showed the reference PET for a 70% opaque roof with g-value of 35%. The results still showed levels of discomfort. Consequently, the overall design strategy consisted of two parts: on one hand identifying a cladding system that allows having a g-value of 35% or less; and on the other hand trying to further improve the PET since the level of summer discomfort was still too high to be accepted.

The preliminary investigations focused on solar energy transmittance for thermal comfort, but considered also other criteria, such as the daylight transmittance. In fact, under the roof, daylight should be guaranteed with a daylight factor sufficient also for the indoor spaces facing the covered square: this required a cladding system with high daylight transmittance (minimum light transmission of 30%). As a consequence, the design strategy needed to consider a balance between limiting the solar transmittance and affecting the daylight transmittance.

§ 6.7.1.2 Advanced investigations

Following the preliminary conclusions, a second group of investigations was conducted, in order to support more specific choices for the cladding design. This included a quite extensive range of analysis and concerned investigations on different systems and material properties. The evaluations ran across the whole cladding design process, allowing a large acquisition of performance data and assessments, based on which the design strategy has been iteratively redefined and the parameterization process accordingly.

Various options were initially taken into account. As visualized in appendix AIII, two main families of alternatives were considered, based respectively on static and adaptive solutions. Both are divided in two sub-groups: the first one based on the use of geometry or material properties in order to reduce the solar transmittance; the second one based on the use of geometry or material properties in order to achieve the desired adaptivity for varying the solar transmittance. Among the possible solutions, the use of louvers and of totally opaque materials was excluded for architectural reasons, the use of adaptive materials, such as termotropic glass, for budget-related issues. Using opaque or translucent materials in order to limit the solar energy transmittance was identified as a solution possibly meeting the architectural requirements and the budget. This included static material properties and static or adaptive geometry.

Specifically, further investigations were developed for the use of translucent shading patterns, such as a serigraphed pattern on glazed panels and a printed pattern on ETFE pneumatic cushions. Both had static material properties; while the first one was investigated for a static geometry only, the second one was investigated both for a static and for an adaptive geometry.

The roof properties were formulated based on an inverse process to meet the thermal and daylight design intentions. Within these boundaries different combinations of glass properties were explored by assessing their effect on the thermal and daylight comfort. Numerous investigations were made concerning the glazed options, for which only the conclusions are recalled here. The analysis conducted on the glazed options showed that when trying to fulfil the design requirements based purely on the material properties of the cladding, it was possible to achieve the desired reduction of thermal discomfort. This was especially true when using light colour serigraphy, which has a lower absorbance than the dark serigraphy. However the resulting daylight factor of the spaces underneath the roof was too low if compared to the daylight requirements.

The problem was approached by extending the inverse computing process used for the material properties of the glass to the geometry of the cladding; and exploring cladding systems allowing three-dimensional variations in geometric configurations. Special attention was given to ETFE pneumatic cushions due to their potentials in acting as a 3D system. In such a system, the different layers of the pneumatic cushions can be customized to control the energy transmission based on various material properties and also on different three-dimensional configurations.

A summary of the preliminary investigations on the ETFE cladding system is presented below.

§ 6.7.2 pre-PAS design strategy for ETFE cladding

ETFE is a material used in structural membrane constructions, which was investigated for the Vela project in the form of two or multilayer air cushions maintained by permanent air support. The system was investigated with the specific goal of using its tridimensional configuration in order to allow the light transmittance to be higher than the direct solar energy transmittance. With this aim, four different options were analysed and compared. The options included three static options based respectively on a uniformly printed top layer and a clear second layer; a top layer partly printed on the south oriented half, a second layer partly printed on the north oriented half; and photovoltaic elements integrated in the top layer. A fourth option was investigated as an adaptive option and is based on a middle layer with adjustable position. The first option is introduced here only briefly, larger attention will be given to the other options.

§ 6.7.2.1 Static options

The first option was based on a uniformly printed top layer and a clear second layer. It was analysed based on different percentages of shading printed pattern. Having assumed an absorption factor of 20%, the results showed that a percentage of 75-80% was needed in order to obtain a solar energy transmittance of 33-36%. The light transmittance was about 31%. Moreover, the results showed that there was a linear relation proportion between the solar energy transmittance and light transmittance occurring for different percentages of printing. This meant that no relevant advantages could be expected with respect to the design goal.

In the second option, the orientation of the pattern of each ETFE cushion was studied to block direct solar radiation and allow the income of indirect light. The system was based on a customized North-South oriented shading pattern, to block most of the direct sun and at the same time allowing diffuse daylight getting through. For this, the top layer should be partly printed on the south oriented half; the second layer partly on the north oriented half. This option and the related parametric models are presented in details in section 6.6.3.1.

The third option was based on the integration of photovoltaic cells in the cushions. It was based on the consideration that photovoltaic has a good shading capacity and can therefore substitute the printed pattern. Studies were conducted on the solar energy absorption of the system, due to the high absorbance of the cells. Two alternatives were compared, one having the cells on the top layer, the other one on the bottom layer. Although there was a lack of data concerning the absorbance of an ETFE module with integrated photovoltaic, the higher absorbance of the cells was expected problematic for the Vela when cells were located on the bottom layer. At the contrary, locating the PV on the top layer of the cushions was expected to not cause any significant increase of the indirect transmittance. From a thermal comfort point of view, top layer cushions with laminated PV were considered preferable. The eventual use of different systems required appropriate demonstration of their suitable thermal behaviour.

§ 6.7.2.2 Adaptive option

The option with an adaptive middle layer was based on two complementary patterns printed on the top and on the middle layers. The middle layer can flip from a closed position (in which it adheres to the top layer) to an open configuration (in which the layer is in a middle or bottom position), allowing the system to switch from one level of transparency to a higher one. This option was calculated in case of a closed position with the top layer fully printed and a clear bottom layer; and in an open position with both top and bottom layers partially printed (with complementary percentages). The first case resulted in a solar energy transmittance of 30% and light transmittance of 26% in the closed configuration, respectively 40% and 35% in the open configuration. The second case resulted in a solar energy transmittance of 27% and light transmittance of 23.5% in the closed configuration, respectively 37% and 33% in the open configuration.

§ 6.7.3 model-PAS: small scale parametric geometry

In order to design the cladding of the Vela, various parametric explorations were made. The one presented here concerns the option of the customized North-South oriented shading pattern, in which geometry plays a key role. For exploring this option, the secondary parameterization was formulated based on a set of key factors affecting the control of the direct transmittance of the roof, as explained below. A parametric model was developed and used to investigate the distribution of the modules and their orientation; and it was used to explore variations of the system, aiming at maximizing the reduction of the g-value and increasing the indirect daylight transmittance. The material properties of the system were explored in parallel, and included additional effects on daylight and solar energy absorption.

§ 6.7.3.1 Secondary parameterization: the ETFE pneumatic module

The parametric study first focused on a generic single ETFE pneumatic module. This was modelled by taking into account three main aspects: its direct relation with the structural geometry, its orientation with respect to the cardinal directions and the geometric key factors affecting the transmission of the solar energy.

Interface with structural system: Focusing on the first aspect, the geometry of the cladding module and the structural geometry of the roof were reciprocally constrained. In order to match the ETFE modules with the tessellation of the top layer of the space frame (described in section 6.4.3.2), the parametric ETFE module was built based on a polygonal frame that acts as an interface between the cushion and the structure. Generally, such a polygonal interface can be built in order to fit different possible structural tessellations allowing applications to different structures. Its potential is great, especially in combination with parametric models of the structure that support the explorations of different structural tessellations. This requires generalizations of the geometry of the cladding modules, but provides advantages in quickly enlarging the solution space of the parametric model. This specific project, however, allowed limiting the parametric solutions to be explored in this phase. In fact, even though at this stage of the process a structure consisting of a bottom layer based on triangles and hexagons and a top layer based on triangles was strongly considered, quadrangular tessellations were shown to be explicitly more effective than the triangular ones when focusing on the shading effects of the printed ETFE cladding. As a result, triangular tessellations were not further embedded in the parametric model and both the space frame and the modular cladding were developed based on quadrangular patterns only. A quadrangular polygon built by vertices was therefore used as the highest entity in the dependency chain of the ETFE module. Based on this polygon, NURBS surfaces were built to describe the inflated top and bottom ETFE layers.

External absolute reference: Focusing on the second aspect, the printed shading parts on the so obtained ETFE layers were modelled taking into account their North-South orientation. Specifically, ETFE modules were made up of 2 layers, a top one and a bottom one. Each layer of each cushion consisted of two parts: one opaque (printed) and one transparent (without printing). For each cushion, the location of the opaque and transparent parts of the layers was determined based on the orientation of the cushion with respect to the North-South axis: the top layer was printed in its south facing part while the bottom layer was printed in its north-facing part. This implied the assumption of an absolute reference that remains constant for whatever shape and orientation of the modules. An external reference, to which the module was constrained but that remained independent of the geometry of the roof in order to maintain its consistency even in case of rotations and variations of the roof structure, fulfilled this requirement. This was seen as a potential also when applying the modules to different structures in further projects.

Variables for exploring solar transmittance: Focusing on the third aspect, different variations of the module were investigated for the solar energy transmission of the system and expressed through independent parameters which acted as variables meaningful for the energy transmission. Among many variables, the most meaningful seemed to be the opening angle between the top and bottom printing. While the printed part of the top layer was constrained to face the South and the printed part of the bottom layer to face the North, the opening angle was the angle of rotation of the top and bottom printed parts around the East-West axis. The variations of such angle affect both the income of direct solar radiation and the daylight transmission, where increasing the angle decreases both. Figure 74 illustrates the external horizontal reference and plane determining the opening angle of the cushion, independently from the position of the cushion itself. A second meaningful variable was identified in the height distance between the top and bottom layers, in their farthest points. This geometric property affects the amount of incoming indirect daylight. Specifically, the ratio between the span and the height of each cushion directly affects the daylight performances of the cladding since the higher the ratio, the better the system performs. However, structural reasons constrained the proportion between the height and the polygonal base of the cushion. This implied a proportion with respect to the short side of the polygonal frame, with a ratio of 0.24. The resulting module was then saved as a replicable feature; in this way, the module could be propagated onto the structural geometry by guaranteeing the relationships with the structural geometry as well as with the North-South direction.

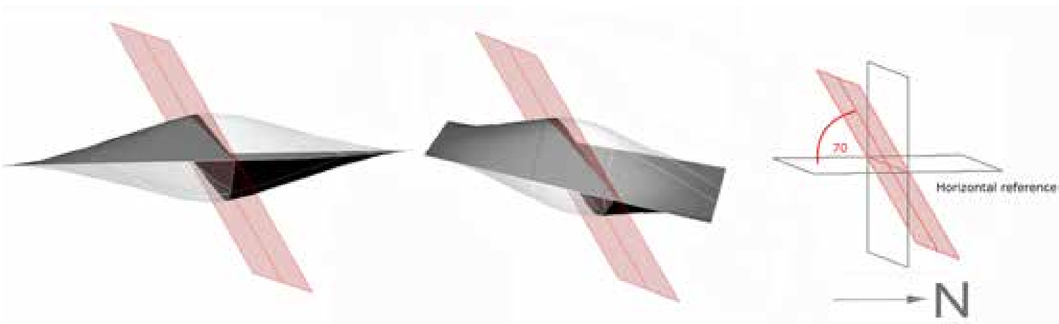


Figure 74
Tridimensional views of ETFE cushions with North-South shading printing on top and bottom layers: horizontal position and tilted position; external horizontal reference and plane determining the opening angle.

Material properties: In parallel to the parametric modelling of the geometric properties, the material properties were also investigated and their effects were considered during the parameterization process. Material properties were investigated based on the solar energy transmission of the system, both for daylight and thermal performances. In both cases, the properties preliminary defined were tailored for the specific ETFE system.

Concerning daylight, in order to provide a high transmission of indirect solar light, the daylight transmittance of the transparent parts of the top and bottom layers was requested to be as high as possible, with a minimum of 85%.

Concerning thermal performances, in order to obtain an acceptably low g-value of the cladding system by reducing the direct transmittance, the average solar energy transmittance of the printed parts was requested to have a maximum value of 30%; in order to obtain an acceptably low g-value of the cladding system reducing the indirect transmittance, opaque parts was required to have a low average absorbance factor of approximately 20%, especially with respect to the bottom printed layer. This resulted in an average external reflectance of at least 45%.

§ 6.7.3.2 Parametric model

The final parametric model allowed the generation of the cladding alternatives based on different opening angles. An example of cladding instance is illustrated in figure 75. The obtained geometric alternatives were evaluated based on their performances, with a combination of manual and software simulated calculations, in reciprocal crossed validation.

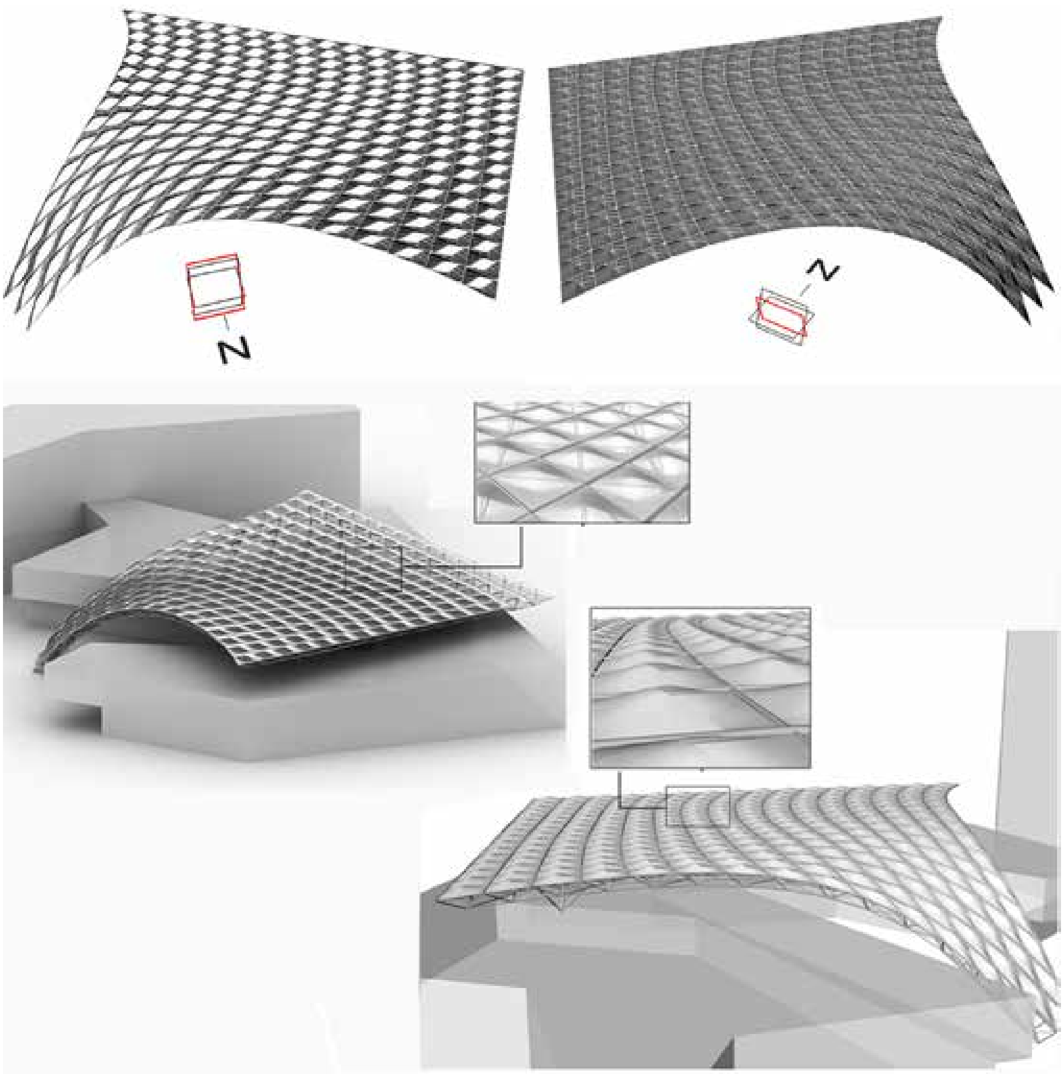


Figure 75
Tridimensional views of the roof with cushions with North-South shading printing on top and bottom layers; views from South and North directions.

§ 6.7.4 explore-PAS: performance evaluations

The performance evaluations included both calculations on simplified models and simulations on the whole tridimensional model of the cladding system.

The properties of the cushions were calculated based on simplified models, for different opening angles. Specifically, the total energy transmittance and the light transmittance were evaluated based on a single ETFE cushion for an average horizontal configuration, based on a simplified model. The program Sombrero 4.01 was used. The direct solar energy transmittance was calculated for a transmittance of the printed part of 30%. The indirect solar energy transmittance was calculated for two values of absorbance of the printed part: 30-40% and 15% (reflective print). The direct solar radiation and daylight performance of the spaces underneath the roof were evaluated by importing the parametric geometry of the entire cladding system. In addition to the numeric analysis, to evaluate the direct radiation underneath the roof also the shading effect of the Vela was simulated. This was done in Ecotect 2009 for different opening angles of the cladding, as illustrated in figure 76.

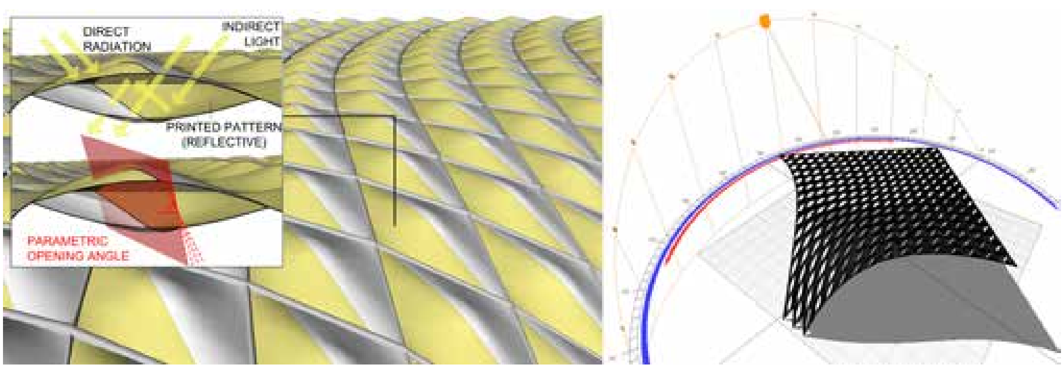
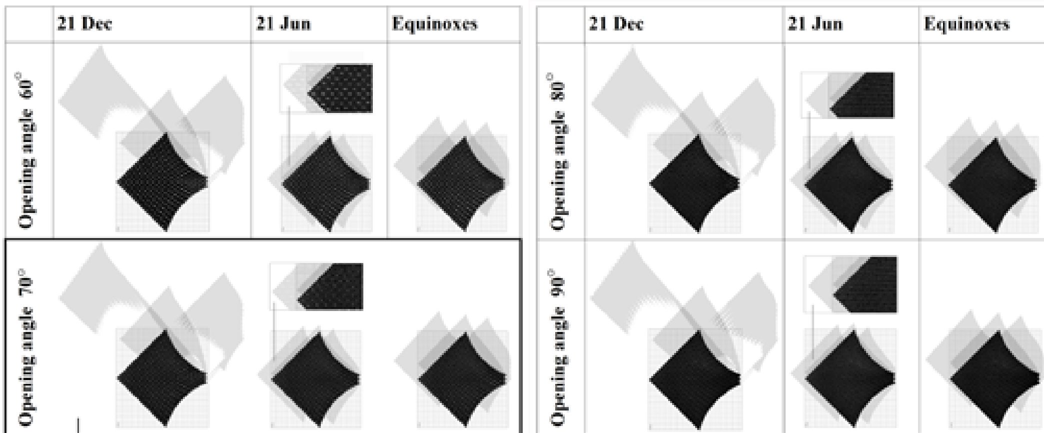


Figure 76
Parametric instances of the tridimensional model of the cladding, generated based on different opening angles, were imported in performance simulation software.

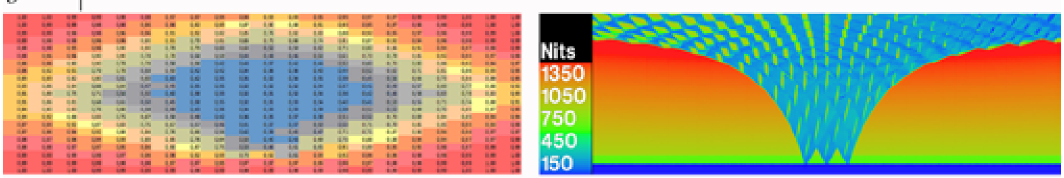
The daylight performances were evaluated by importing the overall tridimensional model of the cladding in Radiance. The effect of the structural space frame was simulated separately, since it remains constant for the different instances of the cladding. Some of the results concerning the properties of the cushions are illustrated in figure 77.

Average monthly g-value (%) for different opening angles												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Opening angle 40°	26	28	32	35	38	39	39	37	34	30	27	25
Opening angle 50°	24	27	30	32	34	35	35	33	31	28	26	23
Opening angle 60°	23	25	28	30	32	33	32	31	29	27	24	22
Opening angle 70°	22	24	27	29	30	30	30	29	28	26	23	21

a



b



c

Diffuse light transmittance factor; g-value; ratio; average physical equivalent temperature (July)				
	LTA %	**g-value %**	**LTA/g**	**Average PET C°**
Opening angle 60°	32	33	0.97	34
Opening angle 70°	30	30	1.00	33,5

d

Figure 77
Some of the key steps of the performance evaluation process for different opening angles: (a) average g-value; (b) shadow simulation; (c) daylight simulation; (d) comparison between daylight and thermal performances, including thermal comfort assessment in July.

It is relevant to notice that for an absorbance of 30-40%, the indirect solar heat transmittance was estimated to be around 10%; for an absorbance of 15%, the indirect solar heat transmittance was estimated to be around 3-4%. This clearly showed the importance of having a low absorption factor of the printed surfaces (which means a high reflectance). The best performance was reached for an opening angle around 60° to 70°, for which the g-value and the light transmittance resulted in respectively 30% and 30% for 60°, 33% and 32% for 70°. Focusing on the spaces underneath the Vela, various patterns of the shading are also shown in figure 77, and emphasize the influence of the different opening angles on the direct radiation. Concerning the daylight, the results for an opening angle of 70% showed a sufficiently good performance. Some of them are also shown in figure 77. The average daylight factor was approximately 35%, which means approximately 26% when considering a 75% reduction for the structural system.

By assuming the described values of the cladding system, the Physical Equivalent Temperature (PET) of the spaces underneath the roof was calculated from h.8.00 to h.24.00, for 20 points at square level and Piastra's roof level. Figure 78 shows the diagram of the PET.

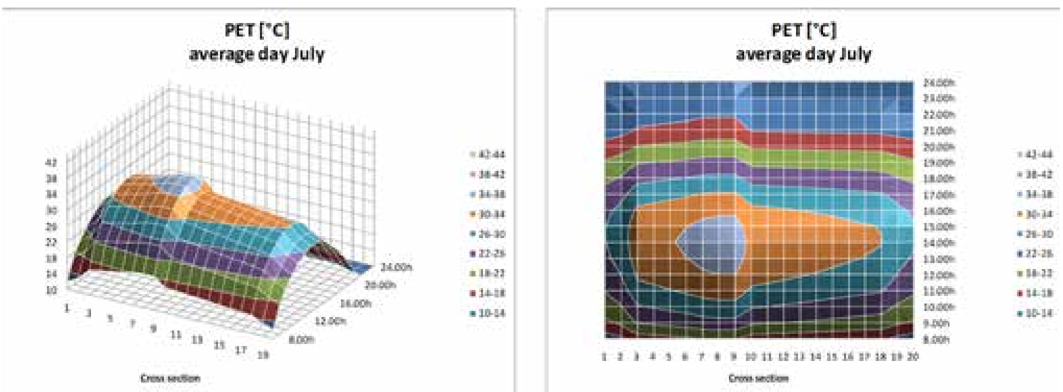


Figure 78
Calculated PET during the day at section D-D' for ETFE cladding. Period: July average; Clothing: Clo = 0,7; Average air speed = 0,5 m/s; Metabolism = 1 Met = 58 W/m2.

§ 6.7.5 Outputs for small scale

The conclusions concerning small-scale geometric explorations are discussed here concerning both the parametric approach and the design of the Vela.

§ 6.7.5.1 Reflections on the parametric design

The parametric process developed for exploring the small scale geometry of the Vela with respect to the solar energy transmittance and daylight provided relevant benefits, such as:

- The easy propagation of the cladding modules along a curved surface by maintaining the orientation of the shading system consistent with an absolute reference.
- The easy generation of meaningful design alternatives based on different opening angles
- The visualization (from the tridimensional models or from renderings of it) of the design alternatives to evaluate their aesthetic and visual properties, including views from the spaces underneath the roof
- The generation of tridimensional models for importing in software for performance simulations.

The process also encountered disadvantages or limitations, especially when dealing with curved geometries (both the ETFE cladding and the structural steel elements). Among them:

- The amount of computation required when dealing with a large number of cladding modules generated based on curved surfaces
- The difficulties in properly exporting from the parametric modeller and importing into the simulation software a large number of complex elements generated based on curved surfaces

Consequently, it is crucial:

- To build the parametric model by allowing its subdivision into specific sub-models. As an example, having the possibility to generate the cladding only without re-generating the structure is a fundamental aspect, allowed in the method since the points act as reference geometry both for structure and for cladding separately. Besides this basic subdivision, additional subdivisions of the model may be considered, according to the design cases.
- To simplify the geometric description of the structure and cladding as much as the goal of the parametric model allows to do.

§ 6.7.5.2 Outputs for the Vela design

The performances of the cladding system were compared with the performances of the other cladding options, including glazed roofs with a variety of glass types. A detailed description of the comparison is provided in appendix IV. The best performing option was the adaptive ETFE, which showed the highest ratio between light and solar energy transmittance, especially when looking at the combination of the g value for closed state and LTA for open state. However, if compared with the ratio provided by the north-south oriented shading the difference was minimal. Even more, the difference became negligible when compared to the additional complexity that the adaptive system has, especially considering the curvature of the Vela.

Moreover, concerning the daylight performances of the spaces underneath the roof, a rough comparison was made between glass and ETFE, which shows a relevant improvement when using ETFE.

Based on this, the north-south printed ETFE cladding was preferred. The properties of the systems were recommended according to the values described in sections 7.3.1 and 7.4. The opening angle was recommended between 60° and 70° in order to limit the direct radiation without compromising the daylight, and the opaque parts of the cushions were recommended to be reflective, in order to keep the indirect transmittance within acceptable values.

In addition, as the analysis of the views from the tridimensional models showed, the option performed properly also concerning the required visibility of the tower from the covered spaces. In order to further improve this aspect, the ETFE pattern may have a dark bottom printing and a light top printing.

As an important remark, it needs to be noticed that other performances were either considered in the process or advised for further investigations, such as the maintenance of the systems, their durability and behaviour in time and the possible glare caused by the lit cladding.

Having chosen this option, the integration of photovoltaic cells was also conclusively evaluated, by substituting the printing of the opaque parts. Possibilities for reducing the disadvantages concerning the absorbance factor of the system were considered. Considering the negative effect, the modules were recommended distributed where they have minor impact on the air temperature under the roof (i.e., the edges of the roof).

§ 6.8 Adiabatic cooling

In order to reduce summer over-heating, additional options were also evaluated, especially concerning adiabatic cooling. Specifically, the use of rainwater collected from the roof, the use of ponds, fountains and sprayed water, the integration of green roofs on the low surrounding buildings and of trees and greenery on the covered square and its adjacencies were considered. Providing the details of these investigations is out of the scope of this dissertation. As conclusions, in combination with the ETFE cladding system described in the previous sections, the use of adiabatic cooling systems was recommended. The diagram in figure 79 illustrates the PET with the suggested integration of ponds, fountains and water nebulisation. The aspect that is emphasized here concerns the possible integration of such strategies into the parametric modelling process, especially when focusing on the overall shape of the roof in relation to rainwater collection.

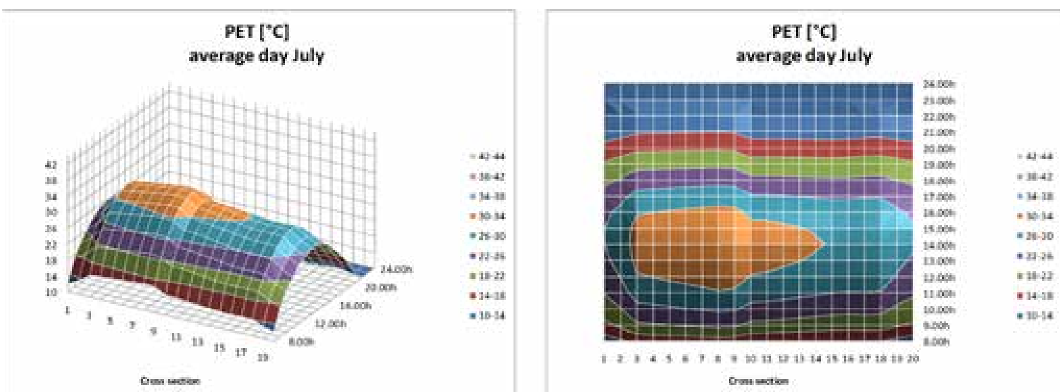


Figure 79
The figure illustrates the distribution of PET during an average day in July, along section D-D'. The PET was calculated for the ETFE cladding with both ponds, fountains at square level and nebulisation. The other parameters were maintained constant (Clothing: Clo = 0,7; Average air speed = 0,5 m/s; Metabolism = 1 Met = 58 W/m2).

§ 6.9 Conclusions on the Vela roof case study

The Vela roof case study focused on passive strategies for reducing the summer overheating of the spaces underneath the roof. It included investigations for increasing the airflow underneath the Vela, reducing the direct solar exposure of the covered spaces, reducing long wave radiation from the roof, and reducing the maximum temperatures using adiabatic cooling.

The overall process can be summarized as follows. In preliminary phases, a high risk of very uncomfortable thermal conditions was detected for the spaces under the roof, with high chances of a climate underneath the Vela-roof highly worse than the outside climate. The large scale geometry of the roof was investigated for increasing the airflow underneath; however other reasons than the summer thermal comfort led its design. Respecting the given overall shape of the roof, openings on the roof were evaluated at the medium scale of its geometry; they were only partially included in the final choice due to the almost irrelevant extra ventilation they provide. Reducing the g-value of the roof (especially by reducing the transparency of the cladding system) and the use of adiabatic cooling resulted to be the most effective. Concerning the transparency of the cladding system, comparisons regarding thermal and daylight performances of various serigraphed glazed cladding and ETFE pneumatic systems were made. Among all, the performances of an ETFE cladding system with adjustable middle layer and of a static ETFE pneumatic system with north-south oriented shading printing resulted as the best. Between these two systems, the first one resulted in a better performance; however when comparing the achievable benefits with the technical complications and current limitations of this system, the advantages proved to be too small; based on this, the second option was evaluated as the best preferable one. The static ETFE pneumatic system with north-south oriented shading printing was therefore chosen, possibly integrating photovoltaic cells in the cladding system along the edges of the roof.

As part of this broader work, the chapter focused specifically on the use of the parametric method PAS in combination with performance evaluations. The conclusions concerning this case study are further discussed concerning the parametric method. Specifically, the role of the geometry is considered first; and the considerations on the specific method follow.

§ 6.9.1 Role of geometry

The Vela roof as a semi-enclosed envelope filters and controls the environmental factors with respect to thermal and daylight comfort in the spaces underneath. This action is based on a combination of geometry and material properties, which are both equally important. The importance of geometry is emphasized here.

In section 2.5.1, the key role that geometry has with respect to engineering performances usually unconsidered during the conceptual phase has been emphasized. The Vela roof case study exemplifies this concept, by allowing a numerical quantification of the benefits deriving from addressing geometric choices based on performance analyses. The geometry of the roof at its different scales showed to play a key role for the heating and cooling effects, as reflected in the data provided in this chapter. Among the large set of data related to each of the considered principles from passive strategies, the case of the cladding system is of specific evidence. Specifically, over a total PET reduction of about 25%, about 12% was due to the combination of geometric and material properties of the cladding. A few key examples are recalled here, referring to the three levels of the covered spaces: (a) the ground floor with a semi-outdoor public square, (b) the first floor with a terrace covered by the roof and (c) the second floor with walkable roofs for public use. Analysing the initial reference geometry, a daily maximum PET of 35.1 Celsius degrees for (a), 37.3° for (b) and 39.7° for (c) were expected under the roof in July for a cladding with 50% transparency. Decreasing the transparency by about 25% using clear opaque colours with respect to solar exposure, without increasing the long wave radiation, was shown beneficial since it allowed a significant increase in comfort, reducing both the time and area with maximum daily PETs between 38-42 degrees (c). However a 70% opaque cladding also affected the daylight, which turned out to be not sufficient. Introducing a cladding system based on a three-dimensional geometry with a north-south oriented shading printed pattern was evaluated to be of great help in limiting the direct solar exposure underneath the roof while allowing the transmission of indirect daylight. This allowed avoiding maximum PETs over 34-38 degrees also in the most critical level (c). Additionally, fountains, ponds, sprayed water mist for adiabatic cooling and slightly increased air flow were combined as well, allowing maximum PETs between 30-34 degrees, which were considered acceptable when compared to the outside. Moreover, it should be emphasized that possible additional benefits could be expected in case of an even earlier integration of performance evaluations in the conceptual phase, when design explorations at a larger scale can be more freely considered, in this case to drive the airflow.

Figure 80 illustrates the built project.

Figure 80
Images of the project. (Courtesy of Open Project Office and Ing. Giovanni Berti, copyright holders).

§ 6.9.1.1 Reflection on adaptive geometry

Focusing on geometry, the case study allowed reflecting on a large series of different aspects. While the general focus remains on the importance of geometry and the consequent potentials in using parametric modelling for performance oriented design, relevant notes can be made also concerning the use of static versus adaptive geometry. This topic is of key relevance both in setting the design exploration and in choosing the final design solution.

Specifically, a recommendation needs to be emphasized concerning a careful evaluation of the benefits brought by the use of adaptive geometry in comparison to the increased complexity implied hereby.

§ 6.9.2 Reflection on PAS

The conclusions concerning the design method PAS are discussed according to the three phases of the method.

§ 6.9.2.1 Reflection on pre-PAS

As mentioned, the Vela case study supported and grounded the formulation of the guidelines for pre-PAS, in a reciprocal iterative process of both definition and encapsulation. With this respect, PAS showed both the effectiveness of its support, and the need of further improving some of its parts.

An aspect that is of key importance is the transition between pre-PAS and model-PAS, once the general geometric properties are identified. At this stage, the borderline between the analysis preliminary to the making of the parametric model and the ones done based on the parametric model or on considerations emerged from it, is blurred. There is actually not a fully distinguishable edge between a pre-PAS phase and a model-PAS phase; instead these phases overlap and iterative exchanges of information characterized the process between the building physics engineers and the responsible for the parameterization and parametric model production. On one hand, this resulted in the production of some parametric models that were not directly used for numeric performance evaluations; in other words, some of the parametric models did not pass through an explore-PAS phase. On the other hand, information extracted also from these parametric models were used in the process, during the preliminary investigations between pre-PAS and model-PAS. Both aspects are a confirmation that the evaluation in the time investment worth for the parametric model is uneasy to predetermine.

Closely related to this aspect, a note must be made also on the importance of the general knowledge extracted in the pre-PAS phase. As the chapter described, the preliminary studies allowed explorations based on which knowledge was gained before setting the parameterization approach and working with the parametric models. This aspect and the way this can iteratively relate to the different phases emerged of crucial importance and will be further addressed in chapter 7.

§ 6.9.2.2 Reflection on model-PAS

In the presented case study, model-PAS proved its potentials. On one hand, the general validity of the proposed approach is recognized. An advantage that the proposed parametric design approach proved is its intuitive applicability to geometries, including complex geometries, also in this case by means of a customizable library of scripts. On the other hand, particularly, emphasis must be given to its proven flexibility in embedding new conditions (such as the specific orientation of the structural grid), by means of a customizable library of scripts. This specifically increases the versatility of the parametric process, which relies on further implementations and variations of the geometric models. Such aspect has crucial importance especially when thinking of the time investment during the process.

Among the limitations, an important aspect that needs to be highlighted concerns the slowness in generating the alternatives, and therefore the need to subdivide the model in subtopics. Also noteworthy is the importance of setting the script in a way that allows that.

§ 6.9.2.3 Reflection on explore-PAS

Focusing on explore-PAS, emphasis is given here to the challenges that emerged in searching for meaningful instances to analyse rather than analysing the overall solution space of the model. With this respect, in this case study the process was conducted by relying on the expertise of the team in selecting parametric instances with high potentials for good performances. Obviously, the importance of the designer's and consultant's expertise needs to be pointed out here. In chapter 8, an alternative method is proposed by introducing computational tools helping to assign values to independent parameters rather than leaving up to the designer the full responsibility in generating and choosing the potentially good instances. However, the importance of the designer's and consultant's expertise still remains vital also during the explore-PAS phase, in a number of cases. That expertise cannot yet be replaced, even less when dealing with topics such as wind analysis through digital simulation, which requires both too much human interaction and computational power to be applied to large ranges of design alternatives.

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7 Case studies on solution spaces

In the previous chapters, PAS has been described, which is a parametric approach for the performance oriented design of large roofs; and one case study from practice has been presented, focusing on each step of the approach. In this chapter, a number of case studies are shown from teaching, focusing on the relation between the knowledge available to the designer in the pre-PAS phase of the process and the challenges of the solution space exploration in explore-PAS. The main goal of this chapter is the discussion of this interrelation; differently from the previous chapter, no emphasis is given to each of the single steps individually.

The first case study focuses on explore-PAS and on the difficulties of exploring the solutions space of the parametric model when few relations between geometry and performances can be formulated in pre-PAS. The second case study focuses on possible ways to increase the knowledge available during pre-PAS, and regards a case where analytical numeric calculations are joined to physical measurements and testing in order to extract the meaningful geometric parameters. The third case study focuses on the application of already available mathematical formulations in the pre-PAS phase.

§ 7.1 Introduction

PAS is a parametric design approach, for applying which expertise and knowledge of the designer are of key importance. These can be both supported and or increased during the phases of PAS. Based on the discussion of the case studies, the chapter stresses the relation existing between the knowledge available during the pre-PAS phase and the challenges emerging during the exploration of the parametric solutions space during explore-PAS.

§ 7.2 A case study on large solution spaces

This case study is presented in order to discuss the challenges of explore-PAS, when the design process mostly relies on it, by investing less effort in pre-PAS, and especially in its Phase 4. It tackles the design process for a pavilion, developed by Mark Antoni

Friedhoff Calvo, a student tutored by the author for a second year master course on Design Informatics[3] . The work presented here focuses on the process for the design explorations concerning daylight (Friedhoff Calvo, 2010).

§ 7.2.1 The design exercise

The design exercise developed by the student was more articulated than the part discussed in the following sections. However, focus is given here only on the aspects of specific interest for PAS.

Design requirements: The indoor spaces of the pavilion were expected to be characterized by a modulation of daylight, including a variety of effects based on the use of direct and/or indirect light only. Specifically, the interior space was desired to be uniformly lit by indirect daylight, with the exception of spots of intense direct light creating differentiated areas. According to the definition given by the student, the design exploration concerned therefore a special quality of light that would mix a homogeneous soft indirect light with concrete points of strong direct light. Based on this, the large envelope of the pavilion was supposed to filter the daylight to create these effects.

Primary generator: The inspiration for the explored primary generator was taken from the work of Escher, with specific reference to Sky and Water. The tessellation proposed in this work was based on two interlocking profiles representing two different animals, a fish and a bird. The idea for the envelope of the pavilion was to use interlocking and complementary shapes having different functions. Specifically, a system based on four interlocking variations of a double rhomboid was preliminarily developed, which included aspects to control the structural behaviour and the daylight.

Preliminary analysis and parameterization strategies: As the student reported, a preliminary analysis was to be made in Autodesk Ecotect software to determine which variables would have been considered and which limits would have been taken into consideration to reduce the scope of the research. Specifically, preliminary studies were conducted on the relation between the openings and the filtered light, leading to a relation between the definition of the openings and the position of the sun. This

3 Design Informatics Study, Computation and Performance track, BT MSc Degree, TUDelft – aa.2009-2010.

was included in the parametric model by relating the components to the sun vector, which controlled their variability. While a performance based design exploration for identifying the suitable design alternatives was set concerning the overall shape of the envelope, the density (and therefore dimensions) of the components, the relation with the solar vector, and the percentage of variable openings; moreover variations in the material and colour of design components were included.

Parametric model: The parameterization for the model was set according to the geometric aspects to be explored. Chapter 5 offers a deeper explanation of the general concepts, here following only recalled concerning the specificities of this case study. The overall shape was parameterized in order to achieve different curvatures; the density of the components was parameterized based on their UV distribution, the relation with the solar vector based on an angle of tolerance, the percentage of opening area based on various distances of offsets and heights of extrusions. Figure 81 illustrates the parametric components and their propagation onto the surface.

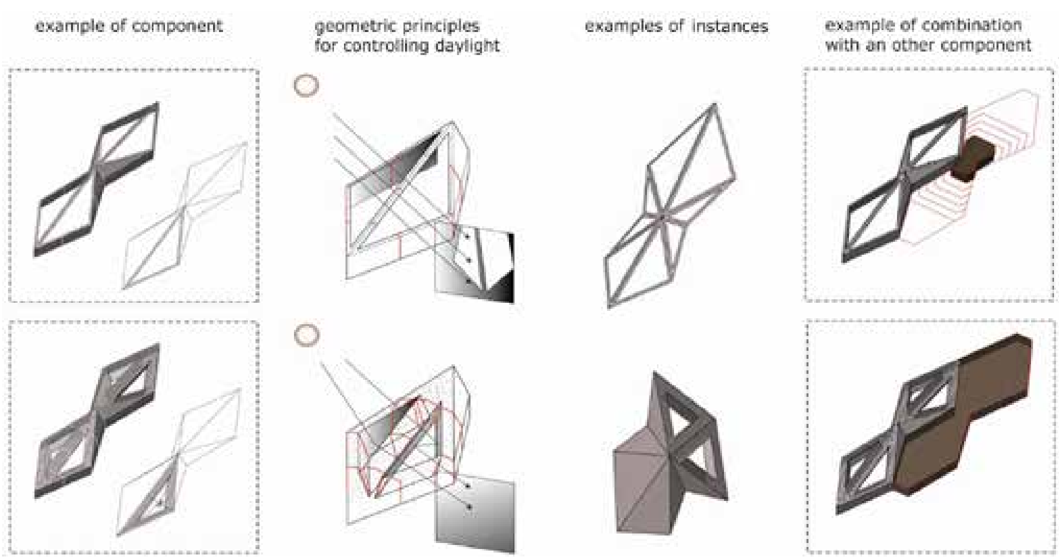

Figure 81
Examples of components: their parametric geometry; the principles for controlling daylight; examples of other instances of the parametric model; and the eventual combination with other components. (Images and design by Mark Antoni Friedhoff Calvo).

Performance evaluations: The exploration of the solution space of the model aimed at investigating the geometric combinations having light qualities with the desired effects. The evaluations were made in Radiance, where a number of instances of the model were imported for running daylight simulations. In addition to the geometric variations, Radiance allowed also the investigations of different material properties on the same geometric solutions. The effects on the daylight produced respectively by the variation in the curvature of the whole envelope, the material qualities and the percentage of close/open area in the components were tested separately. Figure 82 illustrates some examples of the evaluation process.

§ 7.2.2 Reflections on the process

The exercise was successful and engaged the student. As it emerges from the above overall description, large emphasis was given to explore-PAS, while less investment was made in pre-PAS, through all its phases. This was a reasonable choice not uncommon in design processes and as such it is discussed in its advantages and disadvantages.

When focusing on the design method and according to the feedbacks given by the student concerning the process, on one hand great advantages lied in the overall design exploration, especially thanks to the creation of a large set of design alternatives to be numerically analysed. On the other hand, two main levels of difficulties were encountered.

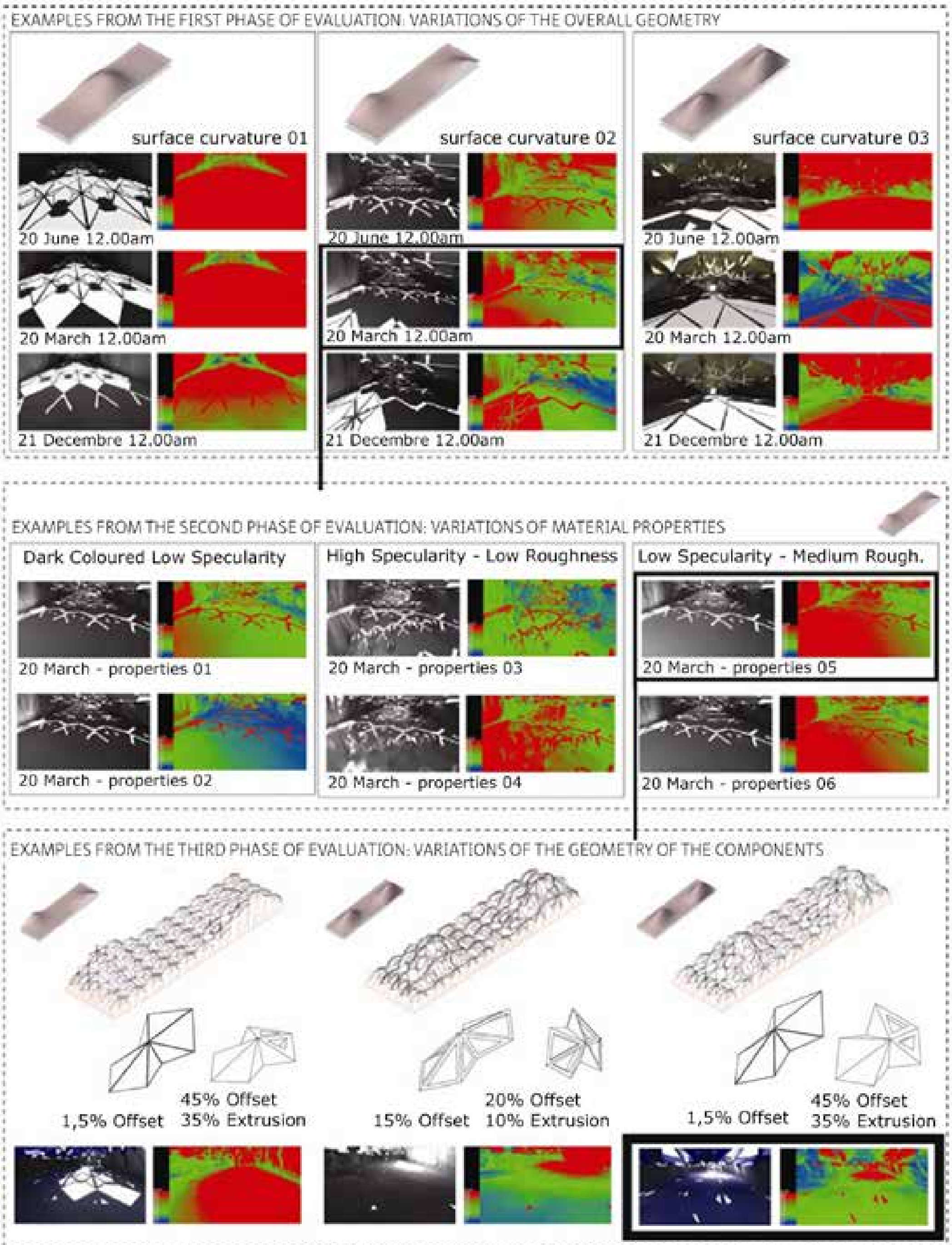

Figure 82

Diagram of the daylight evaluation stages with highlighted candidate for each exploration round; and further variations. (Image and analyses by Mark Antoni Friedhoff Calvo).

The first one regards the difficulties encountered during the parameterization process, which in this exercise was conducted based on the personal and intuitive conception of the designer, preliminarily trying to understand the relations between the geometry and the daylight effects. Considering the complex conception of the components, difficulties are understandable; their origin of the difficulties might be attributed to the minor time and effort investment in the pre-PAS phase of the process.

The second one regards the selection of the instances to be evaluated, which was deemed to be the most challenging aspect. The number of possible instances was simply too high to be manageable. The many possible combinations of variables as well as the complexity of the geometry made the performance behaviour being highly unpredictable, especially by one designer that is not an experienced team. In order to reduce the number of iterations for evaluations, the evaluation process was subdivided into three stages. The effects on the daylight produced respectively by the variation in the curvature of the whole envelope, the material qualities and the percentage of closed/open areas in the components were tested separately (thought re-iterations were done across the three aspects). Still, the options to be evaluated were difficult to choose.

Two possible solutions are proposed for these difficulties. The first one regards both difficulties. It consists of increasing the analysis in the preliminary definition of the parameterization strategies. This helps not only the identification of a proper parameterization, but also the search for well performing solutions. The reason is because it allows reducing the number of variables to be explored and increases the capacity to prediction of their consequences for daylight effects. A case study on this solution is presented in the following section.

The second one has a different perspective. As emphasized in the previous chapters, a major potential of parametric modelling consist mainly in generating a large amount of design alternatives. Enhancing this possibility should definitely be kept as an open and feasible design process direction. With this respect, investing relatively little time and effort in pre-PAS should be maintained as a possible option, up to the choice of the designer. In order to allow this direction, further supports for the possible exploration of a large set of design alternatives are definitely needed and should be developed. This specific subject is discussed in chapters 8 and 9, by means of both a deeper problem formulation and presentation of a tool proposed as a possible solution. Figure 83 illustrates the two possible alternative directions for the process.

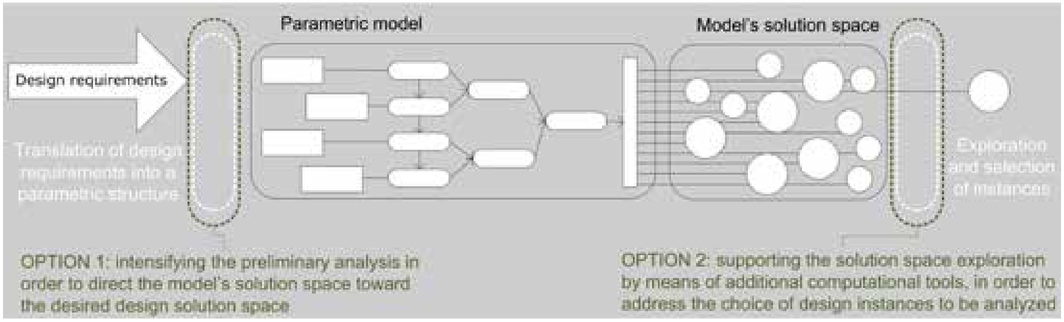

Figure 83
Two possible alternative directions for the process.

§ 7.3 A case study on narrowed solution spaces

This case study is presented in order to discuss the phase 4 of pre-PAS, which emerged as a key step also from the evaluation of the Vela project case study. It tackles the design process for the Schiphol Interchange Station, developed by Daniel Van Kersbergen, for his M.Sc. graduation project (Van Kersbergen, 2011). The Schiphol Interchange Station was a design project, consisting in an infrastructure enclosed and semi-enclosed in a large envelope. The graduation project included a double track in architecture and building technology, for which the author was respectively third and first mentor. While the architectural track focused on functional, spatial and perceptional aspects of the design, the building technology track focused on the integration of passive strategies for thermal and daylight comfort under the large envelope of the interchange station. The student was guided during the process according to the principles described in PAS, but a large degree of freedom was allowed in order to let his own design process emerge with no forced interference; this allowed also detecting eventual incongruence between PAS and the process. The work presented here focused on the process for the design explorations concerning daylight. Specifically, it exemplifies how increasing the preliminary analyses in phase 4 allows narrowing the solution space toward a limited desired ensemble of design solutions, reducing the challenges of the exploration of explore-PAS.

§ 7.3.1 The design experience

As in the case of the previous case study, also in this case the design exercise developed by the student was more articulated than the part discussed in the following sections and the focus is given here only on the aspects of specific interest for PAS.

Design requirements: Concerning the daylight requirements, the project was divided in different zones. For each function requirements were defined according to the building regulations, the architectural design intentions and the level of acceptance for discomfort given by glare, which were expressed based on light intensities (lux) and daylight factors, preferences between direct or indirect light, and required safety (for which glare could create risks).

Primary generator: The overall configuration of the project was taken with a given shape, defined in the graduation process based on a set of different design requirements highly affected by the large geometry, such as the complex functions of the infrastructure and the wind-driven airflow. The overall configuration and a diagram of the functional interconnectivity are illustrated in figure 84. The part of the process described here focuses on the design of the skin, for which four different primary generators were considered.

Preliminary analysis and parameterization strategies: The overall analysis process was articulated in three phases. They are illustrated in figure 85.

Figure 84
Overall configuration of the project and diagram of the functional interconnectivity (Images and design by Daniel Van Kersbergen).

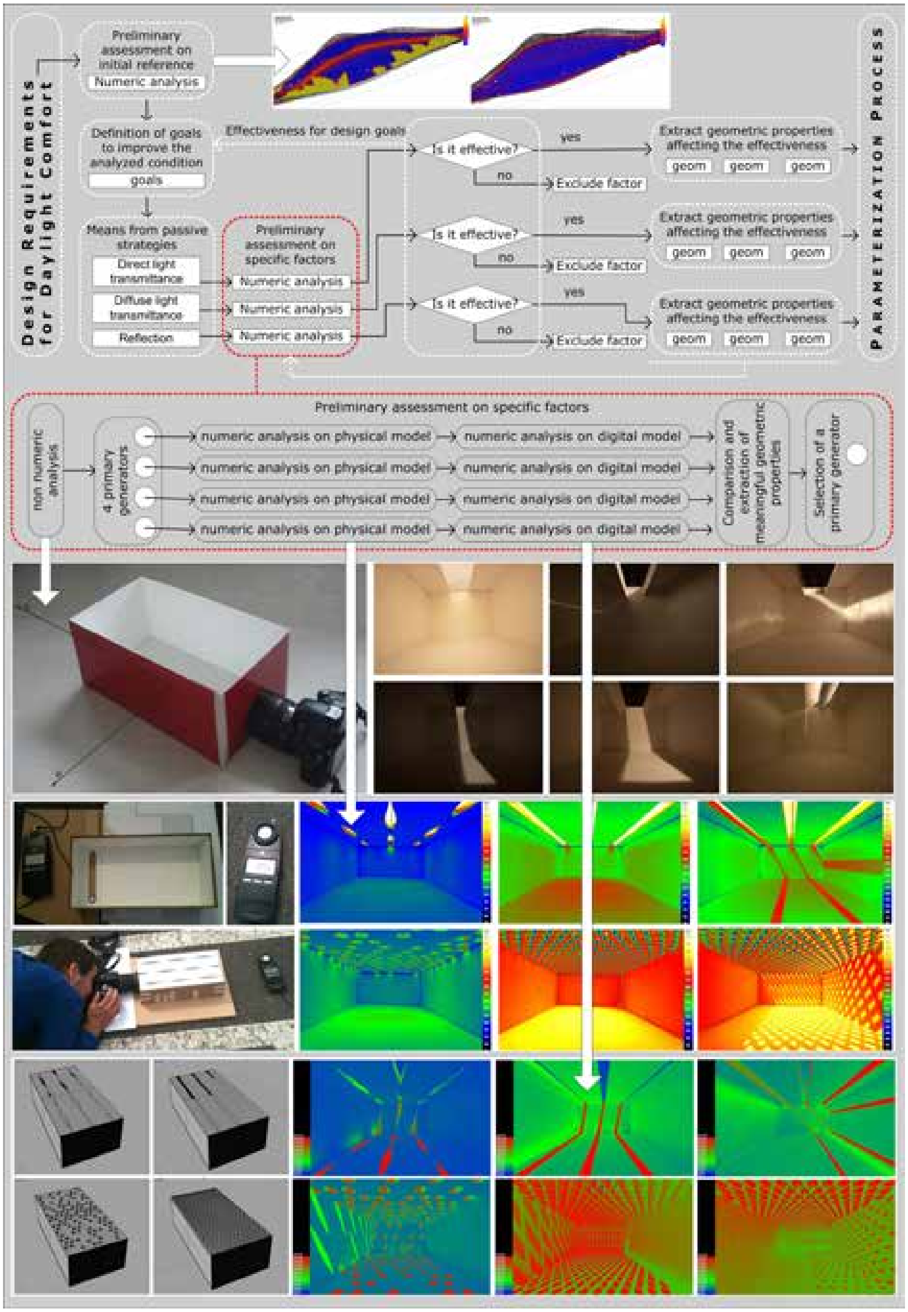

Figure 85

Overall process of the preliminary analyses conducted by the student (Images of the analyses and analyses by Daniel Van Kersbergen).

In the first phase, a very early set of preliminary (non-numeric) analyses based on physical models were made before even the primary generators were conceived. Based on the considerations drawn upon their results, the four generators made use of specific geometric properties, detected as significant. During the second and third phases, a set of preliminary analyses consisted of a substantial part of the overall process and ran transversally across the four different primary generators. For each of the four primary generators, both physical and digital tests were made on partial models, in order to understand the factors affecting the desired daylight performance. The physical tests allowed collecting numeric data used for both a preliminary understanding and calibrating the digital analysis. For the latter, the tests were run on multiple variations of the system.

The process allowed selecting one primary generator (consisting of a diamond based grid) and its meaningful geometric factors. For these, two families of geometric parameters were identified, respectively controlling the horizontal and vertical inclination of the cladding elements. Based on the so identified cladding, the overall surface of the envelope was then tessellated. Additionally, parameters concerning the material properties (translucency of two different panels) were identified as relevant for investigation. These are illustrated in figure 86; while figure 87 illustrates some results.

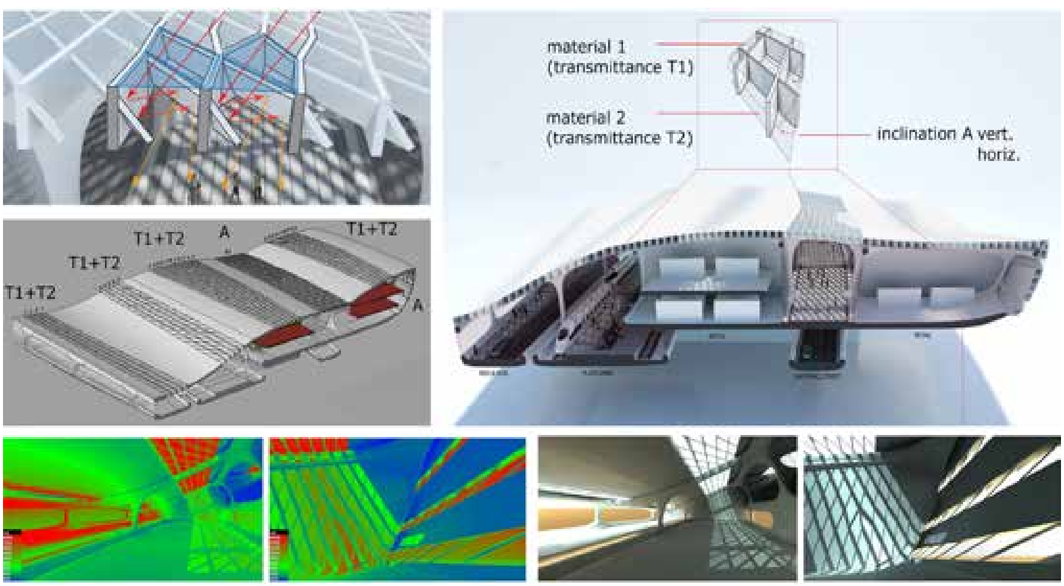

Figure 86
Examples of parameterized geometry and performance evaluation run by the student on the overall project. The top images show the parameterized attributes of the cladding and the distribution on the overall envelope. The row of images at the bottom shows some examples of performance simulations. (Images, analyses and design by Daniel Van Kersbergen).

Figure 87
Examples of visualizations of the final conceptual design. The images visualize some of the indoor and semi-outdoor spaces of the project. (Images and design by Daniel Van Kersbergen).

Performance evaluations: A set of performance evaluations were run for the different areas of the project, according to the different functions and daylight requirements. For these first runs of analysis, a certain configuration of the project was tested, in combination with a number of different levels of translucent materials. The results of the analyses were relevantly close to the desired performance. Examples are also illustrated in figure 86.

§ 7.3.2 Reflections on the process

The case study showed the potentials of performing deep analyses in the preliminary phase of the process, pre-PAS. Besides allowing the identification of meaningful geometric factors, the analysis process described above allowed also drawing a relation between the variation of the geometric factors and the performance trend. In this way, the geometric configuration set as first solution to be analysed has emerged already close to the desired performances. In this case, the further exploration of parametric geometry can be used to improve an already good solution, by easily varying the cladding components onto the tessellation of the surface.

§ 7.4 A case study on deterministic solution spaces

The previous case study showed how relevant a deep preliminary analysis phase is in order to meaningfully narrow the parametric solutions space to be further explored. The case study presented in this section exemplifies this attitude brought at its extreme consequences. In other words, this case study shows a work in which parametric modelling was used to explore a set of geometric variations only after the relation between the changes in geometry and the considered environmental factors were fully understood and mathematically expressed. As a result, the generated instances of the parametric model did not represent alternative design solutions to be explored searching for well performing configurations; instead they represented different configurations of the design satisfying the analysed design requirements under different environmental conditions. For all of them, the performance is actually already guaranteed to be a good performance.

This attitude leads to limiting the parametric solution space to solutions to be explored, in this case for adaptivity. The combined use of parametric geometry and search for good performances was used for the design process of form-active roofs reacting to varying wind load conditions. Specifically, a design tool was developed by the student, which enabled determining the geometric configuration of a discrete structure to minimize its bending moments under variable load conditions. The tool was developed based on Grasshopper (a plug-in for Rhinoceros, McNeel) as parametric modelling software. The process was carried out by a master student, Yannick Liem, co-mentored by the author (Liem, 2010).

§ 7.4.1 The design experience

It should be noted that this case study does not regards climatic performance, but structural performance. However the design method showed important general aspects and for this reason is included here.

Design requirements: The project aimed at designing a large span structure for covering a sport field. The structure was supposed to be a form active structure, adjusting its shape in order to react to different wind load conditions. The ultimate goal of this was minimizing the bending moment in the structure.

Primary generator: after a preliminary exploration of possible adaptive structures, the primary generator was based on a discrete structural system, conceived based on a modular grid structure.

Preliminary analysis and parameterization strategies: Preliminary analyses were quite extensive. They did not focus on the performance evaluation of preliminary configurations of the primary generator only, but they included a deep research on the structural theory and methods applicable in order to find forms based on minimized bending moments. This means the process was conducted with large emphasis on pre-PAS. Moreover, part of the pre-PAS phases of analysis could make use of the engineering knowledge already existent on the topic and the identification of meaningful variables could rely on pre-existent theories.

A second order of considerations needs to be made concerning adaptivity. When focusing on adaptivity, reference is given to the methods presented in section 5.6. Generally, the goal is the identification of suitable configurations with predefined geometric properties of the design, defined with the primary generator. This links to the case specifically presented in section 5.6.2. In contrast to the other cases, in such a case the parameterization is limited within a structure including variables and dependencies that are already identified as meaningful for adaptivity and that are embedded into the design of the form-active system. The design exploration is therefore structured by searching for the specific configurations required for the system under certain contextual conditions. In the case study presented here the suitable configurations were searched under changing environmental conditions (and constant human demand).

The process set by the student combined a solid basis of structural design methods with parametric modelling. The resulting process was an iterative form-finding that outputted a compression-only structure when possible for any change in loading. The inputs expected from the user were a two-dimensional grid of points (representing the structural nodes projected on a plane) and the wind loads. In order to identify the bending moment-free three-dimensional configurations of the structure for variable loads, a combination of several methods was applied. The thrust network analysis (Block, 2009) was used for identifying the reciprocal force grid (planar), which provided multiple solutions in case of systems having more than three bars converging at one node. Next, the complementary energy method was used to identify the suitable (lowest energy) solution among the multiple ones provided. And finally, the force density method was used for determining the third dimension of the structure (Z coordinates of the nodes in structural equilibrium). The details of these methods and their implementations are beyond the scope of this thesis, but are described in publications by the graduated student (Borgart and Liem, 2011).

The focus here is on the strategy embedded into the design tool. A grid point was used for the control of the overall geometry and of the structural modules. The tool was based on a set of scripts which embeded the whole process within the parametric modeller coupled with Excel. Specifically, given as inputs in Grasshopper a planar grid of points (which had variable positions, except for the perimetral supports), and directions and intensities of the wind loads (variable as well and expressed as independent parameters), lines connecting the points were generated, their lengths and reciprocal angles measured and automatically recorded in an Excel spread-sheet. With this information, and by varying the magnitude of a number of support reactions, the reciprocal force grid could be defined and tested with different load distributions, and optimized (by means of a search in Excel) for minimum complementary energy. The optimization was automatically re-run upon any change of input points in Grasshopper or wind loads in Excel. The reciprocal diagram was also automatically drawn in the parametric modelling software to visualize the results and facilitate both the understanding of proper solutions (grid with closed polygons) and the detection of eventual unwanted tensile forces (grid with open elements). Finally, the Z coordinates of the nodes were automatically calculated in Excel and outputted to Grasshopper, where the geometry of the provided structural solution was visualized (figure 88).

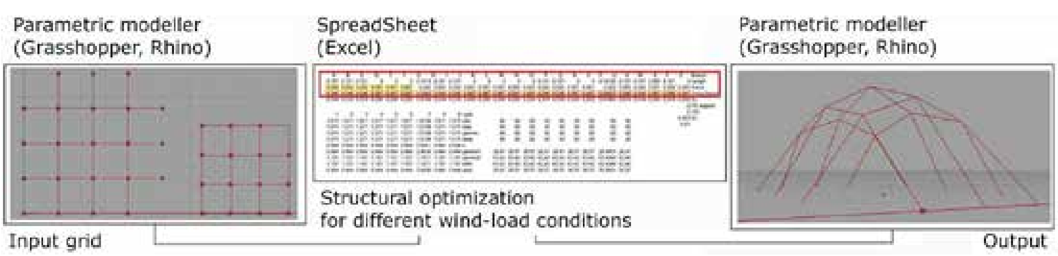

Figure 88
Diagram of the overall process embedded in the parametric tool.

Figure 89 shows examples of outputs. Within the boundaries of form-active discrete systems, a number of possible structures could be included. In order to support the choice of a proper structural typology, the design tool was meant to be used to identify extreme configurations, by determining the range of required geometric variability (examples are shown in figure 89b). In the specific case, the student had chosen to work with Variable Geometry Trusses (Miura and Furuya, 1988) by developing a set of studies for modular aggregations that would satisfy the needed range of variations (figure 89c). Knowing seasonal or daily patterns of the dominant wind directions or the wind behaviour in the area, estimation could also be made concerning the expected predominant configurations of the structure.

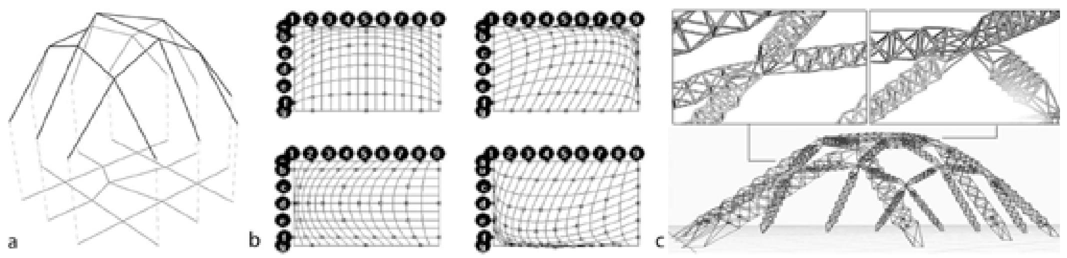

Figure 89
a) example of generation of 3D structural grid; b) four configurations for extreme variations; c) example with Variable Geometry Trusses.

§ 7.4.2 Reflections on the process

The method had limitations and would need further development to enlarge the current range of applications, but it exemplified on one hand a very effective way to limit the parametric design solution space to a set of well performing solutions, on the other hand the search for well performing configurations of a given family of adaptive structures, as form-active discrete systems.

Instead of parameterizing the point grid based on a set of variables to be explored as done in the previous case studies, the distribution of the point grid was calculated based on mathematical formulations and search for solutions to mathematical equations (i.e. minimum complementary energy). This approach presumed a preliminary solid knowledge and understanding of the analysed performances and the possibility to formulate a relation between geometry and performance.

§ 7.5 Conclusions

In this chapter, a number of case studies have been discussed.

The first case study focused on the challenges of explore-PAS when little formulation of relations between geometry and performance are formulated in the pre-PAS phase and are meant to emerge mainly by means of the solution space exploration. This mostly regards the challenges of exploring large solutions spaces.

The second case study showed a possible way to increase the awareness of the designer concerning the relations between geometry and performance during the pre-PAS phase. It focused on increased performance analysis during strategy-definition in order to increase the correspondence between the actual and desired solution spaces, and therefore narrowing the actual solution space of the model.

The third case study showed an example (from the domain of structural performances) in which a mathematical formulation linked the geometry and the performances already in the pre-PAS phase. It focused on the full coincidence between the actual and the desired solution space, based on deterministic (even bijective) relations between geometry and performances, formulated either based on knowledge extracted during strategy-definition or on previously established knowledge.

As conclusions on the presented case studies, a main reflection is here proposed. the choice the designer makes concerning the time and effort investment during the different phases and the awareness concerning the consequences of the attitude taken at the different phases of the process are essential. An absolute judgment concerning the right attitude to be taken is here avoided in favour of a choice that needs to be made according to the different design cases. The choice is especially dependent on the level of knowledge and understanding that is possible to be achieved in pre-PAS within a reasonable time for the process. Ideally, a high availability and use of knowledge has to be recommended; and time investment could be particularly convenient when general knowledge useful also for future projects can be gained. This aspect is further discussed in Turrin et al. (2013a and 2013b). However, such condition is obviously not always achievable. Chapters 8 and 9 will focus on additional computational supports for explore-PAS as a mean for exploring the parametric solution space in order to not only search for well performing solutions, but also extract information and knowledge to be re-used in the pre-PAS phase of further process.

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8 explore-PAS: design optimization and ParaGen

In the previous chapters the potentials and limits of parametric modelling have been discussed. Once the parametric model is set, a large set of design alternatives can be automatically generated and explored based on their performances. A direct relation between the knowledge available in pre-PAS and the challenges of the explorations in explore-PAS have been pointed out also based on case studies. When little knowledge is available in pre-PAS, often, an exhaustive, systematic exploration is not possible in explore-PAS by the designer alone, due to the breadth of the solution space. In this case the exploration can be based on the performance simulations of a limited number of selected design alternatives, where interdisciplinary collaborations are an essential need in addressing the selection of solutions. Limiting the exploration is however a drawback of the potentials of parametric techniques, especially when dealing with complex geometric variations affecting a large set of performances. The utility of further computational supports for exploring large solutions spaces are therefore emphasized. This chapter focuses on this aspect and possible solutions are discussed. Coupling parametric modelling, performance evaluation software and genetic algorithms (GAs) is presented as a possible solution to this problem. It is also suggested as a method to allow extracting information and knowledge to be re-used in the pre-PAS phase of further process.

§ 8.1 Introduction

In the previous chapters, the use of parametric modelling for performance oriented design has been discussed. Aiming at investigating a number of performances and based on a proper parameterization process, a meaningful solution space of the model can be defined. However, when relatively little knowledge is available during the pre-PAS phase, the solution space still may result in being large. Although generating a large set of design alternatives that are meaningful for the criteria to be analysed is a key step in the design process, it cannot in itself effectively support performance oriented design. As illustrated in the previous chapter, the identification of suitable performance oriented solutions is in fact based on a proper exploration of the solution space of the model by searching among the alternatives for instances that satisfy the given specifications. Such exploration is a difficult task and, as pointed out by Aish and Woodbury (2007), exploring the families of designs implied by the parametric models is one of the great challenges for parametric modelling research.

This design phase corresponds to a process of evaluation, for which one of the major obstacles is the breadth of the solution space. In fact, due to the size of the solution space, a systematic performance evaluation by the designer of each parametric solution is generally impossible due to time and other restrictions. This makes a designer-operated selection essential in the evaluation of solution instances. Also, a systematic exploration of the solution space aimed at selecting a subset of instances is challenging when left simply to the intuition of the designer. More specifically, the basis on which to select the instances becomes a key issue that requires searching for the combinations of independent parameters that would lead most likely to well performing solutions. This implies an understanding of the trade-offs of the solution space by analysing them with respect to the performance requirements. This again is a challenging task and becomes even more problematic when dealing with multidisciplinary criteria. It implies the use of interdisciplinary brainstorming and analysis concerning the solution space in order to select a range of design alternatives to be tested for the chosen performance criteria, in an iterative process of selection and testing.

The difficulties in exploring the solution space are a definite drawback when using parametric techniques. Therefore, further digital support is desirable. Based on the recognized difficulties in exploring the solution space of the model, the integration of parametric modelling with other computational techniques, such as search techniques related to the analysis and evaluation of performance values, is proposed here to tackle this problem by allowing a more systematic search for better performing solutions. This opens the scenario described by Monks et al. (2000), as "an alternative approach to design considers the inverse problem — that is, allowing users to create a target and have the algorithm work backward to establish various parameters".

The problem aforementioned is usually mainly considered as a search problem. However, the depth of explore-PAS exceeds a pure search problem and should include the richness of an exploration process. As it was mentioned in chapter 2, this includes supporting the learning process of the designer and allowing dealing with un-structured, un-predicted, ill-defined problems.

A possible solution toward this direction is introduced below, in which however the goal does not pursuit the full automation of the process, preferring instead to enhance the design exploration of the designer by means of interaction.

§ 8.2 Search techniques

Looking to support search in large design solutions spaces, a possible scenario concerns the combination of an automated parametric generation of design alternatives and their performance evaluations with search algorithms to find the satisfying parametric configurations among the entire collection of instances of the parametric model (an exhaustive search). Even though it might provide satisfactory support in case of a relatively small number of independent parameters, this scenario would become impractical as soon as the parametric model is described by a relatively large set of independent variables. The reason for this is the ineffectiveness in terms of time and computational effort of a systematic generation and performance analysis of each instance, resulting in a much too cumbersome process even when automated. With clear analogy to the designer driven process, as well as in the case of an automated or partially automated process, the selection of instances forms a key point for the efficiency of the method. With respect to this, optimization algorithms which guide the generation of parametric design alternatives are a preferred scenario, expected to provide more effective support.

In this section, optimization techniques are introduced; following, specific focus is given to stochastic techniques and, among them, to Genetic Algorithms.

§ 8.2.1 Optimization techniques

In mathematics, optimization is the discipline concerned with finding inputs to a function that minimize or maximize its value, which may be subjected to constraints (Pardalos and Resende, 2002). Optimization algorithms refer to the field of computational optimization, which is the process of designing, implementing and testing computational procedures for solving optimization problems (Baños et al., 2011). The formulation of the mathematical model and the algorithmic design and analysis can be implemented into both stand-alone software and plug-ins. To deal with complex problems, heuristics methods are introduced in optimization, which provide satisfactory, but not necessarily optimal solutions. When complexity is so high that even heuristic methods, or their generalization (so called meta-heuristic methods), fail to efficiently process the solution findings, parallel processing has been developed. This is named parallel meta-heuristic (Alba, 2005; Crainic and Toulouse, 2010), an overview of which can be found in Crainic and Toulouse (2010).

As concerning the analysis techniques of the solutions, the meta-heuristics optimization algorithms can be subdivided in two main categories: trajectory based algorithms and population based algorithms. Trajectory meta-heuristics use a single solution during the search process and provide a single outcome, consisting of the optimized solution. The population based algorithms use a population of solutions evolving during iterations and return a population of solutions when the stop condition is fulfilled (Baños et al., 2011). Though the potentials of trajectory meta-heuristics are also recognized, in this research, population based algorithms are preferred. The main reason for this lies in the success of previous experiences in design. A second reason lies in a good potential for an explorative approach: explicitly exploring ranges of solution results can be informative; possibly more so than following a trajectory based on single solutions toward a good solution. Population based algorithms include genetic algorithms and evolutionary algorithms, scatter search, path relinking, memetic algorithms, ant colony optimization, particle swarm optimization, estimation of distribution algorithm, differential evolution, artificial bee colony optimization, and others (Gendreau and Potvin, 2010; Baños et al., 2011).

As concerning the mathematic search techniques, the optimization algorithms can be subdivided into two main categories: the gradient-based methods and the gradient-free direct methods (Magnier and Haghighat, 2010). While the first ones are based on mathematical procedures and are effective mostly only in case of smooth and continuous functions, the second ones are based on stochastic techniques, which allow dealing also with non-linear behaviour of the values to be optimized (Renner and Ekart, 2003). Building performances are often nonlinear, leading therefore to discontinuous outputs (Wetter and Wright, 2004; Wetter, 2004). Considering this, larger attention is given here to stochastic techniques. Among the trajectory based algorithms, stochastic techniques include simulated annealing and stochastic hill climbing. Among the population based techniques, they include evolutionary algorithms such as genetic algorithms, ant colony systems, particle swarm, shuffled frog leaping, memetic algorithms and others.

When looking at the aforementioned categorization, it must be noticed that hybrid implementations are more and more being developed and are blurring the borders between the mentioned categories. Moreover, it should be considered that both a systematic comparison between techniques and the discussion concerning benefits and limitations of each technique with respect to specific design problems are beyond the scope of this dissertation. However, a number of key methods applied in building design are recalled below in order to locate the research contributions developed by the author as well as to provide the reader with the information necessary to orient himself in the field of design optimization. The topic is briefly introduced for a variety of aspects; specific focus is then given to energy and structural related design aspects.

§ 8.2.1.1 Stochastic optimization and building performance simulations

Looking at stochastic optimization processes for conceptual design in architecture, examples can be found in different fields. One of the most traditional aspects is space layout planning, which was addressed based on stochastic optimization already in the late 90's by Jo and Gero (1998); Park and Grierson (1999) use a multi-objective genetic algorithm in order to optimize the building layout with respect to the project cost and the flexibility of floor space usage; also hybrid techniques are used, such as in the case of the annealed neural network developed by Yeh (2006) by combining simulated annealing and neural network. Layout distribution on floors has been approached several times (Pham and Onder, 1992; Damski and Gero, 1997; Jo and Gero, 1998; Gero and Kazakov, 1998), as well as three dimensional space arrangement (O'Reilly and Ramachandran, 1998). Specifically applying optimization techniques to a performance simulation system, acoustic performance has been evolutionary addressed by Monks et al. (1998 and 2000). Focusing on energy, an exhaustive overview of optimization techniques applied to energy related aspects can be found in Baños et al. (2011). Differently, a more specific focus is given here to precedents using stochastic techniques combined with building performance simulations. These have been variously used. Specific aspects have been tackled through optimization, such as fenestration for daylight and energy performance (Caldas and Norford, 2002; Wright and Mourshed, 2009). Other approaches include broader aspects. Wang et al. (2005) use a multi-objective GA to evaluate design alternatives for both economic and environmental criteria. For thermal comfort and energy consumption, Magnier and Haghighat (2010) offer a recent example concerning design variables affecting the passive solar behaviour (such as size of the windows and thermal mass) and HVAC systems. By increasing the complexity of the optimization, attention is necessary for the time needed to compute the process. Magnier and Haghighat (2010) approach the challenge by diminishing the need of high numbers of GA generations. With this aim, the optimization is combined with a trained Artificial Neural Network. Focusing on similar design problems but on different optimization challenges, Diakaki et al. (2010) aim at supporting the designer in finding globally optimum solutions among alternatives and according to his/her preferences. The latter are considered by making use of weight coefficients to define the relative importance of design criteria. A compromise programming approach is used to optimize the design variables. Case studies are shown for criteria concerning energy consumption, investment cost and release of CO_2 emissions; explorations are based on decision variables representing the selection of alternative materials for the building envelope and systems for space heating, cooling and hot water supply. Other examples can be found in Ooka and Komamura (2009), Mohamed et al. (2011), and others. A last note concerns interdisciplinarity. In the field of energy efficiency, an important contribution toward interdisciplinarity is recalled concerning Wright and Farmani (2001), which developed the simultaneous GA based optimization of building design fabric, HVAC system size and the supervisory control strategy. An integral design is proposed, which the author defines 'whole building design', aiming at overcoming the mono-disciplinarily or less integral nature of precedents research in optimization for thermal aspects.

The topic of outdoor thermal comfort is also tackled through optimization techniques. A major precedent is illustrated in Chen et al. (2008), in which the authors aim at improving the outdoor thermal environment in summer by using GAs and a coupled simulation of convection, radiation, and conduction examined for variations in building and plant arrangements. Optimization for the design of semi-outdoor areas is not largely addressed, and precedents focus mainly on peculiar aspects of semi-indoor spaces. Such is the case of Jungfen et al. (2010), focusing on optimization of water spray systems for adiabatic cooling in the semi-outdoor spaces of the Shanghai Expo; Wang et al. (2010) draw attention to the importance of optimization of adiabatic cooling also for semi-outdoor areas, but do not actually show optimization methods.

In the field of structural design, examples are numerous. Kaveh et al. (2008) use ant colony optimization and finite element in topology optimization to find the stiffest structure given a certain amount of material, in 2D and 3D structural models. Fanjoy and Crossley (2000) and Jakiela et al (2000) offer some of the many examples of use of GA based optimization for structural topology; Ishida and Sugiyama (1995) focus on columns, more commonly, other authors (Galante, 1996; Camp et al., 1998) focus on trusses and beams. Also hybrid methods are largely developed and applied. It is the case of a hybrid optimization algorithm based on the particle swarm and group search, developed by Shikai and Lijuan (2011) and used to investigate truss structures with continuous variables. Also in the field of structural design, multidisciplinarity has been addressed. Miles et al. (2001) focus on a GA based method for structural design, but extend it to an interdisciplinary consideration that includes layout definition, lighting and thermal aspects, and other multidisciplinary criteria.

§ 8.3 Design exploration through optimization

In traditional optimization, a single best solution (or a front of best solutions) is found for a given set of objectives applied to a specific problem. As also shown in the examples mentioned in the previous section, optimization techniques have been mostly used in order to solve a specific (mono-disciplinary or interdisciplinary; single-objective or multi-objective) design problem by searching for an optimum solution. In this light, the role of optimization in design is to find within the design space the configuration that best matches desired performance goals (Monks et al., 2000). This is unquestionably one of the major potentials of optimization techniques. However, this does not support a fully informative exploration of design solutions. In fact, there is a key difference between the process of design exploration and the search for an optimum solution. Grierson (1996) presents this difference by distinguishing the design process in three possible types: routine process, innovative process, and creative process. From routine to creative, the attempt to describe a solution search loses potentials of precise and predetermined definition. A routine process is close to the concept of search, a creative one to a process of exploration. As argued in chapter 2, key needs in design explorations are:

- the learning process of the designer;
- the need of dealing with criteria possibly not included into the optimization process (especially in case of soft issues).

The importance of the learning process of the designer is moreover stressed based on the relation between pre-PAS and explore-PAS presented in chapters 6 and 7. When looking at these two points, most of the mentioned precedents lack in providing the needed support. There are however some precedents tackling these two points, while aiming at optimization processes as exploration tool rather than as search for an optimum. Some of the precedents propose solutions by focusing on:

- the design objectives to be evolved during the process;
- the design variables to be set more freely;
- the sub-optimal solutions to be considered of importance.

Among the ones focusing on the design objectives, Maher and Poon (1995) propose a GA system which allows the co-evolution of the fitness function and design solution by representing the fitness as part of the genotype.

Focusing on the exploration of different design variables, some precedents allow the user to intervene on the process by modifying, adding and/or deleting variables, re-defining the range of modification for variables, and modifying their constraints. It is for example the case of the work by Monks et al. (2000), in which simulated annealing is used to assist in the preliminary design phase for acoustic measures, in which the user can optimize over materials and geometry either separately or simultaneously.

Still, in these examples, once the optimization is initiated, no relevant attention seems to be given to sub-optima. As Mourshed and Shikder (2011) point out, sub-optimal solutions are usually discarded and in most of the precedents they do not contribute to decision making after optimization runs. Mourshed and Shikder stress instead that "the discarded 'inferior' solutions and their fitness contain useful information about underlying sensitivities of the system and can play an important role in creative decision making". Based on this consideration, Mourshed and Shikder propose a visual method to analyse sub-optimal solutions. These are retained during optimization and represented in a fitness array visualization system called phi-array.

In addition to this aspect, also a second point of value can be identified in sub-optima solutions; and this is related to the specific nature of design. Following the description of the act of design given by Herbert Simon (1969), it is often counterproductive to focus on one 'best' solution, because the objective criteria that produce it are usually incomplete. Particularly in the area of form determination, many criteria are not easily expressed numerically. For certain aspects, the approach proposed by Luisa Caldas embraces this point of view and tries to overcome the limited attention to optima, or at least to unique optima. In Caldas and Norford (2002), a tool to optimize design elements of a building in terms of their environmental performance is shown. It uses GA as the search engine, a thermal and lighting simulation program to analyse the building performance and an AutoLisp routine for visualization of results. The aspect emphasized here is the fact that the optima solutions achieved in different runs for the same problem lead to different design configurations with similar performances. While discussing this aspect, the authors highlight its importance, since it "may constitute valuable information to the designer, who is provided with a number of alternative solutions over which he can further overlap other design criteria not included in the optimization process" (Caldas and Norford, 2002). As further development of the design system, Caldas (2006; 2008) presents GENE_ARCH, which uses both standard GA or as a Pareto GA, for multi-objective optimization.

Another precedent worth mentioning concerning a certain attention given to sub-optimal solutions is BGRID (Miles at al., 2001), a decision support system for the conceptual design of commercial office type buildings, employing GAs. It searches for viable design options in light of both structural and architectural criteria. Specifically, it is meant to support defining the layout of columns in floor plans including also lighting requirements and ventilation criteria. BGRID provide the user with a selection of optimal solutions to enhance the understanding of the underlying processes.

In the approach proposed with this research, the definition of the objectives as well as of the design variables is concerned during the parameterization process; and they have been extensively tackled in the previous chapters. Major emphasis is instead given here to the importance of sub-optima. While most of the previous applications of optimizations in architectural design focus on the optimization results (by discarding sub-optimal solutions), the positions taken by Caldas, Miles, and Mourshed and Shikder on the relevance of sub-optima solutions is fully embraced. The importance of exploring also sub-optimal design solutions is stressed here both to extract knowledge from them and to reflect on the requirements of additional criteria. Finally, attention will be given also to the exploration of the design variables, within the boundaries defined in the parametric model. Encouraging the designer to experiment with the design variables and parameters is here recognized as a point of value for both aspects.

§ 8.4 Genetic Algorithms

As emerges evidently from the previous sections, the variety of optimization techniques that has been already shown beneficial in architectural design is high. In architectural design as in any other fields, the variety of design problems does not allow identifying an absolute preference for a specific optimization technique. The advantages and disadvantages offered by each optimization techniques should be considered when looking for an appropriate support to a specific design problem. Also, the choice of an optimization technique depends on the nature of the design space and on the types of constraints (Monks et al., 2000). In this respect, it is worth to mention here a tool that allows for interchangeability of optimization techniques, to be chosen based on the specific nature of the problems analysed. In the commercial software modeFRONTIER (ESTECO srl), various methods are available, which include both trajectory based and population based techniques, such as GAs and Simulated Annealing among others. The key idea of modeFRONTIER is the possible coupling with any computer aided engineering tool for performance simulation, in combination with a large set of optimization tools.

The direction taken in this research leaves this option open. However, focus has been given to GAs for the reasons presented below.

§ 8.4.1 The choice of genetic algorithms

Even though the potentials of other optimization methods are not questioned, also in their eventual hybrid combination, a preference is given to evolutionary algorithms (which use a use a population-based approach). From among the possibilities, evolutionary algorithms are chosen due to their already proven potential in supporting the design process based on design exploration principles, based on a large number of precedents (see previous sections). According to Guliashki et al. (2009), the popularity of EAs is related to a number of aspects, among which: their simplicity in being implemented as compared to other techniques, also in case of parallel processing; their flexibility and robustness for a wide spectrum of problems; their great ability to find multiple optimal solutions. Evolutionary algorithms (EAs) are stochastic search methods that mimic the metaphor of natural biological evolution and/or the social behaviour of species. They include Genetic algorithms, memetic algorithms, particle swarm, ant-colony systems, and shuffled frog leaping. Examples include how ants find the shortest route to a source of food and how birds find their destination during migration. The behaviour of such species is guided by learning, adaptation, and evolution; a comparative study of evolutionary optimization techniques is illustrated in Elbeltagi et al. (2005).

Among the EAs, particularly, GAs are considered in this research. GAs are cyclic search techniques which operate on generations of large sets of design solutions (populations). Operations including re-combination, mutation and selection, progressively shift successive generations toward solutions which perform better when evaluated with respect to a given single or multiple criteria (fitness function). The technique is well known and commonly applied in numerous fields including various engineering disciplines, and therefore not further discussed here. A broad introduction to GAs can be found in many publications (e.g., Goldberg, 1989).

The choice for GAs is not only based on performance. Comparisons made by Caldas (2001; 2008) between Simulated Annealing and GAs for a building design optimization problem showed that GAs performed just marginally better. As also recalled in other articles (Damski and Gero, 1997; Caldas and Norford, 2003; Sariyildiz et al., 2008), the potential of such techniques include the capacity to deal with large parameter spaces, and with discrete parameters, as well as to evade local maxima of the analysed performance trends, which make these evolutionary algorithms well suited for guiding the generation of design solutions. More important for the discussion here, the similarity between the parametric generation of instances and the GA based creation of populations makes combining parametric models with a GA optimization a good fit. More specifically, the evolutionary principles of GAs can be used to search for the combinations of independent parameters that generate well-performing instances within the solution space of the parametric model. This would address the creation of the instances toward the ones which best relate to the fitness function. The fact that the GA has no knowledge of the fitness function allows the optimization cycle to be applied with respect to whatever performance is desired.

This concept is at the base of the ParaGen method presented below, in which genetic algorithms as a means to visualize this link between form and performance.

§ 8.5 ParaGen

In section 8.3, the importance of exploring also sub-optimal design solutions as well as encouraging the designer to experiment with the design variables have been argued. In section 8.4, the choice of GAs as a means to support these explorations has been presented. In this section, a method and tool called ParaGen is presented, which uses GAs for addressing the exploration of optimal and sub-optimal solutions and allows for interaction from the designer.

The approach proposed with ParaGen is different in focus from traditional optimization methods in that it is geared more toward allowing an exploration of a range of solutions rather than limiting the focus to one single 'best' solution. Similar to the work by Luisa Caldas (described in section 8.3), the approach of ParaGen shares the view proposed by Herbert Simon (1969) and proposes the exploration of sub-optima as a key potential through which the designer can consider criteria not included in the fitness function. This is meant to be especially helpful for aesthetic criteria and other ill-defined problems, which are difficult to express numerically, but that a designer can take into consideration while exploring the ranges of good solutions. In this light, in ParaGen, the goal is to expose a range of 'pretty good' solutions or 'satisficing' solutions, which are stored and made available for additional exploration, both visually and eventually numerically. The way in which the tool facilitates the designer in further exploring the optimal and sub-optimal solutions is also meant to be an integral part of the novelty of the tool. Moreover, the tool integrates parametric software, and therefore allows taking full advantage of the parametric modelling technique and approaches described so far in this thesis.

ParaGen was ideated by Dr. Peter von Buelow and is being implemented at the University of Michigan, Taubman College, where it has been used for structural form optimization. Based on current collaborations with Delft University of Technology it is being extended toward interdisciplinary optimization.

In section 8.5.1, the tool is described in its technical setting; while section 8.5.2 describes the use of the tool. The sections are based on Turrin et al. (2011 and 2012).

§ 8.5.1 Technical aspects of the tool

The version of the tool discussed here makes use of a parallel network of PCs running Windows XP and a Linux web server, to run a series of both custom written and commercial software packages. ParaGen cycles each solution through four basic steps:

- The selection of variables: using techniques of selection, recombination and mutation, the GA running on the server provides the values for the independent parameters of each solution.
- The generation of forms: each solution is then passed to one of the parallel PCs where a parametric modeller generates the specific geometry using the variables provided by the GA. Currently this step is based on Generative Components (GC), but the system is open to different parametric modelling software (such as Grasshopper or Digital Project).
- The evaluation of the generated forms: the performance of each geometric solution is analysed using commercial simulation software. Originally, this step used STAAD. Pro as FEA software for structural evaluations. It is now extended to use Ecotect as simulation software for thermal and daylight performance. Any other program that can be used to evaluate some performance criteria could potentially be used as well. Different performance values can be combined as a weighted average, to produce an overall score that is used as a fitness function by the GA.
- The solutions along with related performance values and graphic depictions are returned to the server where all solutions are maintained in a searchable SQL database. A web page provides a graphic interface to the solutions, and allows interactive searches by the designers.

§ 8.5.2 The cycle

The setting described in the previous section allows for a cyclical functioning of the tool. The preparation of the parametric model is preliminary to the use of the tool. Once a parametric model is established based on a range of independent parameters having a dependency chain that is meaningful for the performance to be analysed, ParaGen is ready to run. The GA running on the web server initiates the process by generating random value sets which are used to generate an initial pool of solutions. Each set of values is downloaded to a PC where it becomes an input data file for the parametric geometry modeller (GC). The feeding of the data files to the cluster of PCs happens in parallel and continuously as each PC becomes available after uploading a completed solution to the server. ParaGen continues to generate random solutions until enough solutions have been evaluated to form an initial pool. The initial pool of solutions is intended to be relatively wide ranging in order to include a large variability of the design alternatives.

After sufficient solutions have been evaluated to form the initial pool (based on the complexity of the problem and geometry, but about 50 to 100), the ParaGen GA switches over to breeding pairs of solutions (parents) to generate further solutions. Rather than proceeding with a series of generations, the ParaGen GA uses a steady state breeding (Bäck et al., 1997) and dynamic populations. In this technique there is a continuum of breeding with the selection of parents being made from the evolving pool of solutions. As each solution is uploaded to the server it immediately enters the solution pool and could potentially be selected as a parent. A breeding population is dynamically defined as a subset of the entire pool of all solutions. At the instant a new solution is to be bred, a breeding population is created using a SQL query and sort. For example a population might be created of all solutions having a daylight factor greater than x and a solar gain less than y and a structural efficiency of z then sorted by increasing surface area. It can be seen that such populations can be bases on multiple objectives. In fact each of the two parents can be selected from differently defined populations. The size and composition of these dynamic populations can be adapted over the course of the run to limit premature convergence and ensure a thorough exploration of the design space while still searching toward better solutions based on the fitness functions. Selection preference can be directed toward better performing solutions or more recent solutions. It should be noticed that in this process no solutions are ever destroyed (eliminated from the SQL database of all solutions). As a result all solutions remain available for inspection, comparison or breeding at any time. This is particularly interesting in design problems where assessment criteria may change during the course of the investigation. This approach is referred to as a 'non-destructive dynamic population GA' (von Buelow, 2013).

A low probability mutation operator is also included which can either select just one parent for mutation or produce totally random solutions. In addition, exact duplicates of existing solutions are filtered out in the breeding process. This increases the efficiency of the process by eliminating redundant calculations. Preventing duplicate solutions also makes the visual browsing of the solutions by designers more practical.

After selection, the two parents are bred using Half Uniform Crossover (HUX) (Eshelman and Schaffer, 1995). Each value on the chromosome string has a 50/50 chance of crossing. The values are generally real numbers and are crossed based on a Gaussian distribution of random points about the values. This is a technique generally used in Evolutionary Strategies (Bäck, 1992).

After breeding, the chromosome string of values is downloaded to the PC client machine, where it is converted to an Excel file format and read into GC. The GC script uses the values to fill variables in defining the parametric geometry. The geometry can then be exported from GC in a format convenient for data exchange, in this case a DXF format. Also as an interim step it might be necessary to adjust or clean up the geometry in a more full featured CAD program such as AutoCAD or Rhino. This is a well-known problem having to do with how geometry is described for different types of analysis (e.g. meshing for rendering vs. FEA application). In order to automate the cycle, these data translations are currently solved by making use of scripted routines customized for the different geometric topologies.

Next follows the evaluation of the generated geometry. In work to date, STAAD.Pro for structural analysis and Ecotect for lighting and thermal analysis are being used. The performance data collected from the different analyses is added to the original Excel file containing the values for the geometry variables. In this way the structural or thermal or daylight characteristics are associated with the particular solution. At the conclusion of the part of the cycle run on local PCs, the Excel file containing the original set of variable values plus the newly found performance results, along with data files useful in a more detailed assessment of a particular solution are uploaded to the web server. This allows JPG, DXF, or VRML files to be made available for visualizing the geometry of each solution in detail. Also STAAD and Ecotect data files are saved for a more detailed inspection of the performance characteristics by the designer. Figure 90 illustrates the whole cycle.

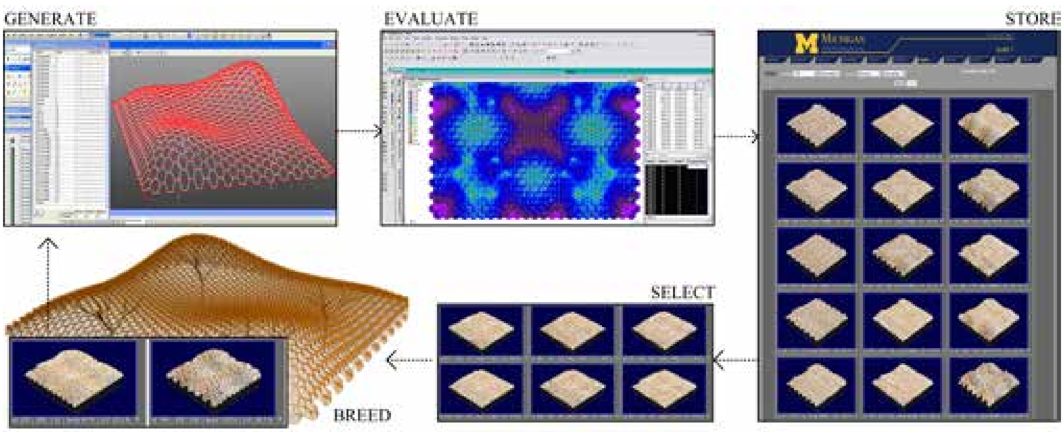

Figure 90
The ParaGen cycle. (Image from: Turrin et al., 2011)

On the server side, both the original variable values along with the performance results are maintained in a SQL database, and linked to the data and image files so that the designer can view, compare and retrieve everything through the web interface. Because all of the data is placed in the SQL database, it is possible to sort and filter the results in a variety of ways. The solutions can be easily sorted by any of the geometry variables or performance data. Using pull-down selection boxes at the top of the web page, all solutions can be sorted and displayed by one or two sort criteria, either ascending or descending. Also filters can be applied to these same variables to narrow the focus of the displayed solutions. This makes interactive exploration by the designer much more convenient, since the SQL search results can be displayed instantly. By selecting any solution on the population web page, a second page is brought up with a more detailed image along with all variable and performance values and links to additional files. Figure 91 shows the general population sort web page and the detail review page.

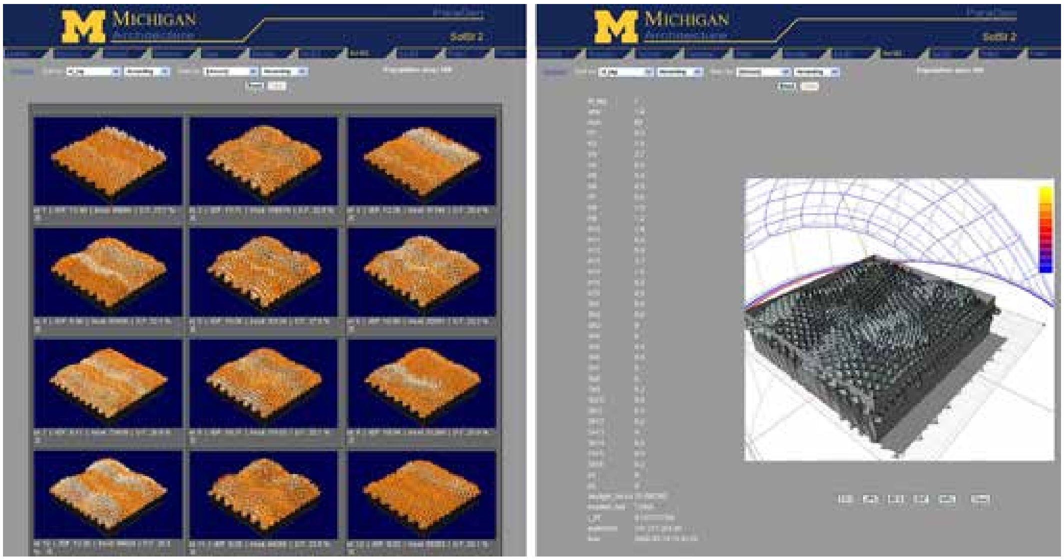

Figure 91
Left: The ParaGEN interface to sort the solutions. Right: The interface to access the SQL database of file. (Image from: Turrin et al., 2011)

It is also possible to generate plots of any variables or performance values. By clicking on the plotted dots the image of the solution is shown. This gives the designer another way to explore the interaction between form and performance.

The database becomes a growing genetic pool of solutions which can be filtered, sorted and viewed by a designer or team of designers through the web interface. The web interface also allows the designers to interact with the process. Breeding can in fact be set to run automatically in a continuous cycle based on defined objectives and selections as described above, or parents can be selected from the web page interactively by the designer. The designer can also select a single parent for mutation or generate a totally random solution for evaluation. These possibilities are specifically discussed below as they relate to the interdisciplinary nature of the performance criteria in architectural design. Depending on the complexity of the problem, the process may continue to explore several 100 or several 1000 solutions. This leads to the identification of well performing solutions toward which the generated solutions converge.

§ 8.5.3 The interaction with the designer

As presented in the previous sections, ParaGen is meant to guide the exploration of the designer, by exposing a range of 'pretty good' solutions that can be compared with one another. This relies on a preference for not fully automated systems, in favour of a more cooperative relationship between man and machine. As Chong (2009), points out, the high valuation of human's abilities such as creativity and flexibility in design tasks are to date still irreplaceable by digital and computational processes. The approach described in this section shares the philosophy embraced by Chong, according to which the cooperation of information technology, or even of artificial intelligence, and human intelligence and creativity can be a successful driving force in the conceptual design process. In this light, the guidance is offered to the designer by means of both visual and quantitative features of which three are discussed here:

- the visualization of the geometry;
- the remote availability of files and data both for visualization and for download;
- the possible interaction of the designer in breeding new solutions.

The visualization aspect mainly relies on the benefits offered by parametric modelling in visualizing the geometric solutions. The visually oriented approach of the ParaGen method offers advantages that can aid the designer in finding an appropriate solution by making preferential selections based on principles that are not completely described by the performance criteria alone (e.g. aesthetics). The tool aims at allowing the comparison of solutions side by side, which quickly highlights the differences in form that may be critical to the design intent. Such visual exploration is made available for the designer through the web interface, which allows following the genetic production of design alternatives using any web browser over the internet. This becomes particularly important in order to uncouple the visualization from the physical location of the computers employed for the computation, and offers the possibility to browse through the design solutions from any place with an available internet connection. Moreover, the web interface allows displaying all of the solutions filtered and ranked using any combination of performance criteria or geometric variables. A designer can quickly scroll through dozens of solutions in order to get an impression of performance sensitivity to the changes in geometry. Finally, the files associated to each visualized solution (JPG, DXF, VRML, Ecotect, STAAD, etc.) are also downloadable from the database via the web interface. Figure 92 illustrates the structure between the server and remote PC clients, which is used to allow visualization and download from remote positions. Having performance data available with the images allows the designer to make informed judgments in choosing which direction to pursue, and this leads to the third aspect discussed below.

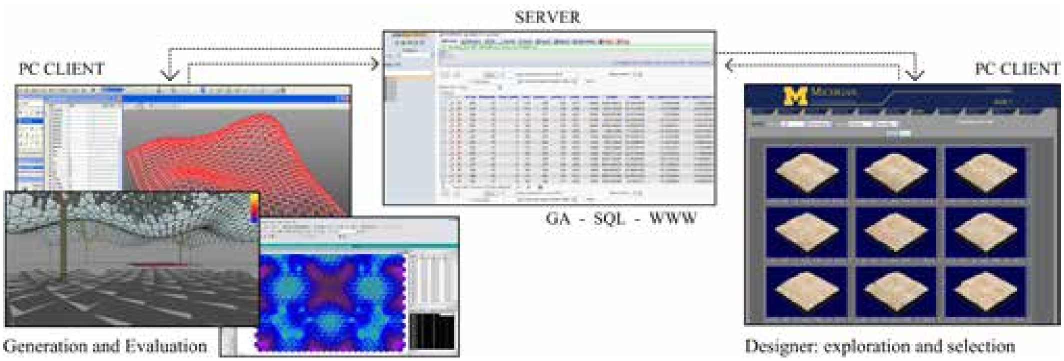

Figure 92
The structure of server and PC clients in ParaGen. (Image from: Turrin et al., 2011)

This last aspect concerns the possible interaction of the designer in creating new solutions. Based on breeding selections made by the designer, ParaGen aims at combining both programmed objectives (such as least weight of structural members or solar energy transmittance) along with subjective selections (such as visual aesthetics) made by the designer. The designer may in fact select some of the generated instances based on criteria not coded into the GA search. On one hand, defining algorithms for assessing and evaluating ill-defined problems can be difficult. This difficulty remains even if most of the design criteria could be coded, including fuzzy concepts such as aesthetics, perception and other performance values which are conventionally described as hardly measurable (Bittermann et al., 2009; Ciftcioglu et al., 2006). Still such tasks are not easily integrated into all processes. In this sense, allowing the designer to interact with the generation of solutions is a way in which the system can take into account the visual appearance of the solutions, based on designer preference. On the other hand, even when focusing on well-known measurable objectives, the designer might want to take into account criteria without coding a fitness function that specifically embeds them. In this sense, the program allows selections based on principles other than the fitness function performance criteria. Based on both of these objectives, the GA code in ParaGen allows new solutions to be interactively generated either by breeding two parents, or by mutating one parent based on the preferences of the designer. Another option allows the designer to select several solutions as a population which is then interbred to produce a larger set of alternatives. Operatively, all of the generated design alternatives are visualized via a web interface. The integrated filters and sorting features also make it possible for the designer to analyse the population in different directions – increasing or decreasing (best or worst) or to show only solutions within certain limits of combinations of variables or performance values. The interactive selection feature of the website integrates the automatic breeding in a continuous cycle, based both on pre-defined objectives and on the intervention of the designer to generate solutions based on subjective preferences.

Because the whole ParaGen procedure is running in parallel, user interaction can occur simultaneous to either the program running itself or with multiple other designers, where each designer simply links to the program through another web client.

§ 8.6 Conclusions

This chapter has dealt with computational support for the design exploration of the parametric solution space during the explore-PAS phase of PAS. Various search techniques have been briefly introduced and precedents in searching for suitable solutions in large design solution spaces have been mentioned, especially focusing on optimization processes. Differences between the approach proposed in this research and precedents have been pointed out, since this approach distinguishes itself in light of the importance attributed to the extraction of knowledge. Moreover, the interaction of the designer has been discussed as a support in favour of a collaborative process between man and machine, discarding fully automated processes.

Specifically, this chapter has described how the combination between parametric modelling and the interdisciplinary range of performance simulation software (discussed in the previous chapters) is coupled with GAs and an on-line accessible database. It has explained how the evolutionary nature of GAs allows not only for finding optimal or near-optimal design solutions, but also for more broadly exploring the design solution space with respect to the analysed performances. In this light, using the database to favour a real-time on-line visualization of the design solutions based on different criteria has been presented to support the designer during the decision making process as well as to disclose relations between the trend of the design variables and the design performance. The first goal has been tackled as additionally supported by means of the system interactivity, allowing the designer to intervene in the GAs generations. For the second goal, the use of filters for sorting the design solutions has been described; while the integration of clustering techniques has emerged as potential improvement.

According to this chapter, the system seems to promisingly join potentials of different techniques with interoperability across knowledge domain edges. Each technique provides beneficial contributions as well as discloses additional research directions and challenges that are discussed in the following chapter based on case studies.

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9 Optimization in explore-PAS: case studies

In the previous chapter, ParaGen has been introduced, which is proposed as a method and tool to support parametric solution space exploration during the explore-PAS phase. In this chapter, two case studies are presented, in which PareGen is used. The potentials of ParaGen have been pointed out concerning the identification of optimal solutions; the extraction of knowledge from sub-optimal solutions; the chance given to the designer to explore and choose among sub-optimal solutions based on criteria different than the ones included in the fitness function; the chance the designer has to interact with the GAs system during the generation of design solutions. The case studies presented in this chapter aim at investigating these aspects.

§ 9.1 Introduction

Following the approach described in the previous chapter and within an investigation of the topic of large roofs, two case studies which use the ParaGen tool are presented in this chapter. The first one concerns the design of a large span roof, with main focus on climatic comfort; the second one concerns a dome and focuses on structural performances.

The presentation of the case studies will not include a detailed documentation concerning the pre-PAS phase, for which only brief information and the conclusions are provided. The model-PAS phase is presented only concerning the aspects that are additional to the ones already presented in chapter 5. The major attention is given to the use of optimization in the explore-PAS phase.

Focusing on the explore-PAS phase of the overall process, the first case study aims at investigating the use of ParaGen in revelling information and knowledge from sub-optima; the second case study at investigating the use of ParaGen as a design support allowing the designer to direct the parametric generation of geometric alternatives by considering also criteria not included into the fitness function.

§ 9.2 Case study 1: the SolSt roof

The potential of ParaGen in exploring high numbers of variations of complex geometries for the design of passive solar roofs is illustrated through a case study. The project consists of a free-form roof covering an area approximately 50m x 50m, and hypothetically located in Milan, Italy. It is called SolSt with reference to 'Solar Structure', in consideration of its key role in controlling the solar energy conditions. In fact, in line with what is discussed in chapter 4, the roof is expected to contribute to the required thermal and daylight comfort in the covered spaces by means of passive strategies. The description of the case study is based on previous publications (Turrin et al., 2010; Turrin et al., 2011; Turrin et al., 2012).

§ 9.2.1 Primary generator

As shown by the EERE statistics data (EERE, World Wide Web reference), the local climate in Milan is characterized by high annual thermal variation of about a 23°C difference between the coldest month, January, and the warmest, July; limited wind speed and North wind direction, especially from September to January; high air humidity and little precipitation. In such a climate, in order to mitigate uncomfortable conditions, the reduction of both summer overheating and winter overcooling is required. On one hand, this leads to increasing the solar gain, possibly to be stored in thermal mass so as to benefit from it during night and to avoiding the heating losses in winter time. On the other hand, it is also desirable to reduce the solar gain in summer time and promote cooling effects, such as through evaporation and ventilation, possibly increased at night to cool the thermal mass. The thermal mass as well as the vegetation and water ponds are here intended to be underneath SolSt, with possible integration of water sprayed on the outer surface. In order to facilitate the air flow for cooling, the overall shape of SolSt is conceived based on roof peaks where heat extraction can occur through top openings due to the stack effect; the airflow needs however to be limited when considering winter conditions. Inclination of the peaks and eventual ponds are meant also to favour the collection of rain water. The cladding system is meant to reduce the summer solar heat gain, but is expected to favor the winter solar heat gain; in both cases it should allow the income of indirect light in order to meet the daylight requirements. According to what described, summer and winter conditions lead to evidently conflicting requirements, especially when focusing on the solar energy transmission, absorption, reflection of the cladding system and on the airflow. Concerning the latter, the top openings of SolSt are meant to be adjustable in order to control the airflow; specifically, they are expected to regulate the airflow by switching from an open to a closed configuration through intermediate positions. While concerning the cladding system, different strategies should be investigated, including two main directions: the use of geometric configurations negotiating conflicting needs and the use of adjustable geometries switching between configurations optimized for different specific conditions. The use of adjustable material properties needs to be mentioned too, but is not discussed within the focus of this thesis. Finally, concerning the structure, at least two structural typologies should be evaluated: a bar frame with the addition of the cladding layer and a structural skin integrating structure and cladding. According to this, preliminary investigations have been made on both a reticulated steel bar frame and a plate based structural skin; focus will be given here to the first option, however information on the second one can be found in previous publications (von Buelow et al., 2010; Falk et al., 2010). In both cases, the load bearing supports of the roof consist of branching columns. These are located in correspondence to the peaks in order also to support the adjustable openings and integrate their activation system. The edges of the roof might be either planar or undulated; the first option would facilitate closing the roof along perimeter buildings. The primary generator of the roof SolSt is illustrated in figure 93.

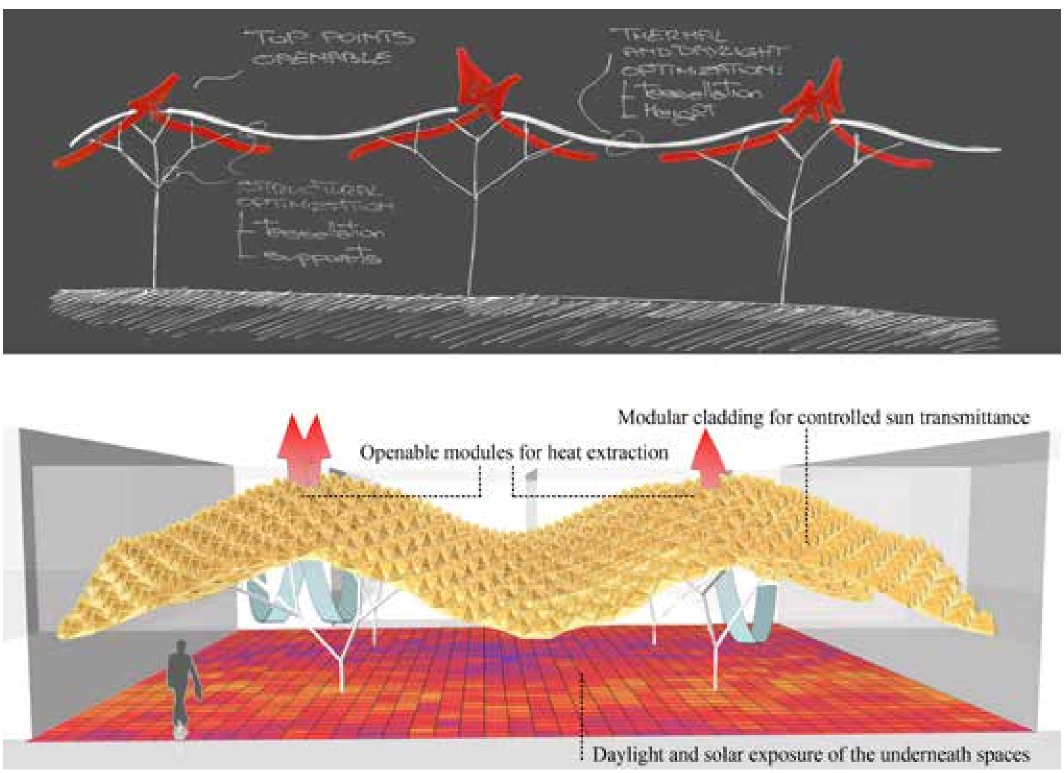

Figure 93
Schemes of the primary generator for SolSt.

§ 9.2.2 pre-PAS: parameterization strategies

With respect to the primary generator, the output of pre-PAS in identifying the meaningful parameters is to be considered. The aspects that are meaningful to the performances driving the design process are identified as the overall shape of the roof, its tessellations for structural geometry and the configuration of its modular cladding system. More specifically, the overall shape is investigated based on different curvatures through which the peaks are achieved; the structural tessellation is investigated based on a variety of different polygonal patterns as well as different densities of each of them; the modular cladding is investigated based on different polygonal patterns each of which with variable densities (matching the structural geometry) and on different geometric configurations of the cladding modules.

§ 9.2.3 model-PAS: parametric model of SolSt

The parametric model of SolSt has been built according to the process presented in chapter 5. During the design exploration, more than one model has been built, in an iterative process of exploration through different parameters. The key models are described here following.

§ 9.2.3.1 Parametric single layer point grid

Similarly to the approach used for the Vela project (chapter 6), a first parametric model parameterized the overall shape of the roof through the Cartesian coordinates of the control points of a NURBS surface; and the structural geometry was parameterized through a set of variables mainly controlling the distribution of a range of points lying on the surface, based on their UV coordinates. This model was also used in ParaGen for a preliminary analysis on the structural behaviour (see next section). Such an approach is powerful and provides a good control of the shape as well as of the point distribution. However, additional considerations were made in order to integrate into the design exploration a set of geometric constraints, meant to facilitate the design of the openable parts. It was considered in fact that integrating openable elements based on planar geometry allows a relevant reduction of complexity, when compared to curved geometries. This was considered both in the case of traditional openable systems, and in the case of foldable or deployable geometries for openable modules. With this intent, the peak surfaces were constrained geometrically. More specifically, a horizontal plane intersecting the top part of the peaks was expected to generate an approximately circular section. Depending on the tessellation which would have been preferred among those possible, different planar polygons would have been inscribed in the circles. When working with a NURBS surface with control points, the need of obtaining a closely approximated circular section when intersecting the top parts of the peaks with a horizontal plane would require the subdivision of the NURBS surface into patches. Instead of that, directly describing the shape of the roof through a mathematical function (section 5.4.1.1 – C) was preferred. Previous examples of such an approach include the roof of the British Museum Great Court where a surface was described by Chris Williams, with height z function of x in the easterly direction and y in the northerly direction to meet different conditions in the curvature as well as in the centre and along the edges; and the nodes of the structural grids were then defined as points lying on the surface (Williams, 2000 and 2001). A similar approach is here proposed for SolSt, but in this case, a mathematical function directly describes the positions of the points, based on Cartesian coordinates. The parametric model is described below.

In order to achieve the geometric conditions described above, the overall shape of the roof has been specified by positioning a set of points based on a mathematical function, using Cartesian coordinates. The x and y values defined the density of the grid as well as its overall dimensions. The z value is described based on a sine function whose amplitude defines the height of the peaks. In order to generate parametric variations of the output points, a set of independent parameters have been introduced in the functions by targeting the geometric aspects to be investigated.

In particular, the points were generated by describing the Cartesian coordinates within a for-next loop. The x and y values were defined by subdividing the sides of the roof by two reference lengths. The resulting equations integrated independent parameters to regulate the density and the proportions of the grid, as shown in table 15. Specifically, the density was regulated by the independent parameter 'density' and the proportions by 'factor'. The reference lengths were both kept at 10 meters for both sides. The z values were defined based on a sine function, which is doubled by following both the x and y directions in order to achieve the desired curvatures in both. Table 15 illustrates the standard case, by including the amplitude of the sine function as independent parameter.

Equations	
Independent parameters	**functions**
density factor	double xstep = xdim/density *i*factor; double ystep = ydim/density *j;
Amp	z = ((Sin(720/xdim1*xstep-90)*amp+Sin(720/ydim1*ystep-90)*amp1)+(2*amp))*1)

Table 15
Equations describing the Cartesian coordinates and integrating independent parameters.

By applying the described function, a distribution of points is obtained which follows the desired peaks; and the edges of the roof also follow the curvature given by the sine function. Since in the test case the edges of the roof were expected to be on a planar square, the z values were smoothly driven towards 0 when close to the edges by multiplying the sine function with an additional function. Specifically, in the boundary areas a zero crossing function was multiplied with the sine function to pull the boundaries down to a zero crossing along the roof edge. This is achieved by subdividing the overall grid in nine zones, corresponding to four parts close to each of the four corners, four parts at the middle of the edges, and one part in the middle area of the grid. In this last part the standard function was applied. Differently, a set of 'if conditions' identified each of the remaining 8 zones, where the whole function was composed by single couples of multiplied functions describing each zone. The resulting total function is exemplified in table 16, by illustrating the standard function and two examples of composed functions; the example is provided for a 50 x 50 meters roof; the factor is given a value of Sqrt(3), which allows for triangular and hexagonal tessellations with regular projections. Figure 94 illustrates the parameterized geometry.

Function

```
Point [][] function (xdim1,ydim1,density,amp) {
 Point pt = {};
   for (int i = 0; i < (density +1)/Sqrt(3); ++i) {
   pt[i] = {};
     for (int j = 0; j < density +1; ++j) {
       double xstep = xdim/density *i*Sqrt(3);
       double ystep = ydim/density *j;
       pt[i][j] = new Point();

       if ((xstep<1)&&(ystep<1)) {
       pt[i][j].ByCartesianCoordinates(baseCS, xstep*5,ystep*5,
        ((Sin(720/xdim1*xstep-90)*amp+Sin(720/ydim1*ystep-90)*amp)+(2*amp))*
         (-1*((xstep-1)*(xstep-1))+1)*  (-1*((ystep-1)*(ystep-1))+1)); }

        else if ((xstep<1)&&(ystep>=1)&&(ystep<=9)) {
        pt[i][j].ByCartesianCoordinates(baseCS, xstep*5,ystep*5,
        ((Sin(720/xdim1*xstep-90)*amp1+Sin(720/ydim1*ystep-90)*amp)+(2*amp))*
        (-1*((xstep-1)*(xstep-1))+1)); }
        ..............
        else  {
        pt[i][j].ByCartesianCoordinates(baseCS, xstep*5,ystep*5,
        ((Sin(720/xdim1*xstep-90)*amp+Sin(720/ydim1*ystep-90)*amp)+(2*amp))*1);}}}
```

Table 16
Standard function and two examples of composed functions.

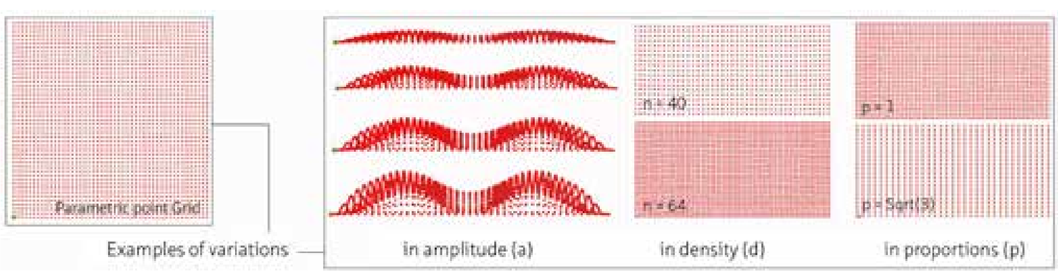

Figure 94
The parametric point grid described based on a number of arithmetically combined functions.

§ 9.2.3.2 Parametric tessellations and structural geometry

Based on the grid of points created, the parametric model was in this case structured to analyse the alternative structural tessellations and claddings separately from each other. Among the possible tessellations and claddings, the exploration of a cladding based on a hexagonal pattern is discussed here.

Based on the distribution of points so obtained, the roof can be tessellated using quadrangular, triangular, hexagonal polygons or combinations thereof. Such tessellations are defined by lines or by polygons modelled by using all or a selection of the points as vertex nodes. The tessellation follows the variable amplitude of the roof shape as well as changes when varying the density or the proportions of the point grid. This allows generating different polygonal patterns each of which is variable in density and can be squeezed or stretched along each one of the roof shapes. Figure 95 illustrates the examples of tessellations. Tessellations correspond also to various alternative modular bar structures of the roof.

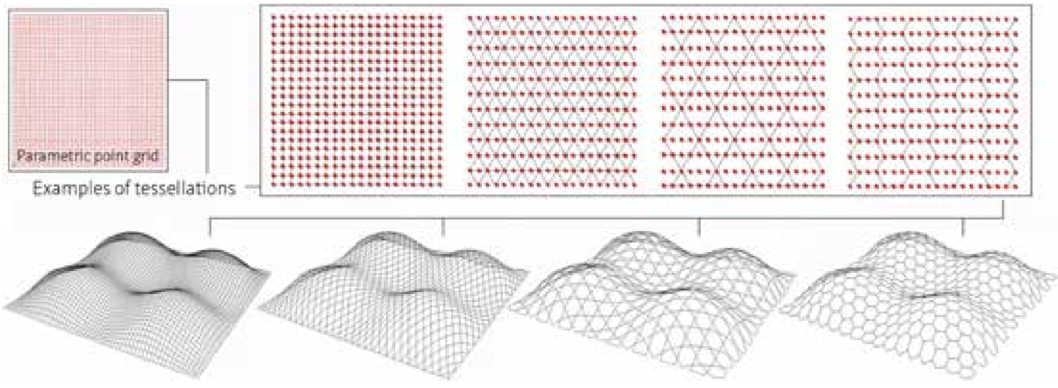

Figure 95
Examples of tessellations based on the point grid.

It also must be mentioned that a number of columns were modelled for the support of the roof. The supporting columns have been modelled for a set of fixed number of polygons, based on straight lines. Each of the four branching columns is divided into three parts with variable lengths and supporting nine vertexes of the hexagons with a base point located on the XY ground plane. Each base point is in correspondence to the centre of the four quadrants of the square surface. From the base points, the bottom segment of the supports starts pointing toward the centroid of the nine top points; while each of the middle parts points to the centroid of its respective group of three top points. This effectively orients the branches so as to minimize bending moments.

§ 9.2.3.3 Cladding

Among the many possible claddings that have been investigated for the design, the process here is demonstrated with one of the examples considered in section 5.4.3. Specifically, performance based explorations will be shown for the hexagonal pattern; two options are considered, one with north facing transparent panels and one with south facing transparent panels. The two options are represented in figure 42 (chapter 5); the first one is also illustrated in figure 96, when propagated onto the roof.

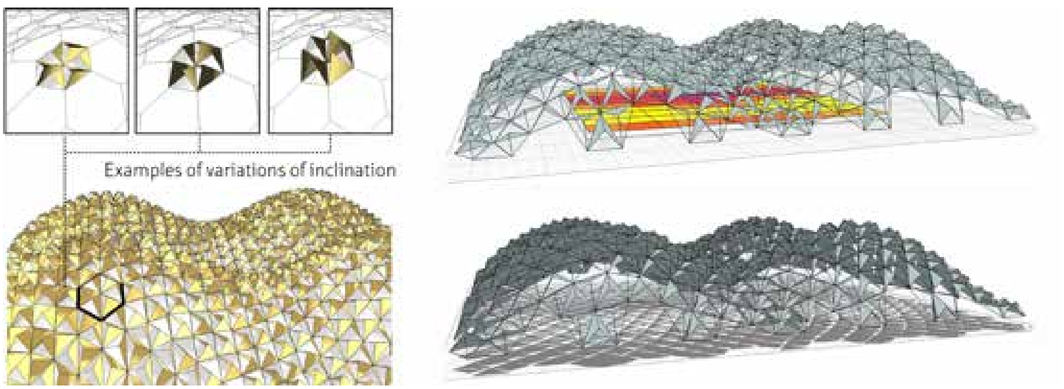

Figure 96
Examples of parametric variations of the cladding and performances evaluation of one instance of the roof, concerning the daylight factor and the incident solar radiation in the covered spaces.

§ 9.2.4 SolSt in ParaGen

Various sets of analyses have been run on SolSt by using ParaGen. These are aimed both at the explorations of design alternatives, and at the implementation of the PareGen tool in a parallel processing environment. Both for understanding how single factors affect the roof and for a proper testing of the tool, some simplification was made at the stage of this research. The analysis presented here does not aim at illustrating the whole spectrum of analyses that would be needed in order to finalize the design of the roof.

§ 9.2.4.1 Preliminary structural analysis

A preliminary analysis of SolSt was done concerning its structural behaviour only. The version of the parametric point grid based on UV coordinates (see previous section) was used. Parametric variations of the overall shape of the roof and of the branching columns were explored for a fixed density of the structural tessellation. The surface has been tessellated with the hexagonal pattern, for a fixed total of 247 hexagons. The parametric model defined in this way can generate approximately 21600 different instances of the geometry as a combination of various curvatures of the roof and various configurations of its supports. The generation of the instances is regulated by seven variables, the five z coordinates and two absolute values setting the proportions of the branching columns. Standard ASTM steel pipe sections were used for member sections. A single uniform load of approximately 1.5 kN/m2 was used to simulate the load of cladding and moderate snow or roof live loads, while the dead load of the steel structure was added in as a separate load. Several iterations were run to get convergence of the design solutions by minimizing the weight of the steel (von Buelow et al, 2010). Figure 97 shows examples of analysed instances.

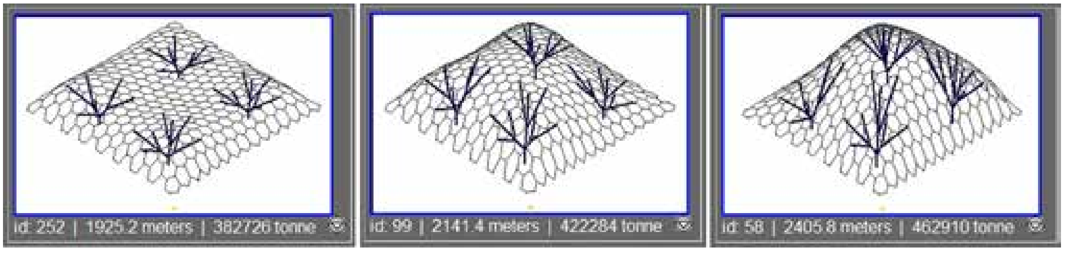

Figure 97
Examples of instances from the first testing analysis (structural behaviour).

The lighter forms were actually the ones which reduced the size of the humps thereby reducing the amount of material in terms of linear meters; no detection of structural aspects possibly compromising the feasibility of the roof were detected. The analysis performed in the following steps focused therefore on solar energy.

§ 9.2.4.2 Analysis on solar energy

A second set of analyses focused on the solar energy behaviour only. This included a number of separated optimization loops focusing on different cladding systems as well as in different objectives for the summer and winter seasons.

The version of the parametric point grid generated through mathematical functions was used in combination with the two cladding systems described in 9.2.3.3. Parametric alternatives were explored by varying the overall shape of the roof, the density of the tessellation, the local inclinations of the cladding panels and, for the south-oriented transparent panels cladding system, also the length of the shading extensions. The roof was evaluated based on the daylight factor and the incident solar radiation of the spaces underneath, following the concept of transparent glazed panels and glazed panels with 90% light colour serigraphy. Several iterations were run first for summer conditions to get convergence of the design solutions by minimizing the solar incident radiation and by maximizing the daylight factor underneath the roof. After this phase, additional iterations were run in new optimization processes through the whole year; in winter both the daylight and the incident solar radiation were to be maximized. In all cases, within a single-objective optimization process, the fitness function targets the ratio between the two. The parametric model, its variables and the cycle performed in ParaGen are illustrated in figure 98.

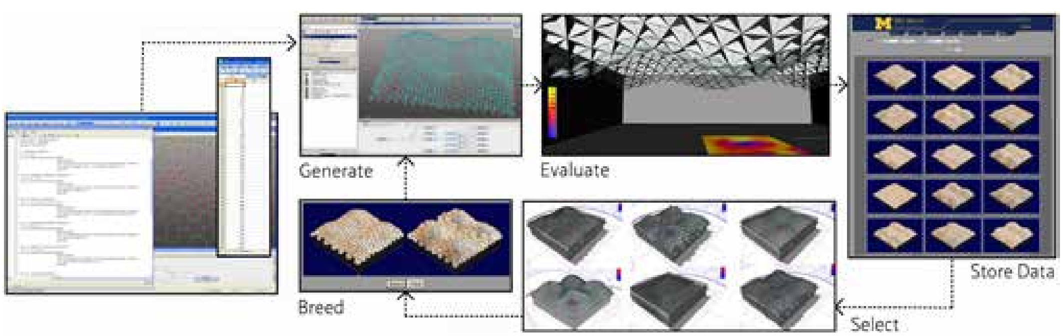

Figure 98
The parametric model, its variables and the cycle performed in ParaGen.

As argued in chapter 8, the goal of the exploration is not limited to the identification of the optimal solution, but consists in exploring the solutions, including the sub-optimal ones. Examples from the analysis in summer time, winter time and through the whole year are presented below not only with respect to the optimal solutions, but also the use of sub-optima for knowledge extraction and design exploration. Examples that can be analysed from the database are illustrated in figure. 99.

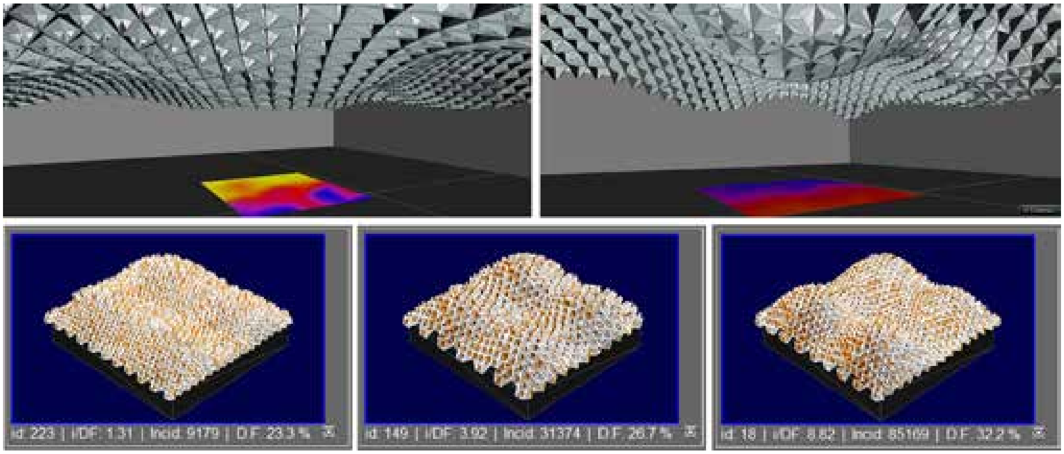

Figure 99

Second testing analysis (solar energy). Top Left: example with north facing opaque panels. Top Right, Bottom: examples with south facing opaque panels.

Focusing on the summer conditions, over a population of 202 individuals the lowest ratio between the monthly incident radiation of June (Watts) and the daylight factor (%) was achieved in solution 202 (12720/24.4) and was about 2.5 times smaller than the highest ratio (solution 54, ratio 38654/29.9). During the evolution in summer conditions, the geometry evolved with emergence of substantial curvatures of the roof (high amplitude), high density of the cladding modules and high inclination of the panels, especially in the south oriented parts of the curved roofs. Figure 100 shows some of the results. In this case, the amplitude and even more the density show high values in correspondence of good solutions (top right corner of the graph a). The proportional way in which the monthly incident radiation of June and the daylight factor vary (figure 100, graph c) shows a limitation of the chosen cladding, since achieving low incident radiation without relevantly affecting the daylight factor would be beneficial to the comfort of the spaces underneath the roof. This leads to the opportunity of comparing the performance of this cladding option with other claddings in order to further support the design process.

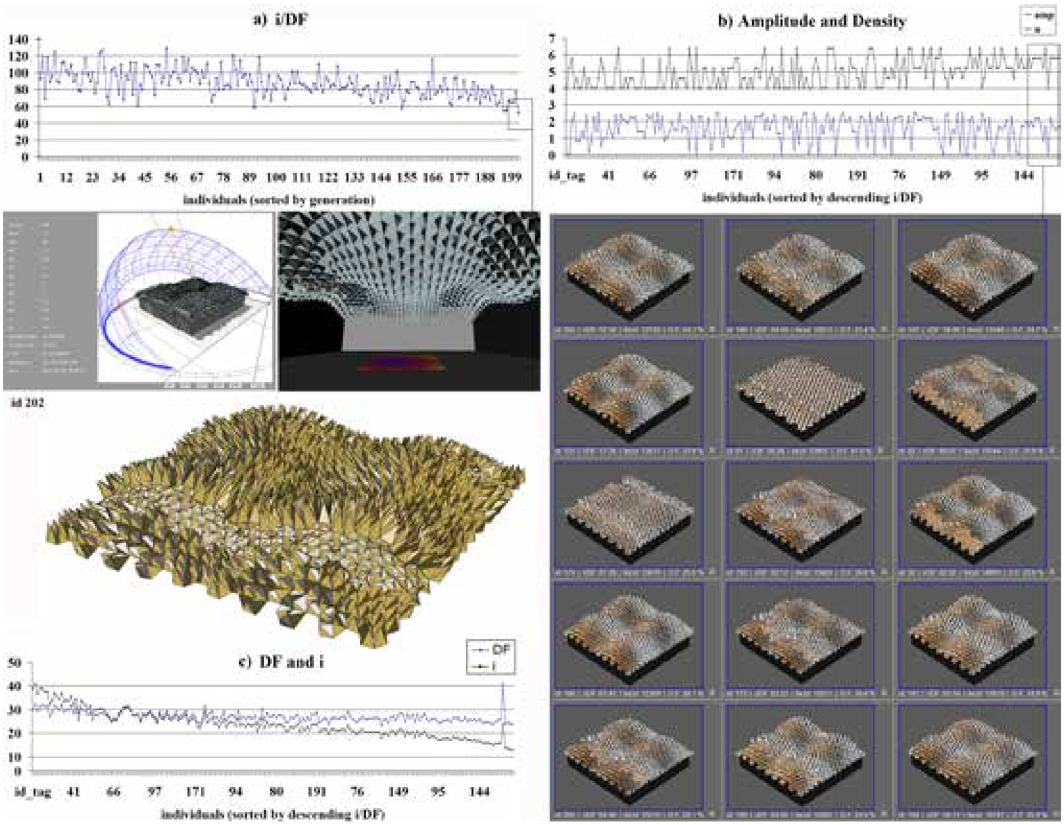

Figure 100

Examples of results from the ParaGen cycle regarding daylight factor (DF) and incident radiation (i) for summer conditions (with normalized values). Fig. 100a illustrates the trend of the ratio over the GA evolution of the design solutions, toward convergence to the minimum values. Fig. 100b shows a set of design solutions visualized from the web interface, by sorting them based on their fitness. By sorting the solutions by fitness, the trends of the amplitude and density (n) of the roof are also illustrated, as examples of how the design variables can be investigated through the database. Fig. 100c illustrates the trends of the monthly incident radiation of June and the daylight factor, after having sorted the solutions according to their fitness, by making explicit the relation between incident radiation and daylight factor.

Focusing on the winter conditions, over a population of 300 individuals the maximum sum of monthly incident radiation of December (W) and the daylight factor (%) was achieved in solution 298 (5441/38.2) and was about 2.3 times bigger than the lowest sum (solution 21, ratio 1745/24.4). During the evolution, very flat configurations prevailed in the good solutions, having also panels almost horizontally oriented and of relatively low density. As for the density, over a large number of best performing solutions, only few did not have the parameter n equal to 46 or 52 (corresponding to a low/medium density of the modules). Figure 101 shows some of the results. In this case, the amplitude shows low or minimum values in correspondence of good solutions (bottom right corner of the graph); the density clearly shows a prevailing value. Also in this case, the relation between incident radiation and daylight factor confirms the limitation of the analysed cladding already concluded from the summer analysis. Further comparison between summer and winter solutions reveals also a coherent correspondence of design variables between the worst summer solutions and the best winter solutions and vice versa (high inclination of the panels and the high density are evident in the worst winter solutions as in the good summer solutions; low amplitude, low density and inclination are evident in the worst summer solutions as in the good winter solutions). Confirmation of coherent design evolution is shown also in an anomalous good summer solution (solution 91), which has a pretty low ratio based on high daylight factor, but also high incident radiation. As would be expected, this solution has the same design variables emerging for good winter solutions.

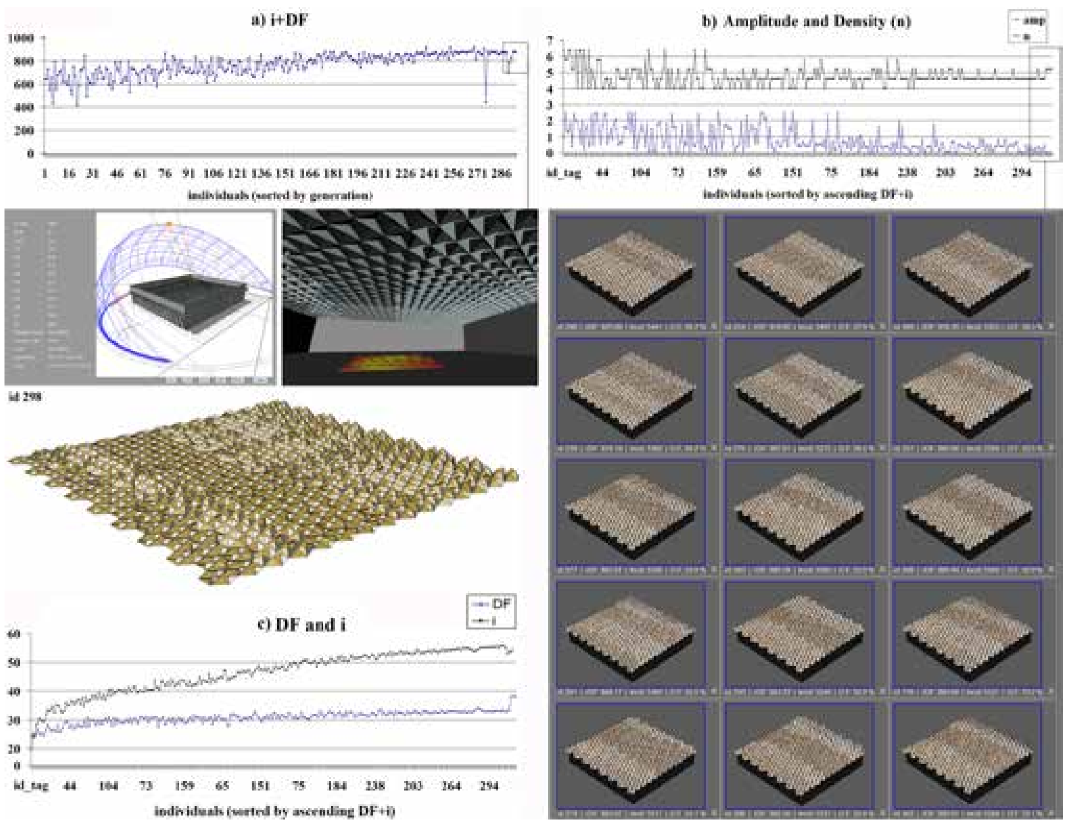

Figure 101

Examples of results from the ParaGen cycle regarding daylight factor (DF) and incident radiation (i) for winter conditions (with normalized values). Fig. 101a illustrates the trend of the sum over the GA evolution of the design solutions, toward convergence to the maximum values. Fig. 101b shows a set of design solutions visualized from the web interface, by sorting them based on their fitness; the trends of the amplitude and density (n) of the roof are also illustrated. Fig. 101c illustrates the trends of the monthly incident radiation of December and the daylight factor, after having sorted the solutions according to their fitness.

Through the whole year, for the hexagonal pattern with north facing transparent panels, over a population size of 370, the lowest ratio between the yearly incident solar radiation and the daylight factor was achieved in solution 278 (67399/23.4). When exploring the solutions stored in the database, the clear relation between the ratio and the trend of the single daylight factor and incident radiation trans emerged clearly, by further confirming the previous results. The lowest ratio was about 3.5 times smaller than the highest ratio (solution 3, ratio 303172/29.6). Similarly good results were achieved in solution 355 (ratio 71037/23.7) and 308 (ratio 70175/23.4). Figure 102 illustrates the evolution with respect to the design objective.

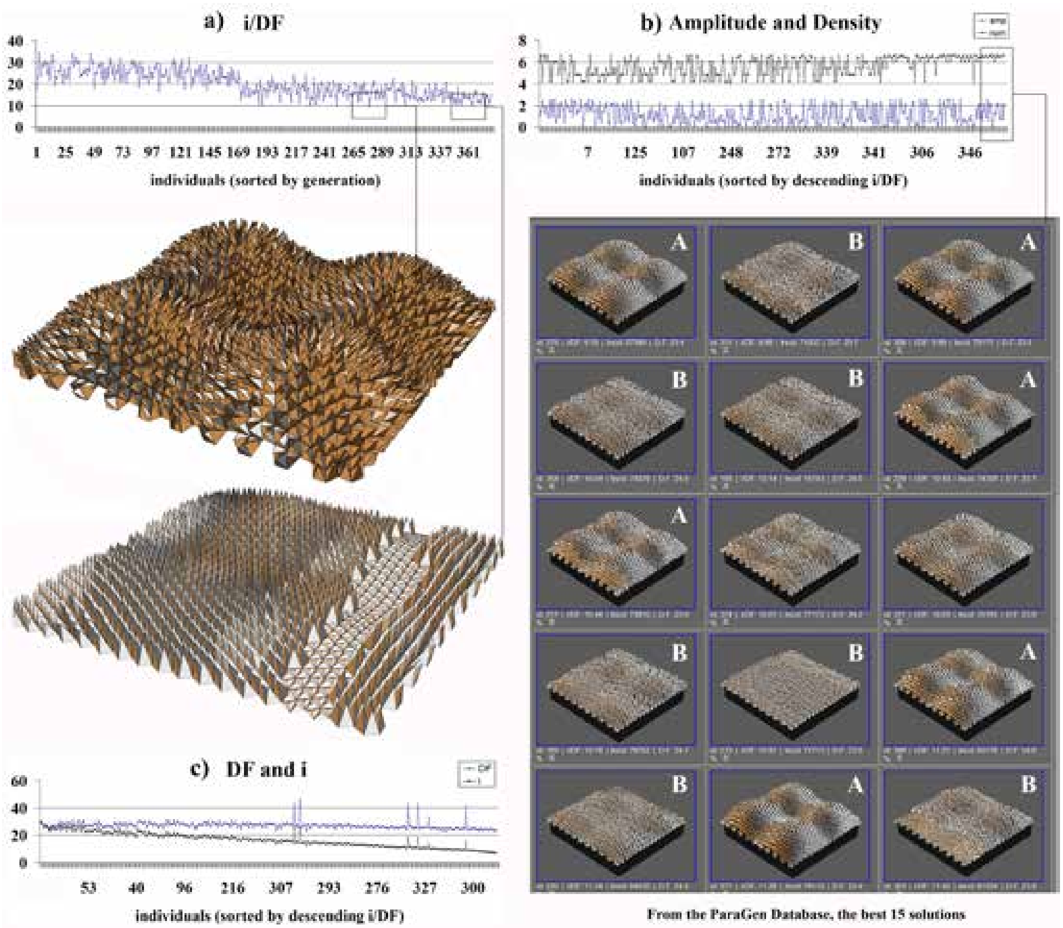

Figure 102

Examples of results from the ParaGen cycle regarding daylight factor (DF) and incident radiation (i). Figure 102b shows the trend of amplitude and density sorted by fitness of the solutions; and the distribution of A and B for a group of best solutions. Figure 102c illustrates the trend of daylight factor and incident radiation sorted by fitness of the solutions.

In relation to the design variables, two main directions emerged, evident already in the two best solutions, conventionally named A and B. Solution 278 shows high amplitude (2.1 on a scale from 0 to 2.5), maximum density, and relatively high inclination of panels evenly distributed (averagely 2.5 on a scale from 1 to 3). Solution 355 shows very low amplitude (0.7), the maximum density, and a maximum inclination of panels in contrast to areas with minimum inclination. As visible in figure 102b, meaningfully, when lower panel inclination appears in solutions with high amplitude, this is distributed on the north facing areas of the curved roof. By sorting the results sorted by fitness of the solutions and looking at the trend of daylight factor and incident radiation (figure 102c), the best and worst solutions correspond almost entirely to both the lowest and highest incident radiation, but also to the minimum and averagely maximum daylight factor (22.7 in member 312; 32.8 in member 230) and minimum and maximum incident radiation (67399 in member 278; 303172 in member 3). As for the daylight factor, five solutions resulted in a values above 40%, in all of which the roof is in its flat configuration (amplitude = 0) with the largest size of cladding components (density = 40); these have been the subject of a deeper investigation, in comparison with other individuals having null amplitude and the lowest density (40), they have a lower daylight factor (lower than 30%).

The proportion between incident radiation and daylight factor that emerged from all the analyses is of specific relevance. As mentioned, it shows a limitation of the chosen cladding, due to an almost proportional variation between the incident solar radiation and the daylight factor of the spaces underneath. In fact, even though daylight factor has high values, these might be problematic for a semi-outdoor urban area faced by indoor spaces; and achieving low incident radiation without relevantly affecting the daylight factor would be beneficial. It is of course in the nature of the design objectives themselves and appears obvious within certain limits. However, design directions could be explored in order to reduce its impact. In this sense, comparing the performance of this cladding option with other claddings is meant to further support the design process. This can be seen when compared to the similar hexagonal option with south facing transparent panels, kept with the same material properties for better comparison. Over a population size of 160, the lowest ratio was achieved for this option at 45727/33.8 and the highest at 132284/15.03, showing a slight potential to decrease the proportionality of the variations between incident radiation and daylight.

§ 9.2.4.3 Combining structural and energy analysis

In this direction, and to further test interdisciplinary exploration, analyses were also partially run by combining different performances. This section briefly introduces them also to suggest the direction of future research.

The third set of analyses was made for exploring the design by combining structural performances and solar energy behaviour. The version of the parametric point grid generated through mathematical functions was used in combination with north-oriented transparent panels cladding systems, for a fixed density of the structural tessellation. Parametric alternatives were explored by varying the overall shape of the roof, the local inclinations of the cladding panels and the proportions of the branching columns. The roof was evaluated based on the weight of the structure using steel pipes, the daylight factor, and the incident solar radiation of the covered spaces. Again the concept of transparent glazed panels and glazed panels with 90% light color serigraphy was used. Several iterations were run for summer conditions to get convergence of the design solutions by minimizing the weight, by minimizing the solar incident radiation and by maximizing the daylight factor underneath the roof (figure 103, left). Further on, the use of timber plates was partially investigated, in collaboration with Andreas Falk (figure 103, right).

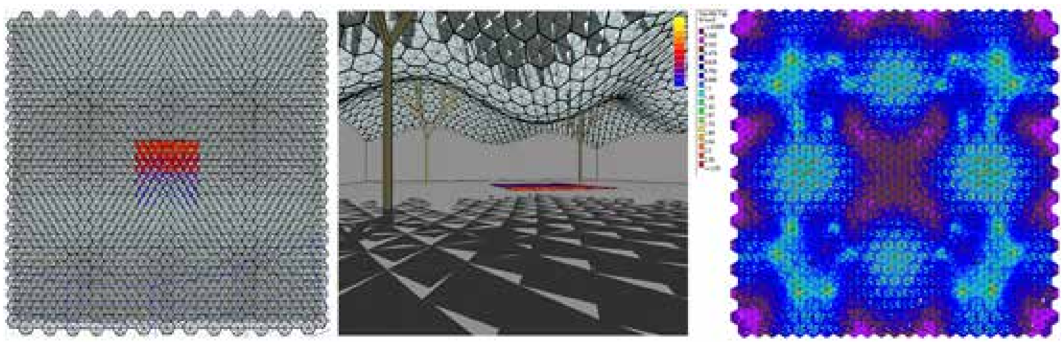

Figure 103
Examples from current analysis: left: solar energy; right: structural behaviour.

§ 9.2.5 Top openings and additional tools

In this section the integration of adaptive modules is tackled, showing the support of including into the parametric process also additional and customized software applications. In the specific case, the process shown below was developed in Processing with major contributions by Axel Kilian.

As mentioned earlier, adjustable openings are to be integrated on the top points of the roof and this can be done with a lower degree of complexity when modules are based on planar and regular polygons. Constraining the hexagons on the top of the four peaks in order to centre them on the peaks, makes possible four regular and flat top polygons. This issue was initially approached in GC, by sliding the tessellation according to pre-calculated values in order to stretch and squeeze the polygons in the lower parts of the roof. However, the method has shown some relevant limitations, such as the effort to predefine the deformed tessellations. A separate tool was developed for exploring the tessellation when constraining the hexagons. Specifically, an application was developed in Processing, based on the use of particle springs. While guaranteeing the top hexagons to be regular and flat, the application simulates the hexagon distribution with a particle spring system with the particle nodes sliding on a mathematically defined surface function. Figure 104 illustrates the results.

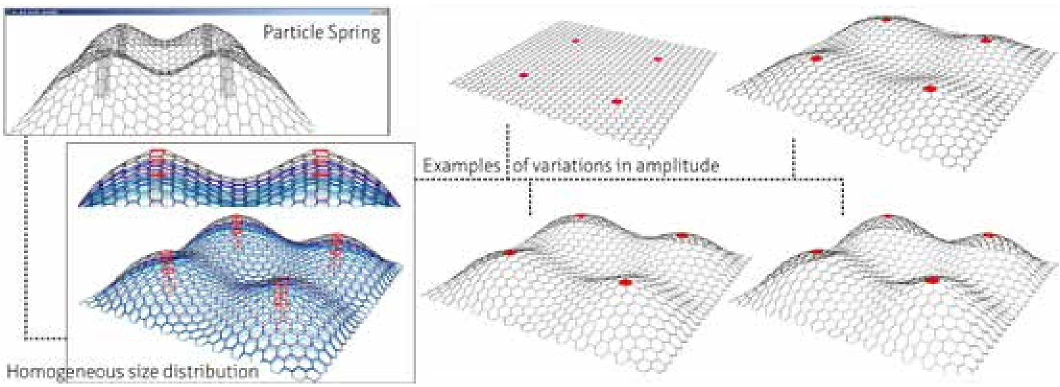

Figure 104
Examples of particle spring based tessellation for various heights of the peaks.

§ 9.2.6 Reflections on the SolSt case study

While more general conclusions can be found in section 5, only one aspect is stressed here. This process has successfully shown the use of ParaGen in revealing the influence of the design variables on the behaviour not only in the optima, but also in the sub-optima solutions. It can further be observed that the interactive exploration of the designer through the web interface supports the investigation, toward understanding and knowledge extraction and despite the complexity of the design. The resulting output has also shown again the importance of overcoming the attention to pure optima in order to inform the design process.

§ 9.3 The RadioDome case study

While the case study discussed in section 9.2 focused on the importance of sub-optima for knowledge extraction, the case study presented in this section focuses on the interaction of the designer with ParaGen, both while exploring the generated design alternatives for criteria different than the ones included into the fitness function and for intervening during the generation guided by the GA system, in order to re-input discarded solutions. This case study did not include design explorations concerning solar energy and focus on structural behaviour only; however it is worth presenting since it offers a good example and test concerning interactivity.

This example shows an application of ParaGen in teaching activities and is taken from an MSc project by Maria Vera van Embden Andres, in which the structural morphology of a dome was explored. Based on its inspiration from radiolarian structures, the dome was called RadioDome.

§ 9.3.1 Primary generator

The dome was conceived by taking natural structures as inspiration. The exercise was developed as a process of learning from nature, with reference to a meaningful selection of geometric principles and the parameterization of the structural geometry. The form was based on a logic extracted from radiolarian structures, in a process of translation from micro-organisms to large scale artificial structures facing different environmental conditions.

The fascination the student had for radiolarian structures was mainly based on the beauty of geometric patterns, naturally grown and developed by radiolarians to properly confront their environment and efficiently behave in it. Based on literature studies (Thompson, 1961; Haeckel, 2005; Afanasieva, 2005), the principle of surface-tension was identified as a key player in radiolarian structures, since radiolarians in ocean conditions aim at a maximum overall size, investing the least amount of material possible in constructing their silicon skeletons; being the sphere the smallest surface area among all surfaces enclosing a given volume, this shape turned out to frequently occur in the numerous known types of radiolarians; on approximately spherical surfaces, a skeletal tissue composed of tiny rods arranged in a polygonal network. Their homogenous skeletons are complex structures, based on a few basic rules, which make them able to evolve into a near infinite array of shell types. Some reoccurring rules were noticeable while examining the skeletons of specific types of radiolarians. Figure 105 illustrates some of the principles.

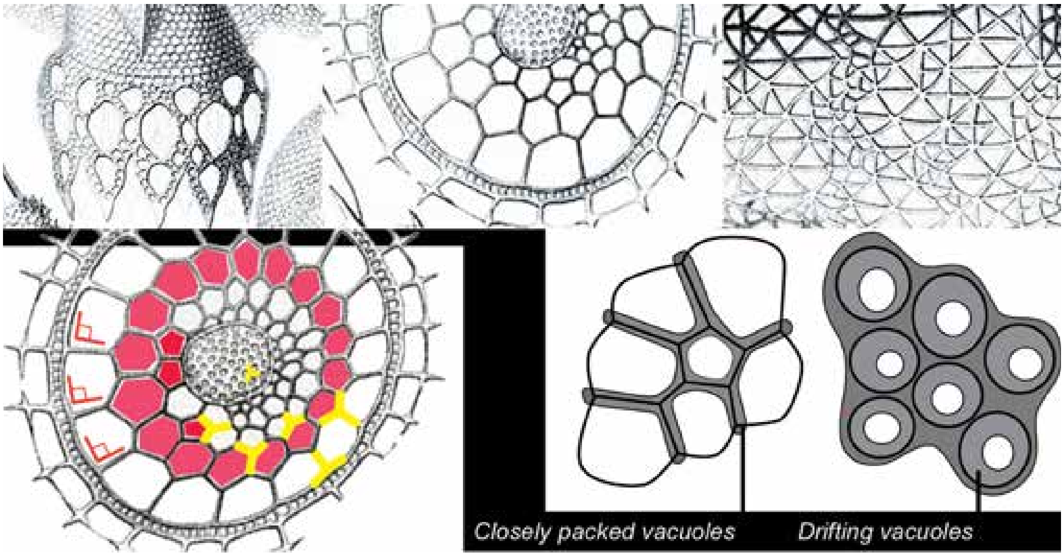

Figure 105

Top row: Various tessellations of radiolarian skeletons (image from Haeckel, 2005); Bottom row: geometric characteristics of radiolarian skeletons. Bottom left: Recurrent geometric principles (image by Maria Vera van Embden Andres). Bottom right: Formation of radiolarian skeletons (image from Afanasieva, 2005).

The mutual tension between the rods tends to fashion them into a honeycomb. Mathematically, it is not possible to close a volume with hexagons. That is the reason why heptagons and pentagons occur incidentally, especially on curved parts. When stronger rods come into play, it is also noticeable that weaker rods will attach perpendicular to the stiffer ones. During the growing process, rods will split repeatedly in two directions; therefore connections with more than three rods usually do not occur. A deeper description of the investigations done on radiolarian principles and the initial case study based on those principles can be found in a previous publication (Van Embden Andres et al., 2009; Van Embden Andres et al., 2011).

The described principles were taken as inspiration for the primary generator of the dome. Within these principles, design alternatives were explored. The generation of different instances was guided by the search for structural configurations with minimal weight and acceptable deformation, in line with the properties of radiolarian structures.

§ 9.3.2 pre-PAS: parameterization strategies

From the preliminary investigations on radiolarians, three main levels of variations were identified: the overall shape of the organisms, their cellular configurations and the geometry of the spine. Also in this case like in the SolSt case study, the design exploration has been used also to test ParaGen. In order to allow a better understanding of the system and to clearly identify problems and opportunities of the method, the design criteria are kept simple. Therefore, the research was limited to a semi-spherical dome shape. The choice of a fixed shape was due to a desired focus on the optimization of the surface tessellation. The parametric structure is therefore meant to vary at the tessellation level, in geometry and density.

§ 9.3.3 model-PAS: parametric model of the RadioDome

The geometry of the dome is controlled through a set of 40 variables. It is first generated on a flat configuration and then projected on the dome. The structural geometry of the dome was modelled based on points. By manipulating the points, an infinite number of structural configurations can be found, which vary in geometry and density according to the pre-PAS parameterization strategy for the dome. The choice of how to organize the point distribution has a significant effect on the solution space of the parametric model. The way the points were projected onto the dome for this project was structured by concentric rings and regular point densities along each ring. This follows the fact that rings or ribs are typical structural elements of dome structures. Specifically, the points are distributed on a number of concentric rings on the xy-plane using a GC script. The script recalls the 40 variables to define different configurations of the point set. The first variable, Rden, controls the selection of the rings to be used for distributing the points, based on a set of conditions. The selected rings can range from 4 to 40. The other 39 variables are entirely or partially used to determine the number of points to be distributed on each of the selected rings, ranging with the diameter of the ring from 5 to 125. Based on this process, the set of 40 parametric variables allows the generation of design alternatives based on different densities and distributions of the points.

For each configuration of the points, tessellations were generated. The tessellation of the structure was initially based on the principles of the Voronoi and the Delaunay diagram. The comparison of two different types of dome tessellations, made it possible to make some conclusions regarding which tessellation is more suited for dome structures in general. An evolved Voronoi version of the dome was to be compared to an evolved Delaunay version of the dome structure.

The creation of such geometries made use of a plug-in to GC, called rcQhull, which enabled the generation of either Voronoi or Delaunay triangulations based on the same set of points. Each Voronoi and Delaunay solution was projected onto the semispheric dome by following a construction based on CR-tangent meshes and using the south pole of the sphere as the centre of the inverse transformation (Togores and Otero, 2002 and 2003). The semispheric dome was in this case a fixed shape. Parametric variations were considered only concerning the radius regulating both the dome and the rings to eventually allow the exploration of parametric variation in scale. As a result of this process, two series of, respectively, Voronoi and Delaunay based domes could be investigated by varying the independent parameters. Figure 106 illustrates the process and shows some examples of both Voronoi and Delaunay based domes; figure 107 shows one example more closely. The so generated tessellations directly correspond to the structural system, where each segment into the tessellation represents a structural bar. As a difference with the tendency in radiolarians, the number of bars converging into the same node was allowed to be also higher than three; this choice was made in consideration of different load cases occurring in large scale architecture as compared to underwater conditions of microorganisms (i.e., asymmetry of loads).

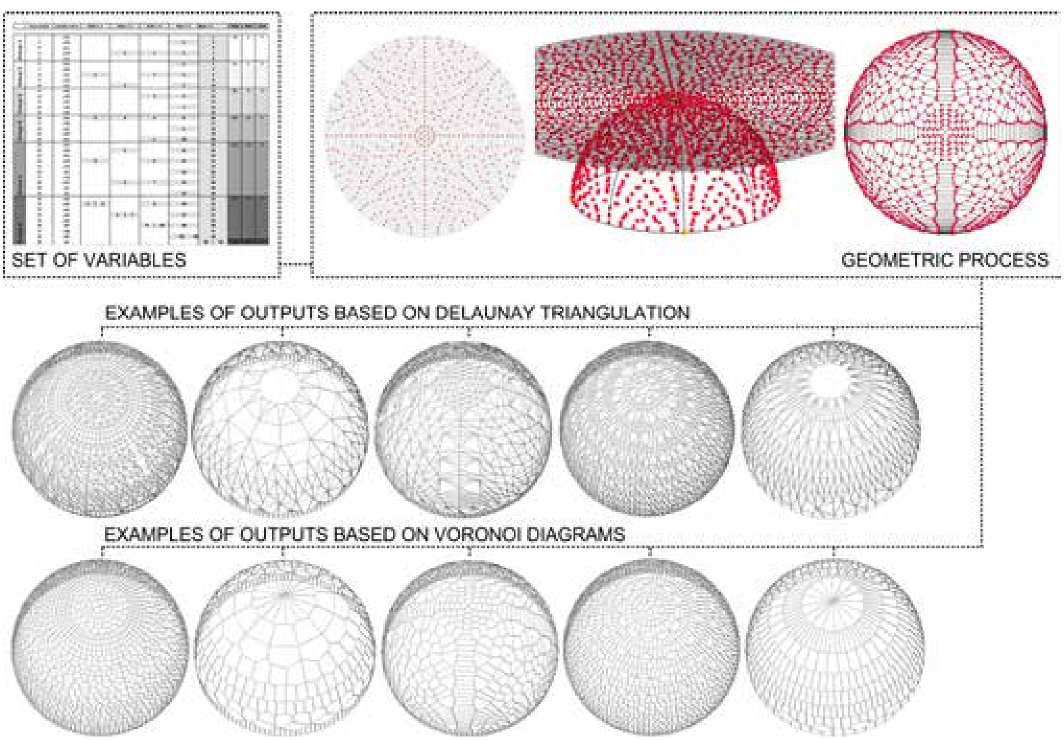

Figure 106
Structure of the parametric model and examples of instances.

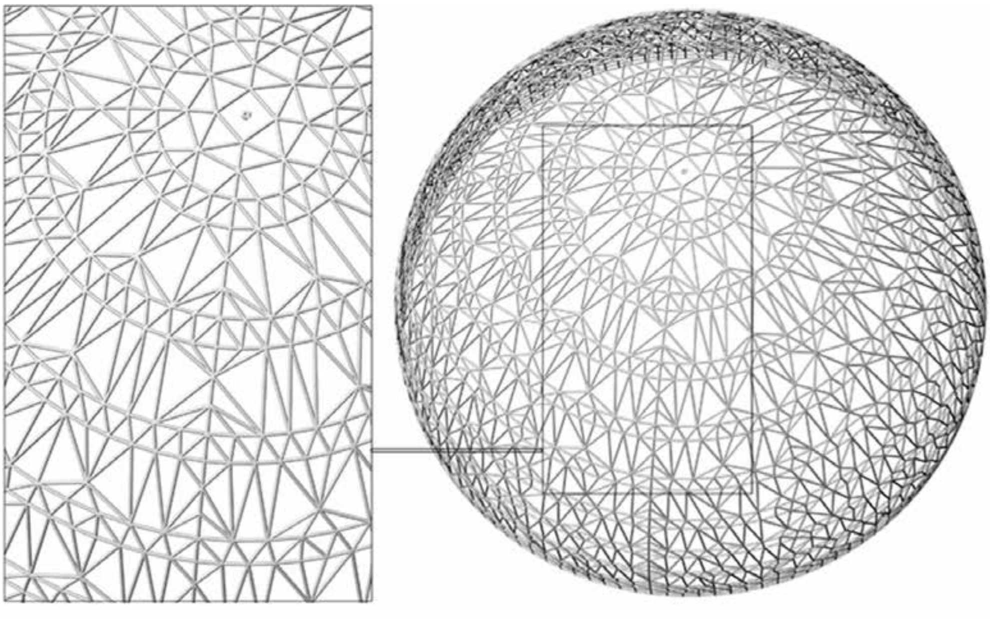

Figure 107
Zooming into an example of an instance of a Delaunay triangulation based dome.

§ 9.3.4 RadioDome in ParaGen

Focusing on a dome with fixed radius, for both the Voronoi and Delaunay solutions, the ParaGen method used a finite element analysis to determine member forces under simulated loads. During the ParaGen cycles, the load conditions were automatically added in STAAD.Pro by the FEA part of the tool, simulating a snow load. After member forces were determined, STAAD selected least weight pipe sizes based on AISC ASD steel code requirements and ASTM schedule 40 pipes. The FEA was then rerun with the proper member properties to recheck member forces and determine deformation levels of the dome. In this way a total weight and stiffness for each dome instance was determined. A couple of initial tests were run respectively on Voronoi and Delaunay solutions, letting the GA work in automatic cycles only. Further details concerning this process and results can be found in a previous publication (van Embden Andres et al., 2009). The preliminary comparison between Voronoi and Delaunay solutions has shown that Voronoi tessellations are better performing in covering a surface, using the least amount of material, but for structural purposes on an architectural scale Delaunay diagrams turn out to be better in dealing with stability issues and the self-weight of the structure. However, on the basis of the aesthetics of the generated individuals, the Voronoi option was chosen for further investigations.

Following this, a more articulated test was run on Voronoi solutions, letting the designer interact with the system. More specifically, during this second test, a first random population of 35 parametric instances was generated and imported into STAAD.Pro using DXF files. The larger the number of initial domes, the larger the solution space of possible dome evolution would be for the project. The limited number of 35 domes illustrates the process sufficiently for this test case. The FEA-part of ParaGen imports the DXF file of the 35 domes into STAAD.Pro, applies loads, materials and supports to the model and runs a Finite Elements Analysis. Due to the higher complexity in programming as well as the higher amount of time to perform the cycles that asymmetrical loads would have required, the test was run with a uniform load only. Specifically, in STAAD.Pro a uniform projected load of 40 psf (2 kN/m2) was applied, as well as materials and supports to the model, before the finite element analysis was run. The output information concerning weight, the number of members, the number of nodes and the total length of members was stored first in an Excel spread-sheet and subsequently uploaded to the SQL database. Each solution was associated with the corresponding parametric values, and tagged with a new ID and the ID of the parents. Parents were selected for breeding new solutions from the SQL database: one parent from a pool of the 30 best individuals, and one parent randomly selected from the whole database. After about 125 breeding cycles, the pool of the 30 best solutions already showed a slight convergence toward a progressively minimized weight. Figure 108 illustrates the cycle.

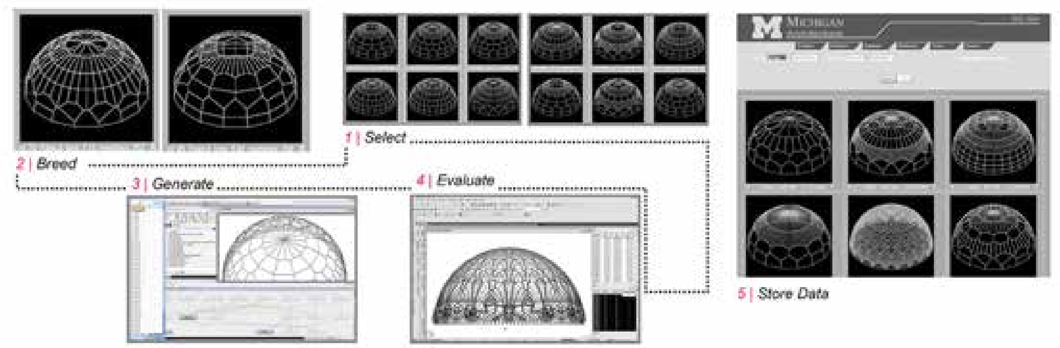

Figure 108
ParaGen cycle for the RadioDome (image by Maria Vera van Embden Andres).

The more fit domes responded to the established fitness function with large members and fewer rings, thereby minimizing the total member length or density of the tessellations with horizontal beams in the lower area. More generally, investigating the dome population until this point, it appears that mainly two strategies have been developed by ParaGen in order to improve the lightness of the dome. The domes with large members, less rings and therefore the least amount of members in the top scored best. Another strategy seems to create a surface tessellation which is as dense as possible with horizontal beams in the lower area of the dome. Since the steel tube size in the FEA software is limited to a minimum of 21 mm diameter, this strategy is limited by the structural optimization. The first strategy is not limited because there is no maximum steel pipe size.

After investigating the domes of the first and second population, the designer, in this case the master student, was left free to choose to either breed two specific individuals from the first generation of domes, breed one selected dome with the top ranked population, or breed 2 random individuals out of the best performing range. For this test case, the designer intervened in the selection of parents to direct the generation of new solutions based on aesthetic preferences. Two domes having the same number of rings and being both aesthetically appreciated by the student, but having very different geometries, were chosen out of the best performing members. A third population was therefore generated, based on the variable sets of those specific domes.

Investigating this third generation showed how the intervention resulted in successfully shifting the generation toward instances that still had pretty good performance values, and also tended to keep the aesthetic qualities of the selected parents. The designer was able to learn and evolve a population of forms into a certain direction. If the results were not satisfactory or the population converged in an unwanted direction, the designer could intervene, by either choosing and crossing different individuals from the existing population, or inserting a new self-designed instance straight from GC and cross it with the best out of the existing generation. The latter is done for this test case and the GA system was run. This intervention was successful in the sense that it positively influenced the geometric qualities of the domes, without losing the more efficient structural set-up in most cases.

Also further in the process, the designer could choose to proceed with the evolution process until it leads to a satisfying result. In this test case, no additional interactions were performed; and the process was kept short.

This overall process is illustrated in figure 109. The selected domes are visualized in figure 110. The final selection is illustrated in figure 111, also with the structural performances.

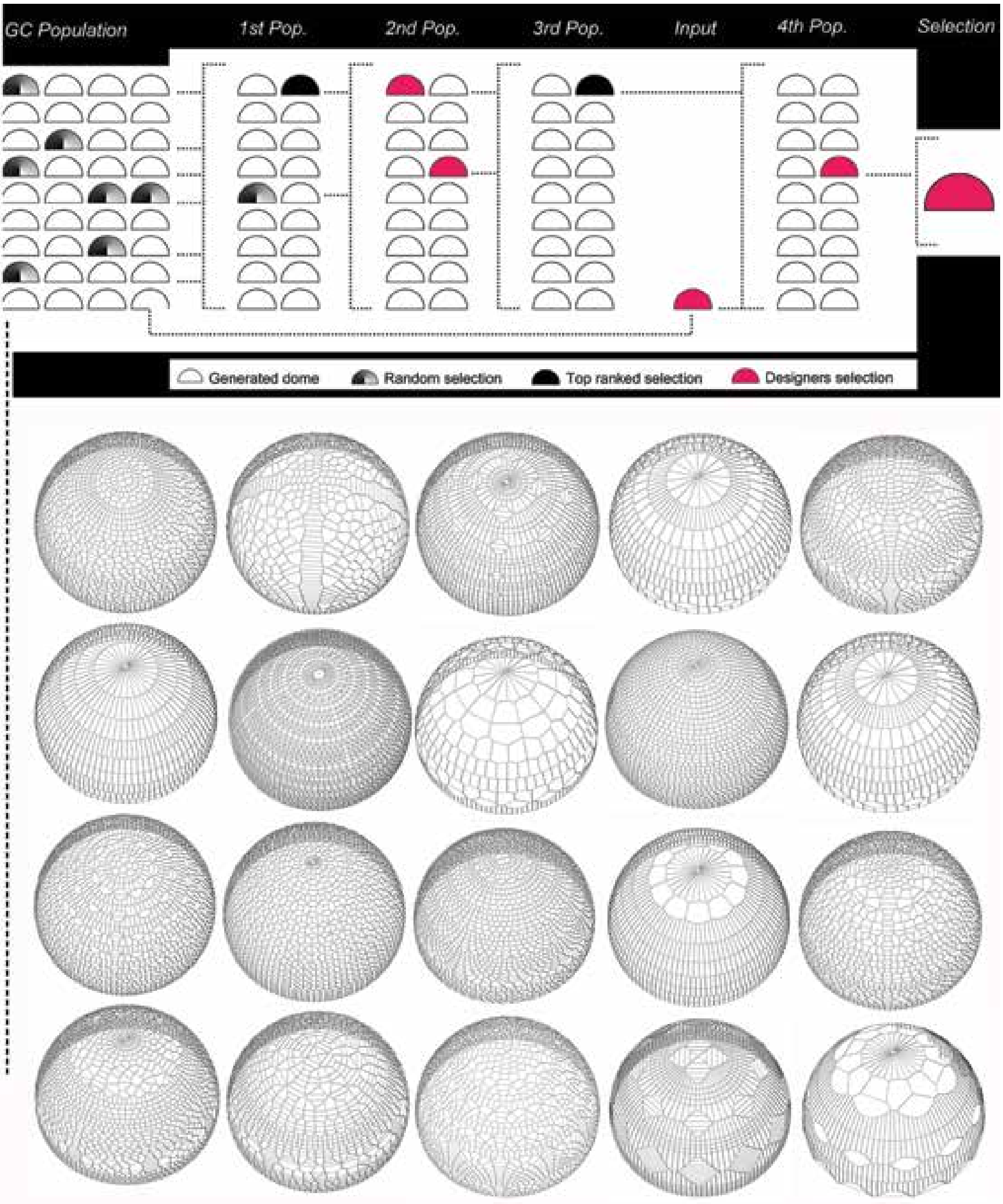

Figure 109

The schematic view shows the overall process, through the dome populations. The process was based on generation guided by the GA system and on the selection of domes by the master student (image and models by Maria Vera van Embden Andres and Michela Turrin).

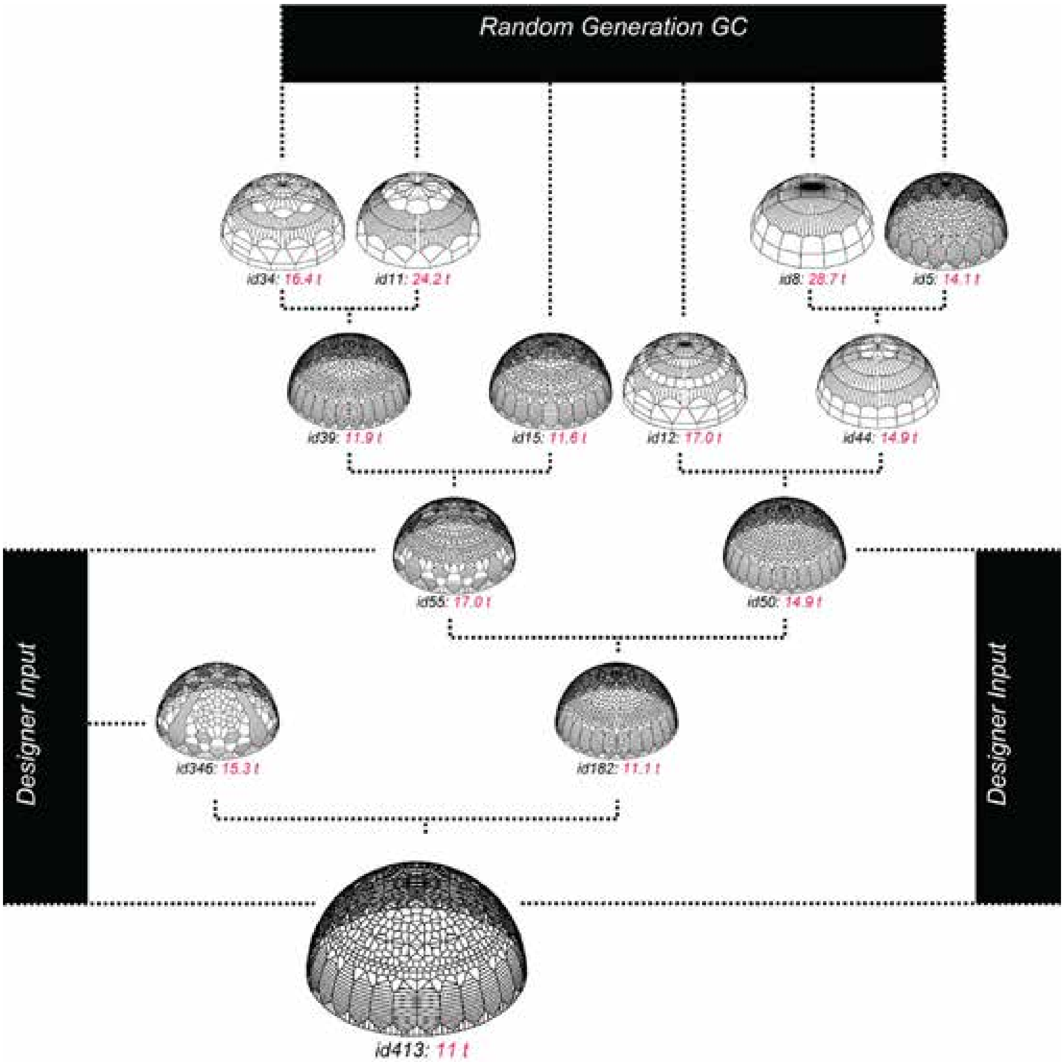

Figure 110
Genealogy tree of the final dome, dome 413 (image by Maria Vera van Embden Andres).

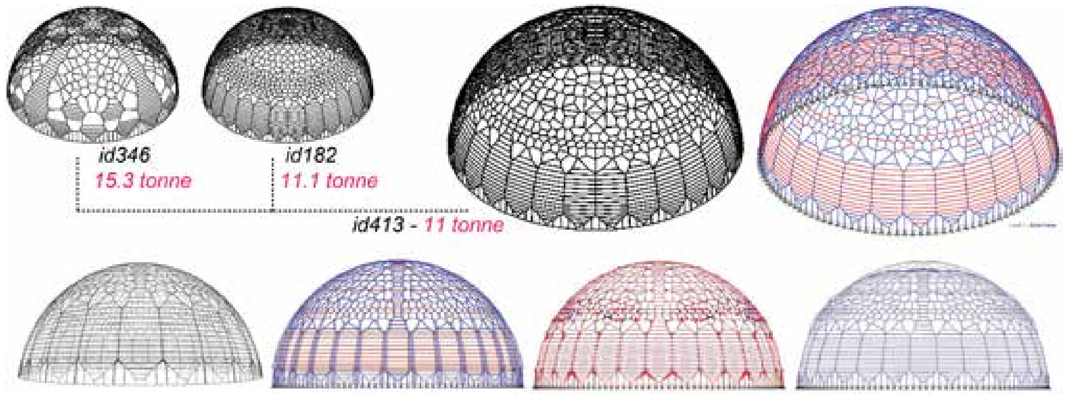

Figure 111
Images from the structural analysis of the final dome - dome 413 (image by Maria Vera van Embden Andres).

§ 9.3.5 Reflections on the RadioDome case study

While more general conclusions on the overall use of ParaGen are proposed in the last section of this chapter, some aspect specifically related to the RadioDome case study is discussed here.

The proposed approach uses ParaGen as a design tool to explore predefined parametric solutions based on a combination of visual and performance rated criteria. The example uses structural criteria and material efficiency to provide a pallet of good solutions. The ParaGen tool was appreciated by the designer (in this case the master student) and considered of value in the decision making process when dealing with design complexity, such as complex geometries generated with computational tools.

By providing a pallet of well performing configurations the ParaGen tool helped the designer to explore the solution space of a specific parametric model. The designer was invited to interact in the genetic selection, and thereby influence the outcome of the design process. The potentials of the genetic optimization component in allowing the designer to direct the evolutions of the geometry in a certain direction, using structural performance as secondary criteria, was particularly appreciated by the student. While observing the learning process of the student, it also must be pointed out that the interactive process seemed to inform the design process, by helping the designer to become familiar with structural behaviour of complex structures.

It can be concluded that, when looking at ParaGen as a tool to support designers without being too restrictive from the perspective of design, the tool seemed pretty well respondent to the expectations of the designer.

§ 9.4 Limitations and simplifications

Both case studies have been approached with simplifications, in order to limit the complexity of the models. The key simplifications are discussed here, addressing possibly more general applications of ParaGen and its eventual use in practice.

In modelling the geometry in Generative Components, the models were limited to a relatively simple structure, both in case of the SolSt roof and the RadioDome. Further levels of complexity can be added at the structural level, including double layer space frames; in the case of the RadioDome, also at the overall shape level in order to investigate possible mesh variations; in case of SolSt, cladding modules, that include curve shapes could also be investigated. Several parametric models have been built integrating both aspects and are meant for further development. However the current system encounters difficulties in quickly generating variations once the model reaches a certain level of complexity. This is the main reason the ParaGen method has been designed to operate in a parallel environment. Any number of machines can be quickly added to the cluster simply by connecting to the website and downloading the input data set for GC. Still, a common use in practice should face this aspect.

In modelling the performances, structural and solar energy models have been also simplified in order to reduce the needed computation. To measure the daylight underneath SolSt, only the Daylight Factor was used; while more complete information on the levels of illuminance should also be considered. Also in the case of the RadioDome, the structural analysis as it was performed limited and directed the search in certain ways. One significant aspect in the finite element analysis that impacted the form was the loading condition used. Normally, in the analysis of a structural system, several loadings and load combinations are considered. These include symmetric as well as asymmetric loadings. For a radial design the asymmetric loadings (such as ½ snow loads or directional wind loads) need to be considered to act in any direction. This is possible to do in the ParaGen method, but adds considerably to the computational time as well as the programming effort. Therefore, the loading was simplified to a uniform projected load of 40 PSF (2 kN/m2). Also, because the emphasis in the design was on the structural frame, added stiffness of infill panels was not considered. To give an approximate load distribution to the members, the total load was calculated based on the projected area and then evenly distributed along the length of the members. This gives the correct total load but does not make a distinction as to the differential size of the cells. In a balance between reducing the needed computation and more precisely modelling the performance behaviour, future research efforts are recommended continuing to refine the simulation models (and techniques) so as to more closely model true environmental conditions and thus enhance the ability to discover better responding forms.

Nonetheless, the case studies were effective at demonstrating the procedural method and potential application to design of the ParaGen technique. More detailed conclusions on this aspect are presented in the following section.

§ 9.5 Conclusions

The two case studies have successfully shown the use of ParaGen in:

- Supporting the designer toward understanding and knowledge extraction. Specifically, by revealing the influence of the design variables on the behaviour not only in the optima, but also in the sub-optima solutions. This occurs by means of interactive exploration through the web interface; and despite the complexity of the design. In general, the resulting outputs have also shown the importance of overcoming the attention to pure optima in order to inform the design process.
- Allowing the designer to direct the generation of well performing solutions while taking into account criteria not included into the fitness functions, such as aesthetic or other ill-defined criteria.

Concerning the understanding and knowledge extraction, future effort could be invested in possible integration of further computational analyses and the depiction of the solutions.

Concerning the performance evaluation with use of performance simulation software within the ParaGen cycle, a current obstacle that restricts such options is the interoperability between software. In some cases in fact, the difficulties in interoperability still need to be overcome based on programmed routines that are customized according to the geometry of the design and to the performance evaluation software, resulting so far in successful, but sometimes relatively laborious, definitions of suitable routines and related programming.

§ 9.6 Acknowledgements

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10 Conclusions, recommendations and future work

§ 10.1 Introduction

How can designers be facilitated in integrating engineering aspects during architectural design conception by means of computational tools, methods and techniques? How can this be achieved in the specific domain of large roofs?

This has been the main research question addressed during this research. It has been addressed first based on literature review; then based on action research and case studies. Its answer has been elaborated during the development of the PAS (Performance Assessment Strategies) design approach, which is the main contribution this research has provided. The overall results regarding PAS are summarized in section 10.2.

In order to answer this main question, a number of sub-questions have been specifically addressed. These are tackled in section 10.3. According to the sub-questions, the first phase of literature review has provided a number of partial conclusions, which guided the action research and case studies. The partial conclusions have been subdivided in two groups. The first group has been drawn based on literature review regarding precedents on CACD methods. It is mainly concerned with the specificities that a computer aided design approach for the conceptual design of performance oriented architecture should have. It is presented in section 10.3.1. The second group have been drawn based on literature review regarding the field of application, which is the domain of large roofs. It is presented in section 10.3.2.

Additionally, the research sub-questions have been elaborated during the development of PAS. A number of conclusive points have been elaborated for each of the three parts of PAS. They are presented in sections 10.3.1 regarding the computer aided design approach; and in section 10.3.2 regarding the design of large roofs.

§ 10.2 PAS

PAS is a parametric design approach for the performance assessment of large structures, with focus on passive climatic comfort. It has been developed to support designers in performance driven explorations during the conceptual phase. The approach has been structured in a framework including guidelines and recommendations in combination with an extensible library of procedures and scripts for parametric modelling. PAS has been structured in three parts: pre-PAS, model-PAS and explore-PAS.

§ 10.2.1 pre-PAS

When working with parametric design, before setting the parametric model making, a pre-established approach is needed for the parameterization. Pre-PAS has been developed in order to guide the preliminary parameterization strategies, including the annotation of variable parameters that impact the design requirements.

The formalized process has been structured in four steps. In first step, given a primary generator and (quantifiable) design requirements describing the desired performances of the project, preliminary numeric analysis are run on a reference geometry to identify and quantify the level of the eventual missed fulfilments (for example: achievement of thermal or daylight comfort). During this first step, preliminary understanding of challenges and potentials to reach the design goals are identified. In second step, based on the previous results, the specific sub-goals are established, which decompose the design requirements into more specific tasks (for example: reduction of summer overheating or of light contrast). The output of this second step consists of the list of sub-goals. In third step, various design aspects are analysed, searching for the ones favouring the achievement of the sub-goals (for example: increasing thermal mass or reduce direct light transmittance). The impact of the design aspects can also be further verified by means of preliminary numeric analysis. The output of this third step consists of the list of properties of the primary generator that impact the achievement of the sub-goals. Finally, in fourth step, geometric properties are extracted for the aspects having positive impact on the goals. These geometric properties are the ones to be parametrically investigated; therefore, their attributes are parameterized. The list of these geometric properties and of their attributes is the output of the pre-PAS phase. In a design process using PAS, once this output is achieved, the model-PAS phase starts.

§ 10.2.2 model-PAS

Model-PAS has been developed in order to support the parametric modelling process, while building the geometric model.

A set of procedures has been proposed for generating geometric entities, which allow modelling the roof according to parametric principles. These principles are the ones defined during the pre-PAS phase, and therefore are peculiar of each specific design. They are integrated in the model according to three levels. The first level corresponds to the primary parameterization, and refers to the general geometric properties of the roof. The other two levels refer respectively to the cladding and the structure, and contain parameters describing specific properties of their modules. These assume the geometric output of the primary parameterization as reference geometry. Overall, the procedures included in model-PAS allow modelling the overall shape of the large structure, the pattern and the density of its modular structural system and cladding. The overall parametric model is the output of the model-PAS phase.

§ 10.2.3 explore-PAS

Explore-PAS has been developed in order to support the exploration of the design alternatives, once the geometric model has been built. It concerns the search for satisfactory design solutions based on the evaluation of the performance, and it has been developed based on the combination of parametric modelling with performance evaluation software and, eventually, computational search techniques. It corresponds to a process of evaluation within the solution space of the parametric model and it highly depends on the way in which the solution space has been set during the pre-PAS phase.

Regarding this aspect, as discussed in chapter 7, three general types of processes are distinguished, in which the solution space of the parametric models is differently set. This usually occurs according to the knowledge the designer has or gains before or when defining the parameterization strategy, in respect to the set of selected performances. The first case includes design processes in which little knowledge is available during pre-PAS, with consequent need of enlarging the design solution space for broad performance explorations. This leads to large parametric solutions spaces; and usually implies intense use of numeric assessments in explore-PAS. During the solution-assessments of the explore-PAS phase, the major obstacle of this case is the breadth of the solution space. Due to it, a systematic performance evaluation by the designer of each parametric solution would be generally impossible due to time and other restrictions. A possible solution consists in a manual selection of design alternatives to be assessed, usually achieved based on interdisciplinary brainstorming. Alternatively, the use of ParaGen has been proposed during the explore-PAS phase.

The second case includes design processes in which relevant knowledge is available during pre-PAS, with consequent chance of bounding the solution space into a more confined collection of alternative design solutions. This leads to narrowed parametric solution spaces; and, unless knowledge is already available, it implies some use of numeric assessment both in the strategy-definition steps of pre-PAS and in the solution-assessments of explore-PAS.

The third case includes design processes in which a clear (mostly bijective) relation between geometry and performance can be set during the parameterization process; this allows consistently relating different geometric solutions with different performance requirements, which leads to bijectively deterministic parametric solution spaces. Unless knowledge is already available, this case implies intense use of numeric assessments in the strategy-definition phase, but it consistently reduces the efforts during explore-PAS.

§ 10.3 Research questions revisited

In this section, all sub-questions are revisited, based on the results from literature review as well as the development of PAS.

§ 10.3.1 Computer aided design approach

Regarding the computer aided design approach, the following questions have been addressed.

- How can computer aided conceptual design support the generation of geometric design alternatives?

As it has been discussed in chapter 1, the design approach should allow the designer to explore alternative shapes; and therefore high priority should be given to geometric manipulations of design concepts. Based on literature review, in chapter 2 procedural and parametric geometry have been identified as a potentially promising means in order to favour the generation of geometric design alternatives. More specifically, in chapter 5 the potentials of parametric modelling have been discussed to support the generation of a larger set of design variations. This has been proposed as beneficial in order to provide a broad range of alternative design solutions. It has been discussed in regard to both vertical design transformations (in which parametric variations are produced for each primary generator) and lateral transformations (since the generation of new primary generators can be favoured based on revelation emerging from parametric variations).

In PAS, this aspect has been addressed mostly in the pre-PAS and model-PAS phases. In pre-PAS, the meaningfulness of the geometric design alternatives in respect to the performance criteria has been addressed. The concern has focused on defining the hierarchical associations based on the explicit representation of a design strategy. With this respect, pre-PAS has been developed to guide toward the definition of a design strategy, unfolded through analytical investigation of geometric properties in relation to the design requirements. During the design process, once the design requirements are captured and rationalized, pre-PAS is meant to support in making explicit the geometric properties that affect their satisfactions. These geometric properties are the ones to be used in order to generate parametric design alternatives.

Differently, in model-PAS the concern has focused on building the geometric associations that are needed in order to guarantee consistency of the geometric model and the proper propagation of parametric variations through the geometry, from large scale to small scale.

- How can computer aided conceptual design support the mutual empowerment of architectural design creativity and engineering principles?

As it has been discussed in chapter 1, the design approach should favour the integration of architectural and engineering aspects (rather than super-impose one to the other), toward their mutual empowerment. Based on literature review, in chapter 2 interdisciplinary exchange of data, as means of transferring information and even favouring the transfer of knowledge, has been identified as crucial in order to enhance the integration of architectural and engineering aspects during the conceptual phase. In chapter 5, parametric modelling has been discussed in relations to its potentials in encouraging this occurrence. Its potential ability in bridging different disciplines toward a more integral design approach in the conceptual stage has been discussed based on a number of points, one of which is recalled here following. Defining a proper structure of the parametric model requires a knowledge and expertise during the parameterization process, and this needs to be mainly based on explicitly organized interdisciplinary collaborations and early brainstorming, which crosses traditional boundaries of expertise. In this respect, parameterizing the geometry including engineering aspects requires early interdisciplinary collaborations; it forces their formalization into the identification of meaningful parameters. In order to be meaningful, parametric design processes impose to the design team the need of setting explicit strategies in their subtasks and interdisciplinary interrelations; of discussing and negotiating about them.

In PAS, this aspect has been addressed mostly in pre-PAS, where the design goals (including engineering aspects) are explicitly related to geometry. In pre-PAS, the preliminary understanding of challenges and potentials to reach the design goals are identified based on the integration of preliminary engineering evaluations performed on the geometry. Specific sub-goals are established, which decompose the design requirements into sub-tasks based on analytical engineering investigations of geometric properties of the design concepts. The systematic engineering analyses of the first and third steps of pre-PAS are meant to provide information to be re-elaborated into the creative process of design conception.

The mutual empowerment of architectural design creativity and engineering principles has been partially addressed also in explore-PAS. When the instances to be assessed are selected from a large solution space and the selection is a manual operation performed by the team, this occurs based on brainstorming. When ParaGen is used, this is especially supported by the extraction of information stored in the database.

- How can computer aided conceptual design support explicit formulations of aspects involved in the design, without compromising the richness embedded in their complexity?

As it has been discussed in chapter 1, the design approach should respect the complexity of the architectural design process; it should allow for explicit formulations, but it should avoid flattering the richness of the creative process. Based on literature review, in chapter 2 decomposition has been identified as crucial in order to favour the management of complexity. In chapter 5, parametric modelling has been discussed in relations to its potentials in forcing the definition of clear strategies and sub-strategies of design exploration by early identifying single goals and objectives of the design. When looking at the design process as progression from requirement toward goal, the identification and definition of subtasks offers a step toward the decomposition and the understanding of the single components of the design complexity. Moreover, the overall picture of the design strategy refers not only to the decomposed subtasks and sub-strategies, but supports in reflecting and making explicit also their interconnections. These are integral parts of the network of design interrelations, to be represented either in one or more parametric explorations (Turrin et al., 2011).

In PAS, this aspect has been addressed mostly in pre-PAS. During this phase, the process in which decomposed goals are related to the decomposition of geometric design properties has been formalized in relation to the analysis for performance evaluation, as discussed for the previous sub-question.

- How can computer aided conceptual design support the use of numeric assessments?

As it has been discussed in chapter 1, the design approach should allow taking advantage of the measurability of most engineering aspects. It should enhance the design process by introducing information from numeric evaluations. Based on literature review, in chapter 2 the integration of BPSTs into the conceptual phase of the design process has been identified as crucial for dealing with measurable criteria. In chapter 5, parametric modelling is discussed, which allows quickly generating 3D design alternatives. The use of 3D models is related to the performance-based exploration of the alternatives, which includes the direct coupling of the parametric model with performance simulation software.

In PAS, this aspect is addressed both in pre-PAS and in explore-PAS. In pre-PAS, numeric assessments are explicitly used in order to formulate the design strategy. They are meant to favour the identification and the understanding of challenges and potentials to reach the design goals. They are also meant to favour identifying the impact of the design aspects on the achievement of the design goals. This allows detecting the properties of the primary generator that affect the achievement of the sub-goals, and that should therefore be parametrically investigated.

In explore-PAS, their use is crucial during the whole assessment process. Specifically, in explore-PAS, the use of 3D models is related to the performance-based exploration of design alternatives, which includes the direct coupling of the parametric model with performance simulation software.

- How can computer aided conceptual design respect the visual language, which is dominant in the elaboration of design concepts?

As it has been discussed in chapter 1, the design approach should respect the visual language of the early design phase and should enrich the visualization by favouring an explicit link between form and numeric evaluations. Based on literature review, in chapter 2, the use of 3D geometric models has been identified as means to favour also the visual communication. With this respect, in chapter 5, parametric modelling is proposed for the description of the form and its possible variations considering the potentials of this modelling technique in visual communication by means of 3D models.

In PAS, this aspect is addressed in each of the three phases, pre-PAS, model-PAS and explore-PAS. A specific note must be made regarding the use of PareGen in explore-PAS. As discussed in chapters 8 and 9, ParaGen also integrates the use of an on-line database, whose interface highly privileges visual communication.

- How can computer aided conceptual design support the learning process of the designer?

As it has been discussed in chapter 1, the design approach should favour the extraction, or even the generation, of knowledge and the enhancement of design understanding during the process. Based on literature review, in chapter 2, backtracking data during the design process and making them available for observation and analyses have been identified as important in order to support the learning process of the designer. Specifically, it has been proposed that data and information regarding the relation between geometry and performances should be made explicit and easy to read, in order to favour the revelation of eventual interrelations. This has also been discussed as means to enhance the alteration or generation of design concepts based on performances.

In PAS, this aspect is addressed both in pre-PAS and in explore-PAS, not only individually taken, but also based on their interrelation. Regarding this second point, firstly, favouring the learning process of the designer has been discussed based on the knowledge available or generated during pre-PAS; for which the cases exemplified in chapter 7 have shown the strong impact on the explore-PAS phase. Secondly, a specific note must be made regarding the use of ParaGen in explore-PAS. As discussed in chapters 8 and 9, ParaGen is meant to favour the extraction of knowledge during the design process. In this respect, PAS and the integration of ParaGen in explore-PAS have been developed by considering sub-optimal design solutions not as simple discarded solutions; rather than this, they have been intended and treated as source of useful information that can play an important role in creative decision making, based on, eventually recursive, learning processes.

- How can computer aided conceptual design allow the coexistence of hard engineering principles with the ill-defined nature of architectural conception?

As it has been discussed in chapter 1, the design approach should respect the ill-defined nature of the conceptual phase, by allowing dealing with un-structured, un-predicted, ill-defined problems. Architectural geometry has been introduced as the potential synthesis of multiple and interdisciplinary performances, including both ill-defined and objective aspects as well as measurable and un-measurable (or difficult to measure) criteria.

This aspect has been addressed especially when confronting the automation in selecting design alternatives during the explore-PAS phase, in combination with ParaGen. The reason for this is that, in regard to the coexistence of ill-defined problems, this automation has possibly constituted the moment of highest risk within the proposed approach. This is because in the original conception of ParaGen the fitness function is meant to expresses clearly defined objectives related to engineering fields. Also in this case, the attention is given to sub-optima. This is in line with what stated by Herbert Simon (1969), who defined counterproductive to focus on one 'best' solution, because the objective criteria that produce it are usually incomplete. In the method proposed with PareGen in chapter 8 and exemplified in chapter 9, the interaction with the designer is the means through which this aspect is approached. Interactively addressing the generation of the design solutions has been proposed to allow for the consideration aspects not included in the fitness function. These obviously can include measurable and clearly defined objectives that the designer might want to take into account without coding a fitness function that specifically embeds them; but more interestingly interactive generation refers to ill-defined criteria and subjective preferences of the designers (Turrin et al., 2011).

§ 10.3.2 Large roofs as application field

While each of the questions revisited in section 10.3.1 can be addressed with general regard to the whole spectrum of architectural design, this research has focused on the topic of large roofs as a specific filed of application.

- How can computer aided conceptual design specifically support the design of large roofs?

As discussed in chapter 4, the research has approached the domain of large roofs by recognizing the relevance of the passive climate control of the covered spaces. In addition to the performances traditionally addressed during the conceptual phase, this has been indicated as a crucially important aspect. Addressing an integral approach, structural performance has been identified as an example of interdisciplinary references. Based on this, a meaningful selection of measurable aspects for consideration during the conceptual design has been identified including numeric indicators for structural performances; numeric indicators for thermal comfort; numeric indicators for daylight comfort. After having identified these aspects based on literature review, these aspects have been considered during the phase of action research and case studies, for the design exploration of the overall geometry as well as the definition of the structural and cladding systems during the conceptual phase.

In its overall approach, PAS has the prerogative to be generally applicable to any design field. However, its specificities have been developed with focused attention on the peculiarities of large roofs. The selected measurable aspects identified on the basis of literature review, have been specifically addressed in each part of the approach. In pre-PAS, they have been regarded as the crucial aspects for identifying meaningful geometric attributes of the roofs. Regarding climate comfort, this has been summarized in figure 29, in which a flow chart illustrates the process for defining the pre-established approach for the parameterization process, concerning the use of passive means both for thermal and daylight comfort. In model-PAS, the procedures for parametric geometry and related scripts have been developed with specific focus on modular systems for structure and cladding of large roofs. In explore-PAS, the assessment has focused on the already recalled performance criteria, selected based on literature review.

§ 10.4 Recommendations and future research

Specific recommendations for the use of PAS have been already provided, especially regarding pre-PAS (sections 5.3.3 and 5.3.4) and the relations between pre-PAS and explore-PAS (section 7.5). These recommendations have been formulated with reference to the current state of PAS and to the current parametric modelling software. The key aspects are summarized and further discussed here following.

A crucial point regards the mono-directionality of parametric modelling. Current parametric modelling software mostly allow for mono-directional geometric associations: this means that the associations (which are used to relate geometric entities within the models) create dependencies that are not reversible. This increases the goal-oriented nature of parametric techniques and must be taken into account when operating according to parametric approaches. In PAS, this aspect requires consideration especially during the pre-PAS phase, which is the crucial part of the process for managing the goal-oriented features of the design process. Nowadays, more flexible parametric tools are being developed, in order to allow higher levels of flexibility and reversibility, and therefore to better fit the unstructured and exploratory nature of the conceptual design thinking. Despite this is here fully acknowledged as a great potential to support creative processes, still externalizing explicit strategies as formulated in pre-PAS is recommended also in combination to these new, eventually more flexible, tools. In this respect, the combination (and not the substitution) of systematically goal-oriented components with flexible tools is proposed.
The integration between loops of geometric exploration in flexible parametric environments could actually enrich the pre-PAS phase, and generate information useful to define the parameterization strategies.

Another crucial point regards the high time investment, which is unquestionably required when dealing with parametric design; and therefore also with the parametric design approach PAS. When considering parametric techniques, and especially when approaching them for the first time, a certain resistance is seen both among students and practitioners. The major reason lies in the absence of clear immediate benefits. Often the time-consuming aspects of parametric techniques do not allow for an immediate return; and foreseen the benefits is uneasy, especially for designers non-experienced in parametric modelling. The development of PAS has tried to take this into account; especially in pre-PAS, where the step by step guided process can facilitate also inexperienced users. Despite achieving sufficient confidence requires sometime, it has been noticed that the resistance tent to decrease with the experience. Experience allows understanding not only the potentials of quickly generating design alternatives, but also of implementing customized libraries in model-PAS; moreover, it allows for a faster identification of what during the design process should be approached parametrically and what not (or not necessarily). Regarding this last point, it should be noticed that PAS does not exclude the combination of parametric and non-parametric modelling software. At the contrary, combining the use of different digital environments within the same design process can be beneficial, especially during the early creative phase. Additional case studies in which fast 3D sketching and preliminary performance assessment of drafts models are integrated in pre-PAS in order to both clarify the design intentions and extract preliminary performance data are actually recommended as possible future work.

When considering future work, a reflection regards also the application field of this research. PAS has been developed with focus on large roofs. A limited number of specific performances have been selected in order to bound this research within a feasible scope. However, the main essence of PAS can be extended beyond the specificities of this application field. Further research is open for developing the approach in alternative application fields. Moreover, also within the boundaries of large roofs, extending the number of considered performances (possibly including additional design criteria) would be a point of interest.

Moreover, a number of more specific considerations are pointed out for each of the three parts of PAS.

Regarding pre-PAS, a meaningful future research direction is identified in a higher formalization of the procedures. Currently, the process to define the geometric aspects for parameterization is guided through guidelines and flowcharts. A promising direction may consider the implementation of a decision support environment.

Regarding model-PAS, the ability to further implement, combine, and customize the described procedures based on parametric modelling can lead to the creation of additional libraries and a larger variety of customizable scripts. A possible output could include an openly implementable design tool, in form of a plug-in or a component within existent software for 3D parametric modelling. The interest of this aspect relies on the recurrence of the problems tackled in model-PAS. The case of tessellation for structural geometry and cladding offer an example of a recurrent design problem. Once the scripts have been finalized within a generic logic, they can be intuitively reused or even called up through a graphic interface. Structuring the library by considering and abstracting design problems that overcome the pure specificity of one case make the effort worthwhile.

Finally, regarding explore-PAS, a number of major research directions could be initiated. One is proposed here as the most relevant, for which further research is suitable in order to better support the design discovery process, favouring loops of design feedback from explore-PAS to pre-PAS. This may occur specifically in ParaGen. Concerning this aspect, the possible integration of further computational analyses and the depiction of the generated design solutions could be evaluated. The performed case studies (presented in chapter 9) have shown how the visual exploration unveils relationships between the trend of the design variables and the design performance. The use of filters for sorting the design solutions exemplified the crucial role of data managing and visualization. As following step, clustering techniques may emerge as promising research direction to further favour designs exploration and knowledge extraction. They may improve the support in investigating the relationships between variables and the satisfaction of the fitness functions; and they may help making explicit the intrinsic relationships between geometry and performance.

§ 10.5 References

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A1 Pantographic structures

Within the domain of reconfigurable structures, there is a sub-domain that has a particular relevance. It is the domain of deployable structures, an engineering field investigated in depth in the past decades. These are structures that "can be transformed from a closed compact configuration to a predetermined, expanded form, in which they are stable and can carry loads" (Gantes, 2001). Within the domain of deployable structures, pantographic structures have particular relevance.

A pantograph, also called Scissor-Like Elements (SLEs), is a system of hinged rods. Each SLE unit is composed of two bars, which can be straight or angled, hinged at an intermediate point. "Each rod of the framework has three nodes, one at each end, connected to end nodes of other members through hinges, and one at an intermediate point, connected to the intermediate node of another member by a pivotal connection. The pivot allows free rotation between the two bars about the axis perpendicular to the plane of the pantograph, but restricts all other degrees of freedom" (Gantes, 2001). These elements can be combined each other's in flat configurations (one layer structures), but can also form basic polygonal units combinable by forming large expandable structures (double layer structures). The 2D as well as the 3D propagation of these units must respect the fundamental deployability constraint in order to compose a structure with the same deployability properties. Systems based on straight bars are the most common. When focusing on straight SLEs, the requirement of being stress-free in the deployed and folded configurations makes the straightness of the bars in these positions giving the first constraint. The mentioned constraint establishes that "the sums of the lengths between pivot and end node of the bars of SLEs that are connected to each other are equal" (Gantes, 2001). This requirement can be expressed as equation that equals the sum of the lengths (named here a,b,c,d) between the pivot end the end point of the bars of SLEs that are connected. The deployability constraint results then in $a+b=c+d$.

Following rules of symmetry when respecting the deployability constraint helps in propagating the SLE units. By starting from one scissor and following a planar two dimensional propagation, four propagation directions can be identified. Denoting the lengths of the semi-bars as a, b, c and d and considering one of the directions as planar mono-directional propagation (see figure 112a) here called RG, the deployability constraint specifies $d+c=a'+b'$, $d'+c'=a''+b''$,..., in general $d_i+c_i=a_{i+1}+b_{i+1}$. Since the variability of the geometric system configuration is governed by variations of the lengths a_i, b_i, c_i and d_i let us consider the possible relations among these lengths. Basically, the most homogeneous unit would be composed of two equal bars hinged at the middle point, resulting in four equal semi-bars, while the most inhomogeneous would be composed of two bars with different lengths hinged at a non-relevant point along them, resulting in four different semi-bars. All the cases in between are considered too. The ones affecting the RG propagation are the seven relations illustrated in figure 112.

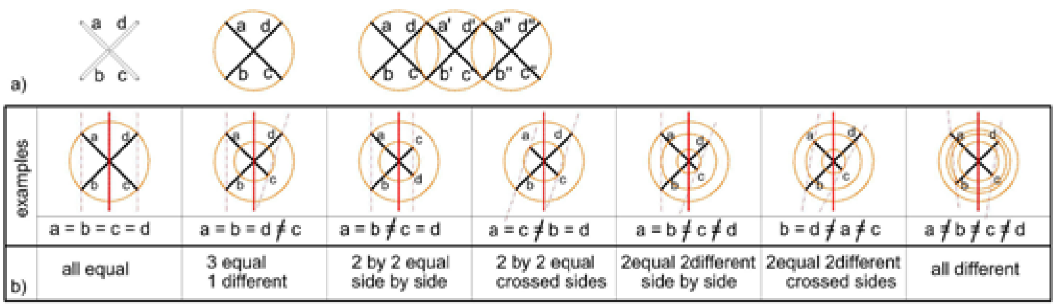

Figure 112

a) RG planar mono-directional propagation; b) Seven relations affecting RG propagation

In light of the described premises, rules of symmetry support exploring the morphological variability of a system based on the propagation of units, leading to a range of alternatives solutions that do not exhaust the entire design space, but still define a relevant sub-group of it. When dealing with the propagation of a generic SLE, symmetry and semi-symmetry can be distinguished, in case of the first one the symmetry operations consider the entire SLE, while in case of the second one the symmetry operations only consider half of the element. With respect to the first case, the SLE is treated as a 2D figure and its propagation on the plane has been studied with respect to reflection symmetry, Rotational symmetry, translational symmetry and glide reflection symmetry. These have been used by the authors to highlight eight symmetrical principles applicable to the RG propagation of a generic unit (figure 113).

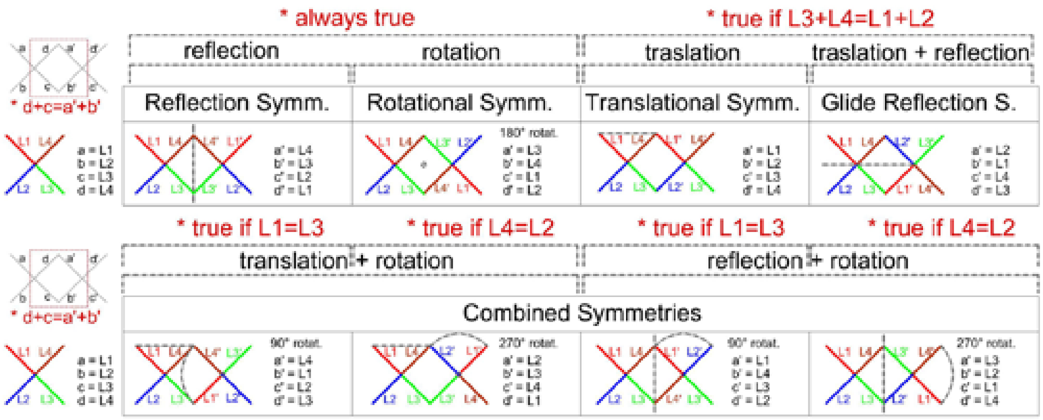

Figure 113
Eight symmetrical principles applicable to the RG propagation of a generic unit

The rules thus identified have been combined with the seven possible relations among the bar lengths to explore the achievable results. In order to hinge the generated symmetrical units, rotation has to be present in most of the cases. An overview is provided in figure 114. As can be easily understood, reflection symmetry and rotational symmetry guarantee all the possible combinations within the design space defined by the deployability constraint, because all others have limitations due to geometric incompatibilities happening during the crossed combination.

Figure 114
Exemplary overview of crossed combinations.

The proposed symmetry-based approach also resulted into a robust design support in 3D, working with planes of symmetry as well as 3D rotations and translations. Additional information can be found in Turrin et al. (2008).

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A II Vela roof: comparison from preliminary analyses

	max			avg daytime		
variant	Ta	PMV	PET	Ta	PMV	PET
0. outside	29,4	1,2	26,9	27,8	0,5	23,4
1. 50% transp	32,3	2,5	35,1	30,2	1,7	29,9
2. > 75% transp	33,3	2,7	36,3	31,1	1,8	30,9
3. 0% transparent	28,9	1,4	28,5	27,4	0,8	24,8
4. 1st level	33,3	2,9	37,3	31,2	2,0	32,0
5. 2nd level	34,3	3,3	39,7	32,2	2,4	34,2
6. increased vent	31,4	2,1	32,7	29,5	1,3	27,8
7. solar control glass	30,7	2,1	32,2	28,9	1,3	27,8
8. s.c.g. + low roof temp	30,7	1,8	30,8	28,9	1,1	26,6
9. radiation shield	32,3	2,3	33,7	30,2	1,5	28,9
10. extra thermal mass	30,4	1,7	30,1	27,9	0,8	25,2
11. ponds and vegetation	31,2	2,2	32,8	29,2	1,3	27,8
12. combination	29,6	1,4	28,2	27,6	0,7	24,2

Figure 115

Comparative table of results from preliminary analyses of the Vela roof, in which various geometric and material combinations were tested.

A III Transparency of the Vela roof

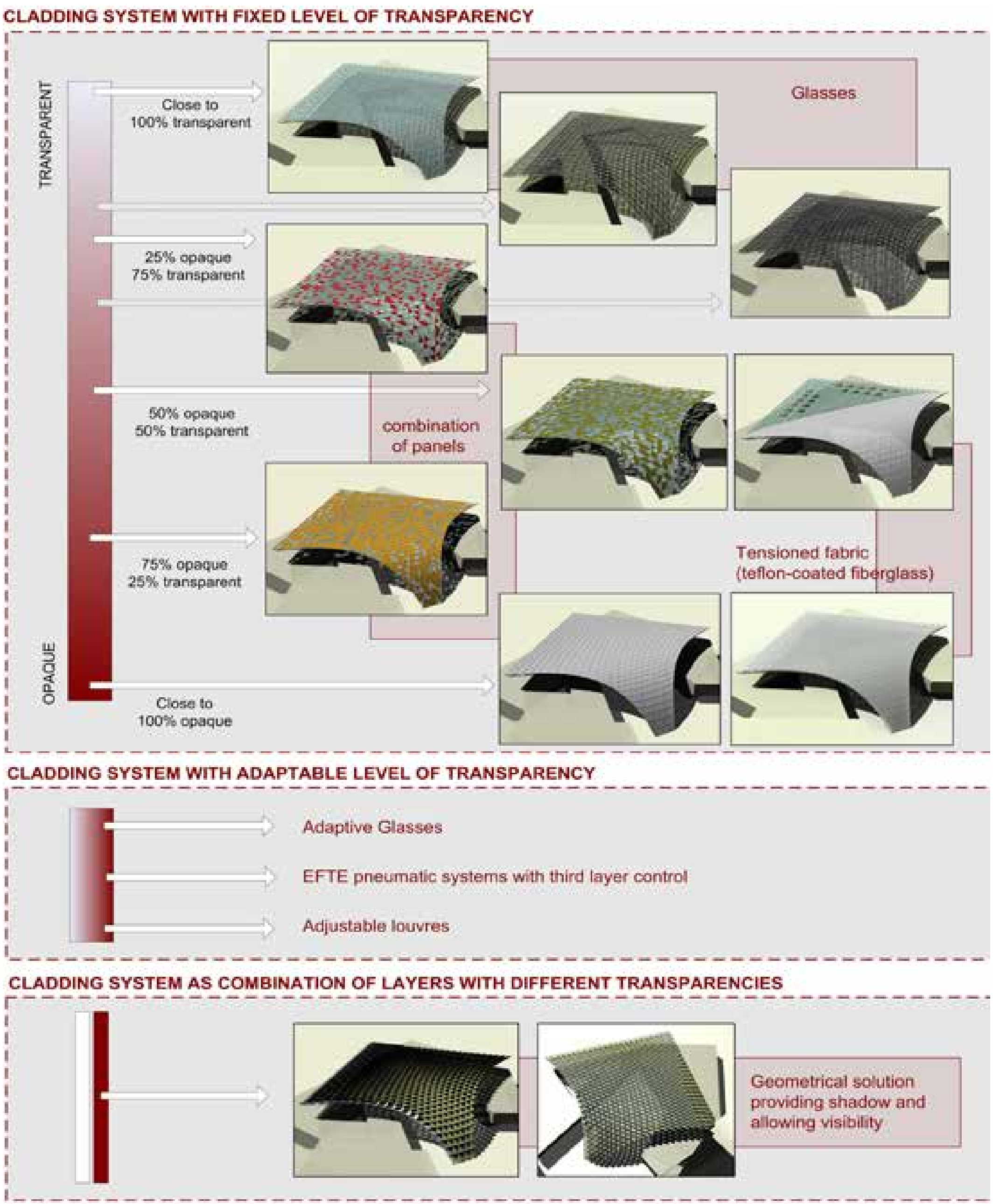

Figure 116
Different options for transparency

A IV Vela roof: performance comparison of claddings

Table 17 shows the comparison among different cladding options for different glasstypes (see table 18) and ETFE options. Specifically, seven options have been selected for exemplifying the comparison, as described in the caption. The cladding options have been compared on the following aspects: solar energy transmittance (g-value); daylight transmittance (LTA); the ratio LTA/g (as a measure for the combined daylight and sun shading performance); the raise of roof temperature (inner surface) with outside solar irradiation of 400 W/m2 (which depends on the solar energy absorbance and the g-value of the roof); the maximum physiological equivalent temperature (PET) for an average day in July, according to the different g-values and the roof temperatures of the cladding options.

Comparison					
option	**LTA (%)**	*g-value (%)*	*LTA/g*	*DT [K]*	*PET [C]*
1	16	*35*	*0.45*	*9*	*39.6*
2	13	**31**	**0.41**	**8**	**38**
3	18	***24***	***0.77***	***4***	***33.5***
4	29	***33***	***0.88***	***3***	***34.9***
5	26	***30***	***0.87***	***1***	***33***
6	30	***33***	***0.91***	***1***	***33.5***
7	30	***30***	***1.00***	***2***	***33.5***
8	32	***33***	***0.97***	***2***	***34***
9 - closed	26	***30***	***0.87***	***1***	***33***
9 - open	35	***40***	***0.88***	***2***	***n/a***
9 - combined	35	***30***	***1.17***	***1***	***33***

Table 17

The table show the comparison among performances for some of the analyzed options. (1) serigraphed glass with low reflectance (glasstype 2, 70% serigraphed); (2) serigraphed glass with low reflectance (glasstype 3, 60% serigraphed); (3) serigraphed glass with high reflectance (glasstype 2, 70% serigraphed); (4) serigraphed glass with high reflectance (glasstype 1, 60% serigraphed); (5) ETFE with uniformly printed top layer (average transmission top layer 30%); (6) ETFE with uniformly printed top layer (average transmission top layer 34%); (7) ETFE with North-South oriented shading printing (average transmittance printed part: 30%; opening angle 70%); (8) ETFE with North-South oriented shading printing (average transmittance printed part: 30%; opening angle 60%) (9a, 9b, 9c) adaptive ETFE. Calculations performed by ir. Eric van den Ham.

Glass - serigraphed light outside color			
	transmission	Reflection	g-value
1	6%	70%	14%
2	4%	70%	13%
3	2%	70%	12%

Table 18

Properties of three types of light outside color serigraphed glazing.

About the author

Michela Turrin received her Master of Science degree in Architecture at IUAV University of Venice. From 2003 to 2006, she taught at the Departments of Architecture and Building Technology of IUAV; and worked as architect and project manager on several projects in Italy. From 2006, she developed research, taught and coordinated studios at the Faculty of Architecture, Delft University of Technology. In 2012 she was Marie Curie Fellow at Beijing University of Technology, as part of the Urban Knowledge Network Asia. She has taught in a number of international events, among which the IFoU Summer School 2012 in Beijing and Winter School 2013 in Hong Kong. In 2013, she was awarded a grant by the Urban Systems and Environment, joint Research Centre between the South China University of Technology and Delft University of Technology. Since September 2012, she holds a position as senior lecturer at Yasar University in Izmir-Turkey, where she also coordinates the collaborations with Delft University of Technology and is involved in joint practice-related architectural design projects.

Since 2003, she has lectured in workshops, symposia and international conferences, focusing both on architectural engineering and computational topics. Since 2005, she has developed a remarkable number of peer-reviewed papers, two of which have received international awards. Since 2007, she has contributed to international events and scientific conferences as co-organizer and scientific committee member; and since 2011, she has peer-reviewed a number of journal papers.

Her research interests focus on parametric and computational processes for performance-oriented design. Her teaching focuses on architectural and engineering integrated design processes, using computational technologies. Both research and teaching are grounded in activities from practice, for which she has developed a number of international collaborations.

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