Physiomimetic Façade Design

Systematics for a function-oriented transfer of biological principles to thermally-adaptive façade design concepts

Susanne Gosztonyi

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Physiomimetic Façade Design

Systematics for a function-oriented transfer of biological principles to thermally-adaptive façade design concepts

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by

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"The more clearly we can focus our attention
on the wonders and realities of the universe about us,
the less taste we shall have for destruction."
- Rachel Carson (1945)

*For all the inspiring, professional and private 'teachers' who,
like my former chemistry teacher Charly Jetzinger,
are passionate about showing the interlinked elements of our world
and the joy of discovering them.*

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Contents (concise)

Preamble

The motivation for this dissertation evolved from observing the developments of adaptive façades for energy-efficient buildings and the simultaneously growing desire to find solutions that reduce the complexity and imbalance between design and technology.

Adaptive façades have become increasingly attractive in recent years: the dynamic control of energy flows through the façade seems to lower energy consumption even more effectively while maintaining a consistently high level of indoor comfort. Such façades currently consist of many individual technical parts, which again consist of technical subsystems that need to interact with each other. In order to interconnect these subsystems, additional control technology is applied, which adds another level of complexity in design, realization and operation. As a result, these systems are highly susceptible to failure and costly to maintain, in addition to the extra planning effort. Enabling adaptive functionality through design itself seems to play little role.

As an architect with a passion for sustainability, I explored over the years the possibilities of energy-efficient buildings in practice and research. Energy efficiency became more linked to building technology services, renewable energy technologies and technical façade systems driven by intelligent controls than to building design concepts. The unity of form and function seemed to be neglected to me. It was when I encountered the research discipline biomimetics that I could revive this claim - and combine my private enjoyment for natural phenomena with my professional passion. My attention was drawn to nature's mastery of creating responsive systems that ensure adaptive functionality through an resource-efficient combination of structure and material.

Expectations in regards to biomimetics were high: they led to the assumption that applying biological principles to technical systems would solve problems in the building sector. And yet biomimetic solutions are hardly to be found as market-ready products for use in energy-efficient buildings. One possible reason for this could be the difficulty of transferring the principles of biological role models to the requirements in the building sector, especially when it comes to the functional preservation of thermo-physical effects. Biomimetic concepts in architecture and façade design often remain on a visually imitative level that often neglects the principles of functionality. The functional effectiveness of the biological solution gets often lost when focusing on the obvious. Hence, the discrepancy between design and functionality became apparent once again and was the reason for me to explore function-oriented transfer methods for the particular field of façade design and engineering.

The intention of this dissertation is to contribute to the discussion and possible reduction of the growing separation between design and functionality in regards to performative building components. The goal is further to seek ways to enable the transfer of biological principles targeting at thermally adaptive processes by the application and empowerment of (passive) design rules - without sacrificing functionality. The design maxim "*form follows function*" propagated by Louis Sullivan in the late 1890s is once again gaining proverbial significance and encourages to dive under the obvious and to reveal applicable, design-driven principles in nature.

This vision took me on an exciting journey with many detours, setbacks and surprises, for which an satisfying explanation could not always be given. The stages of this journey are brought together in this dissertation - with all the open questions and necessary refinements that still need to made, and also with the understanding that there will be no one true and valid method to achieve the goal; but also with the hope that the results encourage more of these and also raise the awareness of the natural wonders in our world by promoting the understanding of the interplay of form and function.

Acknowledgements

First and foremost, I would like to thank my supervisor Ulrich Knaack for his endless patience on this long journey, his constructive comments and his positive urging to get it done. When I was looking for a scientific home for my dissertation project, I came across Ulrich Knaack's refreshing lecture on a conference – and knew in that moment that I had to write my thesis under the guidance of him if I wanted to tackle the complexity of my project. The many exciting and fruitful discussions that followed confirmed how right my decision was. I am glad that Ulrich did not reject my application, kept at it over the many years and supported me in mastering this challenge – despite the many unforeseen delays and personal life turbulences along my path. Special thanks for the trust and support!

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This acknowledgement would be incomplete without mentioning the initial phase of my journey into biomimetics, which I started completely clueless by a research study about biomimetics and energy-efficient buildings that I submitted – and was lucky enough to gain a great advisory board: George Jeronimidis, who guided the start of my dissertation and gave me valuable feedback at the end of it, as well as Thomas Speck, Petra Gruber, and Susanne Geissler. I will never forget the many interesting discussions with them about various biological role models, which opened up a whole new exciting world for me. Not only did I benefit enormously from their knowledge, but I was also infected by their enthusiasm and sympathetic joy in communicating the uniqueness of biology and its usability for sustainable building solutions. This opened up a completely new perspective in my research career and was ultimately the reason why I decided to write a dissertation in this field.

Special thanks are also due to my dear friend Edeltraude Haselsteiner, for whose valuable feedback and many fruitful conversations on the topic I am very grateful.

I would furthermore like to express my deepest appreciation to the Doctorate Committee members who took the time to critically read ad evaluate the thesis.

My thanks further go to those who accompanied me in the formal realisation of this work, in particular Véro Crickx for supporting pleasantly and highly professional the layout tasks for the thesis book, and Usch Engelmann for the dutch translation of the summary. I would also like to thank the many known contributors for their kind permissions to use their images, and I am very grateful to the many anonymous contributors on CC0 picture databases, especially Pxhere. Without this option, it would have been much harder to illustrate the book with the appropriate images.

There are many more I have to thank for supporting me indirectly or directly in these years in many ways, but they are too many to mention all. I am grateful for the generosity of my employers in regards to flexible working times so that I was able to realise my "*PhD hobby*" alongside my full-time job. Here I would particularly like to mention Andreas Luible and Albin Kenel from the Lucerne University of Applied Sciences and Arts, and Maria Wall from the Lund University.

And I am very thankful for the emotional and practical support of dear friends when the double load of full-time job and dissertation challenged my energy reserves. Special thanks go here to Ralf Dammel, who spreads an incredibly infectious optimism and a hands-on mentality and got never tired of providing the same whenever needed. And last but not least, I am also pleased for the flexibility of my dog-sitters, who willingly took care of my beloved dog Milo whenever I needed. Milo himself deserves a lifetime of treats for his patient endurance on many weekends and late into the nights during the final phase of the dissertation.

It was a long and sometimes exhaustive but also humanly enriching period of life for me, which many people helped to shape. Thanks to you all!

Lucerne, September 2021

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Summary

Modern responsive façades contribute to differentiated sustainable energy use by changing their role from passive protectors to active regulators of the indoor and outdoor climatic environments. In the context of increasing cooling energy demand, this responsiveness becomes even more relevant, as highly insulated and airtight façade systems may no longer provide a sufficient solution. Under the umbrella term "adaptive façades", responsive façade components that actively adapt the exchange of matter and energy flows continuously and accordingly to demand and conditions have been developed for some time. However, the objective of regulating these flows can lead to conflicts in the functionality and design of the façade solutions.

For example, thermal insulation has been improved over the years to minimise heat loss through the building envelope and thus reduce energy consumption in the cold season. Of course, this also reduces the heat flow in the warm season, which is disadvantageous as the accumulated heat can be dissipated less effectively in the cooler hours. Therefore, maintaining thermal comfort is usually controlled by building services systems. Architectural design measures, such as shading systems, offer only limited solutions for such active regulation of thermal flows.

Embedding thermo-adaptive functions into façade designs would be an opportunity to assign the task to the construction, but proves to be a huge challenge. The analysis of adaptive façades cases carried out in this research work shows the technical complexity of connecting reactive and passive components by control mechanisms. The associated higher development effort, maintenance, and costs lead to fewer implementations. If embedded adaptivity is to work in a design, the geometry and arrangement of the material must be brought into focus.

Identifying such design-oriented approaches for thermo-adaptive façades, therefore, frames the objectives of this research work. The underlying motivation is to downsize the technical complexity while maintaining functional complexity by embedding thermodynamic processes in the design.

Embedded functionality in a "structure" is also at the heart of the design of biological organisms that must respond autonomously and independently of external control elements. Nature offers a wide range of evolutionarily well-developed examples of inherent thermal adaptability. Using all scales, from nano to macro, and smart design rules,

nature offers fascinating role models for thermal adaptation processes in manifold ways. Biomimetic methods are used to analyse these processes to transfer applicable principles to the domain of design and engineering. In façade design, however, many essential functional characteristics are put in the background in favour of design inspirations – and thus, the thermo-adaptive properties are not or only inconsistently transferred.

This research work examines common parameters and conditions of both domains, biology and adaptive façade designs, that shall support a function-oriented transfer of thermo-adaptive principles in the early design stage of façades using established design methods. The aim is not only to make the functional characteristics of biological models visible but also to establish a transfer process that subordinates the design to the functional mechanisms while still allowing creative solutions. Thus, the work provides systematics for the generation of function-imitating biomimetic façade designs, so-called *physio-mimetic* façade designs.

The following questions define the research objective: Can the technical complexity of thermally adaptive façades be reduced by applying biomimetic approaches? What role do geometric design strategies play for thermo-adaptive processes?, and: Can a standardised process support the function-driven transfer of biological role models to thermo-adaptive façade designs? The research is subjected to the constraint that only known material shall be considered, and known design methods shall be applied for the models.

To achieve this goal, the research work initially investigates existing design measures for façades at component and system level that aim at thermo-adaptive functionalities. Various strategies and case studies displaying the state-of-the-art of thermally adaptive façades are analysed to obtain key objectives and criteria describing the performance and design effectiveness of the solutions.

Furthermore, use cases are defined to evaluate the similarities and differences between the existing and proposed façade designs. Systematic specification lists and criteria checklists are derived from the analysis results. These serve as a selection, design and evaluation tool in the developed transfer process as well as an identification and analysis tool of biological role models.

The core of the research work is the transfer process itself; it works similar to the top-down process in biomimetics but is supplemented by the above-mentioned tools and methods from product design and semantic databases. As a result, a function-oriented transfer can be made by defining a stringent language use: parametric terms are assigned to physical factors and design components, which in turn are linked by a semantic language to describe the adaptation mechanism. This connection is called "*physio-mimetic terms*".

To test these systematics, two exemplary biological role models are chosen from a database of 72 identified potential approaches in nature and transferred into functional façade models. These models are explained by sketches and parametric information about their physical setting (system design) and functional settings (adaptation mechanisms). Finally, they are compared with the earlier defined use cases to identify their strengths, weaknesses, their similarities and differences and to reflect on the usability of the developed systematics.

Regarding the models, it can be concluded that extrinsic and intrinsic adaptation mechanisms are similarly distributed in the use cases and functional models. However, the control and actuation processes in the functional models concentrate on material properties with adaptive behaviour, while only ~50% of the use cases use this approach. There are no significant differences in the response settings: both, models and use cases, react fast, dynamic within seconds or minutes and are reversible. The physical design of the models, however, mainly employs adaptive material, whereas the use cases possess little material smartness and more extrinsic technical components. The main difference, finally, lies in the communication with the environment: while the functional models mimic the biological role models that react directly to local microclimatic changes, the use cases are largely detached from such and are controlled by external systems. This gives them great flexibility and security in providing the required indoor comfort and energy performance, but only with the use of supplemental energy. The use of local resources for adaptation processes are not exploited.

The developed systematics uses a stringent function-oriented transfer method by using parametric terms in semantic formulations that address the languages of physics and design alike. Maintaining this approach throughout the transfer process comes with some disadvantages: the parametric criteria are assigned to unique IDs, which are linked by semantic descriptions, but whose dependencies cannot be clearly determined. The use of the systematics also becomes complex due to the parametric specifications. The intention to develop an easy-to-use tool for the early design stage failed in this respect. For optimisation, extensive knowledge from various fields would be necessary, which is only possible in teamwork. However, the discussion triggered by the development of such systematics is considered a milestone. This is because the reveal of the thermophysical effects of architectural design measures, such as surface expanding geometries or positioning of elements in relation to the environment show that design can indeed integrate thermo-adaptive tasks. In order to refine this and further develop the tool into a usable instrument, mathematical modelling and testing must be carried out in future research.

Samenvatting

Moderne responsieve gevels dragen bij tot een gedifferentieerd duurzaam energiegebruik door hun rol te veranderen van passieve beschermers in actieve regulatoren van het binnen- en buitenklimaat. In de context van een toenemende vraag naar koelenergie wordt dit reactievermogen zelfs nog relevanter, aangezien sterk geïsoleerde en luchtdichte gevelsystemen mogelijk niet langer een afdoende oplossing bieden. Onder de overkoepelende term „adaptieve gevels“ worden al geruime tijd responsieve gevelcomponenten ontwikkeld die de uitwisseling van materie en energiestromen continu en actief aanpassen aan de vraag en de omstandigheden. De doelstelling om deze stromen te reguleren kan echter leiden tot conflicten in de functionaliteit en het ontwerp van de geveloplossingen.

Zo is de thermische isolatie in de loop der jaren verbeterd om het warmteverlies via de gebouwschil tot een minimum te beperken en zo het energieverbruik in het koude jaargetijde te verminderen. Natuurlijk vermindert dit ook de warmtestroom in het warme seizoen, wat nadelig is omdat de geaccumuleerde warmte in de koelere uren minder effectief kan worden afgevoerd. De handhaving van het thermisch comfort wordt daarom meestal geregeld door installatiesystemen voor gebouwen. Architectonische ontwerpmaatregelen, zoals zonweringssystemen, bieden slechts beperkte oplossingen voor een dergelijke actieve regeling van thermische stromen.

Het integreren van thermo-adaptieve functies in gevelontwerpen zou een mogelijkheid zijn om deze taak aan de constructie toe te vertrouwen, maar blijkt een enorme uitdaging te zijn. De in dit onderzoekswerk uitgevoerde analyse van adaptieve gevelcases toont de technische complexiteit aan van het verbinden van reactieve en passieve componenten door regelmechanismen. De daarmee gepaard gaande hogere ontwikkelingsinspanning, onderhoud en kosten leiden tot minder implementaties. Om ingebedde adaptiviteit in een ontwerp te laten functioneren, moeten de geometrie en de ordening van het materiaal in beeld worden gebracht.

Het identificeren van dergelijke ontwerpgerichte benaderingen voor thermo-adaptieve gevels omkadert daarom de doelstellingen van dit onderzoekswerk. De onderliggende motivatie is om de technische complexiteit te reduceren, maar de functionele complexiteit tegelijkertijd bij te houden door thermodynamische processen in het ontwerp in te bouwen.

Ingebedde functionaliteit in een „structuur“ ligt ook aan de basis van het ontwerp van biologische organismen die autonoom en onafhankelijk van externe controle-elementen moeten reageren. De natuur biedt een breed scala van evolutionair goed ontwikkelde voorbeelden van inherent thermisch aanpassingsvermogen. Door gebruik te maken van alle schalen, van nano tot macro, en van slimme ontwerpregels, biedt de natuur op velerlei manieren fascinerende rolmodellen voor thermische aanpassingsprocessen. Biomimetische methoden worden gebruikt om deze processen te analyseren en toepasbare principes over te brengen naar het domein van ontwerp en engineering. Bij het ontwerpen van gevels worden echter veel essentiële functionele kenmerken naar de achtergrond geschoven ten gunste van ontwerpinspiraties - en dus worden de thermo-adaptieve eigenschappen niet of slechts inconsistent overgedragen.

Dit onderzoek onderzoekt gemeenschappelijke parameters en voorwaarden van beide domeinen, biologie en adaptieve gevelontwerpen, die een functiegerichte overdracht van thermo-adaptieve principes moeten ondersteunen in de vroege ontwerpfase van gevels met behulp van gevestigde ontwerpmethoden. Het doel is niet alleen om de functionele kenmerken van biologische modellen zichtbaar te maken, maar ook om een overdrachtsproces op gang te brengen dat het ontwerp ondergeschikt maakt aan de functionele mechanismen en toch creatieve oplossingen mogelijk maakt. Het werk biedt dus een systematiek voor het genereren van functie-imiterende biomimetische gevelontwerpen, zogenaamde fysio-mimetische gevelontwerpen.

De volgende vragen definiëren de onderzoeksdoelstelling: Kan de technische complexiteit van thermisch adaptieve gevels worden gereduceerd door biomimetische benaderingen toe te passen? Welke rol spelen geometrische ontwerpstrategieën voor thermo-adaptieve processen?, en: Kan een gestandaardiseerd proces de functie gedreven overdracht van biologische rolmodellen naar thermo-adaptieve gevelontwerpen ondersteunen? Het onderzoek is onderworpen aan de beperking dat alleen bekende materialen in aanmerking worden genomen, en bekende ontwerpmethoden worden toegepast voor de modellen.

Om dit doel te bereiken, worden in het onderzoek in eerste instantie bestaande ontwerpmaatregelen voor gevels op component- en systeemniveau geëxamineerd die thermo-adaptieve functionaliteiten beogen. Verschillende strategieën en casestudies die de state-of-the-art van thermisch adaptieve gevels weergeven, worden geanalyseerd om kerndoelstellingen en criteria te verkrijgen die de prestaties en ontwerpeffectiviteit van de oplossingen beschrijven.

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Verder worden use cases gedefinieerd om de overeenkomsten en verschillen tussen de bestaande en voorgestelde gevelontwerpen te evalueren. Uit de analyseresultaten worden systematische specificatielijsten en criteriachecklists afgeleid. Deze dienen als selectie-, ontwerp- en evaluatie-instrument in het ontwikkelde overdrachtsproces, alsook als identificatie- en analyse-instrument van biologische rolmodellen.

De kern van het onderzoekswerk is het transferproces zelf; het werkt zoals het top-down proces in de biomimetica, maar wordt aangevuld met de bovenvermelde hulpmiddelen en methoden uit de productontwerpen en semantische databanken. Zo kan een functiegerichte transfer worden gemaakt door een stringent taalgebruik te definiëren: aan fysische factoren en ontwerpcomponenten worden parametrische termen toegekend, die op hun beurt door een semantische taal worden verbonden om het aanpassingsmechanisme te beschrijven. Deze verbinding wordt „fysio-mimetische termen“ genoemd.

Om deze systematiek te testen worden twee exemplarische biologische rolmodellen gekozen uit een database van 72 geïdentificeerde potentiële benaderingen in de natuur en omgezet in functionele gevelmodellen. Deze modellen worden toegelicht aan de hand van schetsen en parametrische informatie over hun fysische setting (systeemontwerp) en functionele settings (aanpassingsmechanismen). Tenslotte worden zij vergeleken met de eerder gedefinieerde use cases om hun sterke en zwakke punten, hun overeenkomsten en verschillen vast te stellen en om na te denken over de bruikbaarheid van de ontwikkelde systematiek.

Wat de modellen betreft, kan worden geconcludeerd dat de extrinsieke en intrinsieke aanpassingsmechanismen in de use cases en functionele modellen gelijk zijn verdeeld. De besturings- en actuatieprocessen in de functionele modellen zijn echter toegespitst op materiaaleigenschappen met adaptief gedrag, terwijl slechts ~50% van de use cases deze benadering gebruiken. Er zijn geen significante verschillen in de reactie-instellingen: beide, modellen en use cases, reageren snel, dynamisch binnen seconden of minuten en zijn omkeerbaar. Bij het fysieke ontwerp van de modellen wordt echter hoofdzakelijk gebruik gemaakt van adaptief materiaal, terwijl de use cases weinig materiële slimheid bezitten en meer extrinsieke technische componenten. Het belangrijkste verschil ligt tenslotte in de communicatie met de omgeving: terwijl de functionele modellen de biologische rolmodellen nabootsen die rechtstreeks reageren op plaatselijke microklimaatveranderingen, staan de use cases daar grotendeels los van en worden zij gecontroleerd door externe systemen. Dit geeft hen een grote flexibiliteit en zekerheid bij het leveren van het vereiste binnencomfort en de vereiste energieprestaties, maar alleen met gebruikmaking van aanvullende energie. Het gebruik van lokale hulpbronnen voor aanpassingsprocessen wordt niet benut.

De ontwikkelde systematiek maakt gebruik van een strikte functie-georiënteerde overdrachtsmethode door gebruik te maken van parametrische termen in semantische formuleringen die zowel de talen van de fysica als die van het ontwerp aanspreken. Het aanhouden van deze benadering gedurende het gehele overdrachtsproces brengt enkele nadelen met zich mee: de parametrische criteria worden toegekend aan unieke ID's, die door semantische beschrijvingen met elkaar verbonden zijn, maar waarvan de afhankelijkheden niet duidelijk kunnen worden vastgesteld. Het gebruik van de systematiek wordt ook ingewikkeld door de parametrische specificaties. Het voornemen om een eenvoudig te gebruiken instrument voor de vroege ontwerpfase te ontwikkelen, is in dit opzicht mislukt. Voor optimalisatie zou uitgebreide kennis uit verschillende vakgebieden nodig zijn, wat alleen in teamverband mogelijk is. De discussie die door de ontwikkeling van een dergelijke systematiek op gang is gebracht, wordt echter als een mijlpaal beschouwd. De identificatie van de thermofysische effecten van architectonische ontwerpmaatregelen, zoals oppervlakte-uitbreidende geometrieën of positionering van elementen ten opzichte van de omgeving, toont immers aan dat in het ontwerp inderdaad thermo-adaptieve taken kunnen worden geïntegreerd. Om dit te verfijnen en het instrument verder te ontwikkelen tot een bruikbaar instrument, moeten in toekomstig onderzoek wiskundige modellering en tests worden uitgevoerd.

Zusammenfassung

Moderne, reaktionsfähige Fassaden tragen zu einer differenzierten, nachhaltigen Energienutzung bei, indem sie ihre Rolle von passiven Schutzvorrichtungen zu aktiven Reglern des Innen- und Außenklimas gewandelt haben. Vor dem Hintergrund des steigenden Kühlenergiebedarfs wird diese Reaktionsfähigkeit sogar noch bedeutender, da hochgedämmte und luftdichte Fassadensysteme voraussichtlich keine ausreichende Lösung mehr darstellen. Unter dem Oberbegriff „*adaptive Fassaden*“ werden seit einiger Zeit reaktionsfähige Fassadenkomponenten entwickelt, die den Austausch von Stoff- und Energieströmen kontinuierlich und bedarfsgerecht anpassen. Das Ziel, diese Ströme zu regulieren, führt jedoch auch zu Konflikten in der Funktionalität und Gestaltung der Fassadenlösungen.

So wurde beispielsweise die Wärmedämmung im Laufe der Jahre verbessert, um den Wärmeverlust durch die Gebäudehülle zu minimieren und so den Energieverbrauch in der kalten Jahreszeit zu senken. Natürlich verringert sich dadurch auch der Wärmestrom in der warmen Jahreszeit, was nachteilig ist, da die angestaute Wärme in den kühleren Stunden weniger effektiv abgeführt werden kann. Die Aufrechterhaltung der thermischen Behaglichkeit wird daher in der Regel durch gebäudetechnische Anlagen gesteuert. Architektonische Maßnahmen, wie z.B. Beschattungssysteme, bieten nur bedingt Lösungen für eine solche aktive Regulierung der Wärmeströme.

Die Einbettung von thermoadaptiven Funktionen in Fassadenkonstruktionen wäre eine Möglichkeit, diese Aufgabe an das Design zu übertragen, erweist sich aber als große Herausforderung. Die in dieser Forschungsarbeit durchgeführte Analyse von adaptiven Fassaden zeigt, wie technisch komplex es ist, reaktive und passive Komponenten durch Steuerungsmechanismen miteinander in Kommunikation zu setzen. Der damit verbundene höhere Entwicklungsaufwand, sowie Wartung und Kosten führen zu weniger Implementierungen. Soll eingebettete Adaptivität in einem Design funktionieren, muss die Geometrie und Anordnung des Materials in den Fokus gerückt werden.

Solche designorientierten Ansätze für thermoadaptive Fassaden zu identifizieren bildet daher den Rahmen für die Zielsetzung dieser Forschungsarbeit. Die zugrundeliegende Motivation ist die Reduktion der technischen Komplexität unter Beibehaltung der funktionalen Komplexität durch die Einbettung thermodynamischer Prozesse in den Entwurf.

In dieser Arbeit werden gemeinsame Parameter und Bedingungen beider Bereiche, der Biologie und des adaptiven Fassadendesigns, untersucht, die eine funktionsorientierte Übertragung von thermoadaptiven Prinzipien für die frühe Entwurfsphase von Fassaden mit etablierten Entwurfsmethoden unterstützen sollen. Ziel ist es, nicht nur die funktionalen Eigenschaften biologischer Vorbilder sichtbar zu machen, sondern auch einen Transferprozess zu etablieren, der das Design den funktionalen Mechanismen unterordnet und dennoch kreative Lösungen ermöglicht. Damit liefert die Arbeit eine Systematik für die Generierung funktionsnachahmender biomimetischer Fassadendesigns, sogenannter *physio-mimetischer Fassadendesigns*.

Folgende Fragen definieren das Forschungsziel: Kann die technische Komplexität von thermisch adaptiven Fassaden durch biomimetische Ansätze reduziert werden? Welche Rolle spielen geometrische Gestaltungsstrategien für thermoadaptive Prozesse? und: Kann ein standardisierter Prozess die funktionsgetriebene Übertragung von biologischen Rollenmodellen auf thermoadaptive Fassadenkonstruktionen unterstützen? Darüber hinaus werden Randbedingungen definiert: Es sollen nur bekannte Materialien berücksichtigt und vertraute Entwurfsmethoden für die Modelle angewendet werden.

Um dieses Ziel zu erreichen, werden zunächst bestehende Gestaltungsmaßnahmen für Fassaden auf Komponenten- und Systemebene untersucht, die auf thermoadaptive Funktionalitäten abzielen. Verschiedene Strategien und Fallstudien, die den Stand der Technik bei thermisch adaptiven Fassaden darstellen, werden analysiert, um Schlüsselziele und -kriterien zu erhalten, die die Leistung und Design-Effektivität der Lösungen beschreiben.

Darüber hinaus werden Anwendungsfälle definiert, um später die Gemeinsamkeiten und Unterschiede zwischen den bestehenden Lösungen und den vorgeschlagenen, physiomimetischen Fassadenmodellen zu bewerten. Aus den Analyseergebnissen werden systematische Anforderungslisten und Kriterienchecklisten abgeleitet. Diese dienen als Auswahl-, Entwurfs- und Bewertungswerkzeug im entwickelten Transferprozess. Darüber hinaus dienen sie als Identifikations- und Analyseinstrument für biologische Vorbilder.

Der Transferprozess selbst ist der Kern der Forschungsarbeit. Er funktioniert ähnlich wie der Top-Down-Prozess in der Biomimetik, wird aber durch die oben genannten Werkzeuge sowie Methoden aus dem Produktdesign und aus semantischen Datenbanken ergänzt. Ein funktionsorientierter Transfer wird durch die Definition eines stringenten Sprachgebrauchs ermöglicht: Physikalischen Faktoren und Designkomponenten werden parametrischen Begriffen zugeordnet, die wiederum durch eine semantische Sprache zur Beschreibung des Anpassungsmechanismus verknüpft werden. Diese Verbindung wird „*physio-mimetische Begriffe*“ bezeichnet.

Um diese Systematik zu testen, werden aus einer Datenbank von 72 identifizierten Ansätzen in der Natur zwei exemplarische biologische Rollenmodelle ausgewählt und in funktionale Fassadenmodelle übertragen. Die Modelle werden durch Skizzen und parametrische Informationen über ihr physikalisches Setting (Systemdesign) und ihre funktionellen Einstellungen (Anpassungsmechanismen) erläutert. Abschließend werden sie mit den zuvor definierten Anwendungsfällen verglichen, um ihre Stärken und Schwächen, ihre Gemeinsamkeiten und Unterschiede zu identifizieren und die Nutzbarkeit der entwickelten Systematik zu reflektieren.

In Bezug auf die Modelle lässt sich feststellen, dass extrinsische und intrinsische Anpassungsmechanismen in den Anwendungsfällen und Funktionsmodellen ähnlich verteilt sind. Allerdings konzentrieren sich die Steuerungs- und Aktivierungsprozesse in den Funktionsmodellen auf Materialeigenschaften mit adaptivem Verhalten, während nur ~50 % der Anwendungsfälle diesen Ansatz verwenden. Es gibt keine großen Unterschiede in der Reaktionsfähigkeit: beide, Modelle und Anwendungsfälle, reagieren schnell, dynamisch innerhalb von Sekunden oder Minuten und sind reversibel. Das physische Design der Modelle verwendet jedoch hauptsächlich adaptives Material, während die Anwendungsfälle wenig materielle Anpassungsfähigkeit und mehr extrinsische, technische Komponenten aufweisen. Der Hauptunterschied liegt schließlich in der Kommunikation mit der Umwelt: Während die Funktionsmodelle die biologischen Vorbilder nachahmen, welche direkt auf lokale mikroklimatische Veränderungen reagieren, sind die Anwendungsfälle davon weitgehend losgelöst und werden von externen Systemen gesteuert. Dies gibt ihnen eine große Flexibilität und Sicherheit bei der Bereitstellung des geforderten Innenraumkomforts und der Energieverbrauchs, allerdings nur unter Einsatz von zusätzlicher Energie. Die Nutzung lokaler Ressourcen für die Anpassungsprozesse wird nicht ausgeschöpft.

Die entwickelte Systematik verwendet eine stringent funktionsorientierte Übertragungsmethode, indem sie parametrische Begriffe in semantischen Formulierungen verwendet, die die Sprachen der Physik und des Designs gleichermaßen ansprechen. Die Beibehaltung dieses Ansatzes im gesamten Übertragungsprozess bringt einige Nachteile mit sich: Die parametrischen Kriterien werden eindeutigen IDs zugeordnet, die zwar durch semantische Beschreibungen verknüpft sind, deren Abhängigkeiten aber nicht eindeutig bestimmt werden können. Auch die Nutzung der Systematik wird durch die parametrischen Vorgaben komplex. Die Absicht, ein einfach zu bedienendes Werkzeug für die frühe Entwurfsphase zu entwickeln, ist in dieser Hinsicht gescheitert. Für die Optimierung wäre umfangreiches Wissen aus verschiedenen Bereichen notwendig, was nur in Teamarbeit möglich ist. Die durch die Entwicklung einer solchen Systematik ausgelöste Diskussion wird jedoch als Meilenstein gewertet. Denn die Aufdeckung der thermophysikalischen Auswirkungen von architektonischen Gestaltungsmaßnahmen, wie flächenerweiternde Geometrien oder deren ändernde Positionierung zur Umgebung zeigen, dass Gestaltung durchaus thermoadaptive Aufgaben übernehmen kann. Um dies zu verfeinern und das Werkzeug zu einem brauchbaren Werkzeug weiterzuentwickeln, müssen in der zukünftigen Forschung mathematische Modellierungen und weitere Nutzungstests durchgeführt werden.

Glossary

Symbol	Description	Unit
Thermo-physical material properties (intensive properties)		
c_p	specific heat capacity	J/(kg K)
λ	thermal conductivity	W/(m K)
$\varepsilon_{\lambda T}$	thermal emissivity (wavelength-dependend)	-
$\alpha_{e\lambda}$	absorptivity of energetic radiation (wavelength-dependend)	-
$\rho_{e\lambda}$	reflectivity of energetic radiation (wavelength-dependend)	-
$\tau_{e\lambda}$	transmissivity of energetic radiation (wavelength-dependend)	-
$\tau_{uv\lambda}$	transmissivity of energetic UV-radiation (wavelength-dependend)	-
P	permeability	$cm^3 cm/cm^2$ s Pa
η	water vapour diffusivity	-
v_r	vapour resistivity (permeability)	MNs/gm
V_r	vapour resistance	MNs/g
ν (μ)	kinematic viscosity	kg/(m s)
σ	Stefan-Boltzmann constant	$W/(m^2K^4)$
Nu	Nusselt number	-
Geometry-related parameters		
A	surface area	m^2
V	volume	m^3
l, d	length, width	m
d	thickness	m
k	layer	-
L	characteristic length	m
ζ	thermal boundary layer thickness	
m	mass	kg
sd	thickness of gaseous layer (air)	m
x	azimuth angle	°degree
y	inclination angle	°degree
w	relative angle of surface to normal	° degree
e, s_k	air cavity width between component and construction	mm
General parameters /indices		
t	time / time lag	sec, s
λ_{nm}	wavelength	nm
n	index of component	-

Symbol	Description	Unit
State variables		
T_a, θ_a	air temperature	°C
T_n	environmental temperature	°C
ΔT	air temperature difference	K
I_s	solar irradiation on surface	W/m²
Rh, ϕ	relative humidity	%
X	water vapour content in air	g/kg air
P	air pressure	Pa
p_v	water vapour pressure	Pa
v, u	velocity, air flow perpendicular or along surface	m/s
ρ	density	kg/m³
H	enthalpy in air	kJ/kg air
S	entropy	J/K
Parameters related to thermodynamic processes (extensive properties)		
Q, Φ	thermal energy (heat flux)	W (J)
q_n	heat flow density (area-related heat flux)	W/m²
q_i/q_e	secondary degree of heat emission inward/ outward	W/m²
R_s	thermal resistance to surface	(m² K)/W
R	thermal resistance in matter	(m² K)/W
h_{th}	heat transfer coefficient in gaseous layers (fluids)	W/(m²K)
U	heat transfer coefficient, thermal transmittance	W/(m²K)
Ψ	linear thermal transmittance	W/(m K)
χ	punctual thermal transmittance	W/K
g	solar heat gain coefficient	-
g_{tot}	total solar heat gain coefficient	-
f_{Rsi}	temperature factor on inner surface	-
M	water vapour resistance factor	-
A_w	water absorption coefficient	kg/(m² h0.5)
F_B (B)	buoyancy	N
α_{th}	thermal diffusivity	mm²/s
β	thermal effusivity	J/m²K √1/s
δ_{th}	thermal penetration depth	mm
L	latent heat	J/kg
Cr	thermal storage capacity	kJ
ACH	Air exchange rate per hour	Ac/h

1 Introduction

1.1 Background

The International Panel of Climate Change IPCC reports that extreme climate events will very likely increase, with a reduction of cold and increase of warm days and nights on global scale (*AR5 Climate Change 2014*, 2014). They also anticipate the frequency of heat waves to continue to increase in parts of Europe, Asia and Australia. Furthermore, urban building stock and anthropogenic heat causes accelerate urban heat island effects, while evaporation decreases due to the declination of permeable surfaces and vegetation in megacities. These outlooks point to a necessary change of perspective in the implementation strategies for energy efficiency in buildings. In many parts of Europe, buildings will need more cooling than heating. According to the report „*The Future of Cooling. Opportunities for Energy-efficient Air Conditioning*" by the International Energy Agency IEA, the global energy demand for space cooling in residential buildings is expected to increase to almost 70% by 2050 (and most of it in emerging countries in warmer climatic zones) (IEA/OECD, 2018, p. 21). Thus, cooling measures represent a particular challenge for the coming decades.

1.1.1 Energy goals and the role of adaptive façades

The building envelope plays a crucial role in the energy consumption of a building and works as an energy regulating interface between exterior and interior environments. Thus, it can profoundly account to a building's energy saving potential. Great importance is already given to the measures for thermally insulated building envelopes. For this purpose, the European Union has issued special recommendations in the Buildings Directive on Energy Performance of Buildings (EU EPBD, 2018). The Directive recommends specific measures to reduce heat losses by well insulated and airtight building envelopes and to consider a meaningful use of solar radiation by dynamic solar shading systems. These recommendations are implemented in most European countries by their national building standards.

The IEA report “*Technology Roadmap for energy efficient building envelopes*” particularly pointed already in 2013, amongst other goals, to the need for active façade functions to optimize indoor comfort and energy consumption simultaneously and continuously (IEA, 2013). This challenges the role of façades: façades must act multifunctional and adaptive in order to actively contribute to sustainable energy use (Knaack, 2017). Glare-free daylight provision, maximal solar inputs in winter and minimal solar gains in summer, natural ventilation or integrated solar energy generation are, amongst others, required targets with needed dynamic behaviour. Their objectives are often contradictory, such as e.g. the need for daylight and cooling: the use of solar radiation reverses along the seasons, while the demand for daylight is the same all year round.

Modern façade trends therefore concentrate on so-called *adaptive façade systems* (Romano et al., 2018), which employ responsive materials and technical components for the adaptive duties that façades now hold. These façades, also known as '*multifunctional*', '*intelligent*' or '*responsive*' façades (Loonen et al., 2015) (Klein, 2013), are commonly characterized by their dynamic reaction to the environment. They adapt in real-time to dynamically changing conditions and shall provide individualized indoor comfort and improved energy efficiency. The most frequent design measures applied in adaptive façades are as following, according to the COST TU1403 'Adaptive façades network' database (Aelenei et al., 2018): shading concepts to avoid overheating or regulate solar incidence, adaptive thermal storage capacities to regulate the heat losses and gains, integrated ventilation systems to regulate fresh air exchange and integrated active solar energy technologies.

1.1.2 The capability of biomimetics for adaptive façades

The challenges associated with adaptive façades are the technical complexity in the assembly of reactive components and control mechanisms of the system. Adaptation processes, detached from the technical application field, can be found in biological processes in manifold ways. Herein, three types of adaptation are defined: morphological, physiological and behavioural adaptation (Booth & Biro, 2019). While the third is closely linked to motion (behavioural aspects of living organisms), the other two are enabled by a highly integrative design of the biological systems (Jeronimidis, 2008). Morphological adaptations aim at adaptation capabilities by specific form appearances, resulting from evolutionarily optimized structural arrangements of the materials used. Physiological adaptations are caused by biochemical or radiative processes within a 'system' that adapts by changing properties in the matter - without changing the form itself. Both adaptation processes are also found to a limited extent in the building envelope, which are further exploited by adaptive façades employing smart materials or systems. In nature, however, the implementation of adaptation principles is more versatile. Using all scales, from nano to macro, and smart design rules, nature developed fascinating solutions for the dynamic reaction by morphological means (e.g. photonic structures) or by physiological attributes (e.g. biochemical reactions) (Speck & Speck, 2019).

Many biological adaptation mechanisms have a particular characteristic that could be of great advantage for façades: they are so-called open systems, meaning that they interact directly within environmental settings, and thus are communicating directly via exchanging information, energy or matter (Brauckmann, 2000). Mechanical solutions for façades are mainly closed systems that do not interact directly with the environment but are activated and controlled by additional sub-systems. This approach requires a well-designed communication of the subsystems, controls and sensors – and makes it more complex and prone to failure. The potential of open systems, as applied in nature, has not yet been widely transferred to such applications but promises more robustness in maintenance and possibly also more smartness in functionality.

Employing biomimetic methods to generate architectural solutions is not new. Examples range from entire building designs based on biomimetic considerations to the development of particular components. Most of the examples, however, are still on conceptual level, especially in regards to adaptive façade solutions.

1.2 Problem statement

The regulation of thermal flows is usually controlled by building services systems. Architectural design measures rarely offer possibilities for active regulation – with exception of shading systems that are an architectural task simply because they are historically anchored in the façade design. In general, however, design measures in regards to thermal flows are static. Their goal is to provide a constant reduction in thermal flow and thus preservation of the indoor thermal conditions. This is usually achieved by steady-state air tightness, thermal insulation and thermal storage measures. Active balancing of the thermal comfort is a matter to building service technologies. The concern that this balancing would not be sufficiently controllable by passive-adaptive façade design solutions led to a separation of comfort-related and façade design/construction-related tasks.

It is indeed a challenge to embed adaptive functions in façades: the technical subsystems of adaptive façades require additional knowledge in e.g. electric and mechanical engineering (e.g. automated, kinetic mechanisms), information and computer sciences (e.g. controls, actuators and sensors) or material sciences (e.g. behaviour of smart materials and systems). The reliability and proper functioning of such systems depends largely on the system settings, choice of components, interfaces, communication protocols, sensor positioning, and many more. With further developments in materials sciences, smart materials may take over some of these tasks. So far, however, there is no way around a mixture of materials, devices and (extrinsic) control systems. Besides the complex system design, adaptive façades have also to deal with structural requirements and operation safety, with architectural and economic goals, and the respective national building regulations. The expectations of the advantages of adaptive façades are contrasted by this density of challenges and requirements. A downsizing of the complexity while keeping the functional goals is therefore at the centre of considerations.

One approach would be to put active functionality into the material or construction. Intrinsic control and embedded activators could, on the one hand, significantly ease maintenance and, on the other hand, possibly simplify the complexity in planning and realization. Embedded adaptability must be defined in the early design stage of a façade planning, also in consideration to the controllability of the effects. In that stage, architectural and constructive parameters play a decisive role, but these are not associated with adaptive functions (Knaack et al., 2013). If embedded adaptivity is to work, material and construction, design and geometry of the system, must be placed at the centre of the planning.

Embedded functionality in the 'structure' is a central advantage of biological organisms that function autonomously and independently of external control elements. Nature offers a wide range of evolutionarily well-developed examples for inherent functionality and also adaptability. One specific target, structural optimization, has already been well investigated and applied to technical solutions: the biomimetic, structure-optimised pavilions of the University of Stuttgart (ICD/ ITKE University of Stuttgart, 2020), for example, show how great the opportunities for material-effective systems are when a function-oriented combination of construction and material is pursued. However, there are few biomimetic examples related to façade design and thermal energy optimisation. Most are only few concepts and not nearly as mature as the solutions for structural optimization.

Most biomimetic concepts for thermal modifications are the result of inspirations with an inconsistency in the transfer of functional characteristics. The technical transfer of biological functions is not trivial and therefore often seems to fail due to the transfer complexity, particularly when pursueing thermal flow modifications. Thus, the outcomes are a fallback to known (technical) solutions with some "*bioinspirational*" ideas embedded mainly in the appearance. The greatest challenge lies in translating the functions while maintaining their coherence. It seems that an applicable translation guidance for façade designer is missing.

1.3 Objectives

In order to find out to what extent and by which means constructive measures can take over functions for thermal adaptation, a function-oriented transfer systematics would be necessary that makes biological models usable for the development of façade concepts. Thus, this work aims, on the one hand, at the investigation of thermally-adaptive principles in nature in order to identify strategies for function-oriented design concepts of façades. On the other hand, a systematic method is to be developed that focuses on making these functional strategies tangible for an applicable implementation in the design process, especially in the early design stage. The following hypotheses guide these objectives:

- *Reducing the additive approach of current technical solutions*: the assembly of individual devices into a complex system can be reduced through biomimetic solutions with integrated functionality. This shall lead to robust solutions.

- *Reducing the need for new material and smart device developments*: the biomimetic solutions can be realized by using standard design methods and existing materials. This leads to a reduction in the development time of new solutions.

- *Reducing the gap between design and adapative functionality in the façade design due to biomimetic approache*s: a function-oriented systematics would overcome the gap between design and adaptive technology and provide a stronger role to design. This systematics can be best developed on the basis of climate-sensitive and parametric methods with the aim to increase embedded adaptivity in the design.

Furthermore, criteria for the design effectivity and transferability are to be considered: design effectivity criteria target at easy-to-apply solutions and transferability criteria target at the applicability of biological principles for the design process of façades.

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1.3.1 Research questions

Following research questions are defined:

Question 1

Can the technical complexity of thermally adaptive façades be reduced by applying biomimetic approaches?

A What are the challenges for thermally adaptive measures of façades?
B Which criteria support the evaluation of technical complexity of adaptive façades?
C What are the baseline aspects for (thermal) adaptability in biology and technology?
D Are biomimetic solutions for thermally adaptive façades less complex?

Question 2

What role do geometric strategies play in the modulation of thermal energy?

A Do biological role models use geometric design rules for thermally adaptive functions?
B To what extent and by which means can constructive measures of façades take over functions for thermal adaptation?
C Can the gap between design and functionality (for adaptation) be reduced by using biomimetic processes?

Question 3

Can a standardized systematic process support the transfer of biological principles for thermal flow modulation to façade design?

A How can functional characteristics of biological role models be preserved when transferred for the use in the façade design?
B What are the the critical aspects for the transfer process in the established context?
C How effective is a parameterized systematics for its applicability in the early design stage of adaptive façades?

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1.4 Methodology

The approach for this work is derived from the study of similar works dealing with transdisciplinary issues and their translation using a systematics. Since the development of design models is the goal, methods from the field of product design were also explored. And finally, methods applied in biomimetics, the vehicle of this work, also serve as a basis. In the following, selected approaches are briefly presented, followed by a description of the applied approach derived from these.

1.4.1 Approaches identified

In the industrial product development sector, design and function are closely linked to each other. Thus, systematics to deal with the multi-complex challenges have been developed. Both product and building designs deal with various design constraints, of which time and effort to reach the targets are the most critical to be considered. Günther and Ehrlenspiel (1999) once proposed a "*minimum design guideline*" for practitioner to support the design process and reduce risks of failure, which became an established guideline with following steps: 1) list requirements, 2) list sub-problem(s), 3) design principal solution, 4) design concept, 5) analyses concept, and 6) evaluate advantages and disadvantages. They pointed out that success in practice is closely linked to minimize time and effort, which put a huge challenge to the quality.

Ehrlenspiel (2009) also developed a procedure for the integrated product development, which Lorenz (2008) examined besides other design processes in his PhD thesis about the handling of uncertainties in product design (Lorenz, 2008, p. 68). From that list of discussed design processes, the approach by Ehrlenspiel is rather comparable to the biomimetic top-down or "*Technology Pull*" approach proposed by the VDI 6226-1: "*Biomimetics - architecture, civil engineering, industrial design - basic principles*" (VDI, 2015, p. 7). For both, the technical question(s) and the exact clarification of the contextual conditions and objectives are the first steps in the process, in order to subsequently generate a well-prepared search matrix for the investigation and analyses of potentials, e.g. in biological databases.

Menges (2012), Knippers et al. (2016), Schleicher et al. (2015) or Helfman Cohen et al. (2014) took such considerations into the parametric design in the structural engineering field by examining certain role models in nature to generate light-weight structures. In his publication about biomimetic design processes, Menges (2012), for example, emphasized the potential of evolutionary computational design algorithms for morphogenetic form finding that allows the simulation of function-oriented variants. This approach focuses the potential of function-oriented modelling of biological processes to generate designs, which emerged into a whole discipline the recent years (Cogdell, 2019).

Soar took this idea further to additive manufacturing applying digital agents that integrate the processes of sensing, controlling and acting in biological systems (Soar, 2016). This approach attempts an exact parameterisation and integration of the various mechanisms within the process.

Bejan and Lorente (2010) discuss how physical laws affect constructions in nature and theorised about the 'law of construction', which is the "*law of physics that accounts for the phenomenon of evolution (configuration, form, design) throughout nature, inanimate flow systems and animate systems*" (Bejan, 2012). The existing biomimetic lightweight construction projects prove that the application of this law, the focus on physical functions, is a solid basis to realise aesthetically pleasing constructions

Another 'problem-solving' approach is the established TRIZ method, invented by Genrich Altshuller, which sets up contradictory parameters of a problem in order to derive solutions. Julian Vincent and Denis Cavallucci suggest to integrate this approach into the semantic language of ontologies, which would bridge the descriptive biology with the statistical engineering (Vincent & Cavallucci, 2018). The idea is to visualize the trade-off's that a biological system makes to function. This again requires a systematics that allows a correct representation of the complexity of the system.

1.4.2 Applied approach

The methodological approach of this work is based on the selected approaches and complemented by the function-oriented systematics using ontologies, developed in the thesis of Gaag (2010), and the top-down approach in biomimetics proposed in the guideline VDI 6226-1 (VDI, 2015). These approaches were selected by a preparatory literature review to base the work on existing methods that handle complex targets with uncertain ambiguities and transdisciplinary information:

Ehrlenspiel's phases for a 'problem - solution cycle' (Ehrlenspiel, 2009) serve as the framework:

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- **Clarify the problem** – Goal: define, analyze, structure and formulate the problem.
- **Seek potentials** – Goal: collect, identify, systemize and describe potentials.
(Ehrlenspiel proposes an analysis of existing solutions from other areas in order to consider inventions already made.)
- **Select solutions** – Goal: generate, analyze, evaluate and determine new solutions.

1 Clarify the problem

The initial step is to define, analyse and structure the problem, which leads to the definition of search key words. This step is needed to gain clarity about the contextual framework and intentions. By defining the field of investigation (I) and analysing the available information (II), the status quo of a problem is assessed and evaluation criteria for subsequent solutions are established (III). Furthermore, underlying fundamentals of the problem are studied to prepare an effective structure for the search process in biological databases (IV). This step requires, on the one hand, the translation of technical termini to abstracted termini in life sciences. On the other hand, a systematics must be developed that guides the biomimetic search and analyses process (Fig. 1.1).

Literature review, expert interviews, numerical assessments to understand processes, case studies and classifications in structured databases using matrices and schemes are the applied methods.

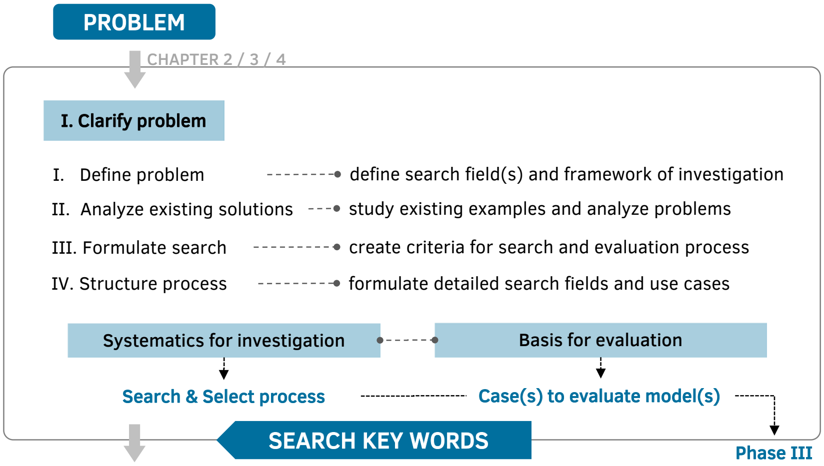

FIG. 1.1 Phase I: Clarify the problem targeting the outcome '*search key words*'

2 Seek potentials

In this phase, meta-searches are conducted based on the defined search key words in the life sciences. To conduct an effective analogy search in life sciences, it is essential not only to overcome language barriers through various terminologies in the involved disciplines, but also to get useable information about the identified analogies. The study of these reveals the applied strategies and feasibility for transfer. The major challenge is to collect useable data of biological role models referring to the search key words and to select those which promise high potential.

This phase includes the search and collection of biological role models (I), the identification and selection of useable role models by studying the key information (II), the analyses of the strategies (III), and a systematic description of these as biological concepts (IV) (Fig. 1.2).

For this purpose, searches in meta-search engines, such as academic online-libraries, scientific journals, and biomimetic databases, is conducted. Already collected data and expert interviews in the preliminary research study BioSkin (Gosztonyi et al., 2013), which the author developed and coordinated, supports the process. Involvement of biologists and experts from relevant domains is essential at this stage to avoid misunderstanding of biological principles. Access to experts in biology, mathematics, physics or mechanics is provided by the established network of BioSkin and the biomimetic network BIOKON International (Biokon e.V., 2021).

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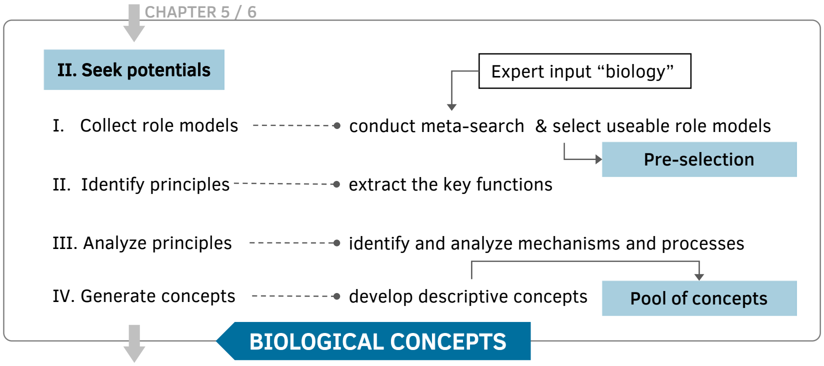

FIG. 1.2 Phase II: Seek potentials targeting the outcome '*biological concepts*'

3 Select solutions

The tasks in the final phase are divided into two steps: the transfer of the biological concepts into 'functional models' (and thus the translation back to the domain façade design) and the evaluation of the results and systematics: first, the principles of the biological concepts are transferred to design parameters, considering the dependencies and relationships between constructive and material components by supplementary qualitative and quantitative analyses (I). Then, the design parameters are systemically arranged in schemes to allow variations in the design without loss of functionality (II). The physical model and its adaptation mechanisms are described by sketches. This process is subject to constant revision and a reality check because the identified principles and processes allow many solutions. There is also a risk of compromising the functionality by making too many assumptions and neglecting important conditions. However, this process allows a guided approach to the important design freedom at this stage. To understand the functional idiosyncrasy of the designed functional models, qualitative comparisons to the defined cases in phase 1 are conducted. The functional models and the transfer systematics are finally evaluated to reflect the applicability (IV) (Fig. 1.3).

The applied methods are design sketches, simple numerical and empirical analyses, literature studies if needed, and the use of the schemes and classifications for the description and evaluation.

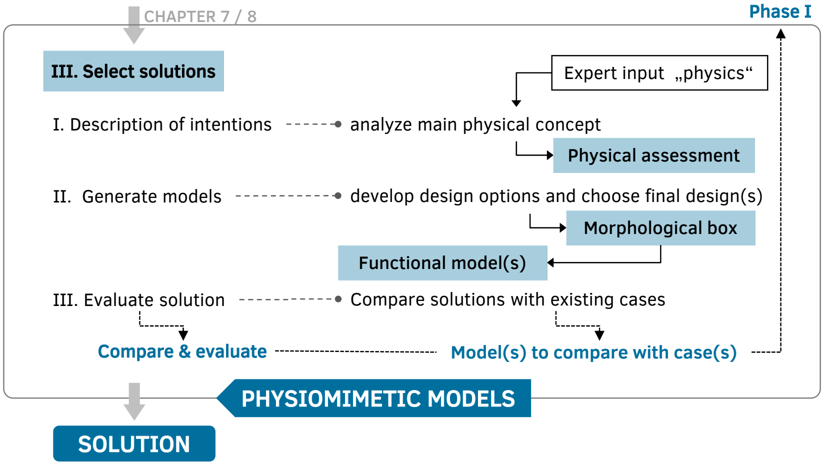

FIG. 1.3 Phase III: Select solutions targeting the outcome '*functional façade models*'

1.5 Relevance

1.5.1 Scientific relevance

The work contributes a systematic approach for the application of biomimetics in the field of architectural engineering in the early design stage, especially in the field of adaptive façade engineering. It offers a differentiated view of the top-down process, as established by the Biomimetics research community and defined in the VDI 6226-1. The "*design by analogy*" process, as it is also called, takes place in several steps of abstraction, which are often interpreted in such a way that imitations of the morphological rather than the inherent functional features take place.

The detailed analysis steps and the attempt to classify and parameterise the interim results in this work support the tracing of the sought functionality in the transfer process between biology and technology. By addressing the common basis that forms the functional intersection between the target and the search fields (which in this case are thermodynamic processes), the biomimetic process follows a function-oriented logic - the physical functionality determines the design. Thus, the title of the work is called *physio*-mimetic instead of biomimetic design – derived from the medical sciences mimicking process-related functions in the human body. And the denotation follows also the “*physiomimetic*” concept of Rupert C. Soar, who uses "*scripted functionalities*” and “*digital agents*” to generate digitally designed solutions. But in contrast to the use of digital tools, the approach in this work offers a manual approach. This means that it can be used in the early design stage, where creative processes are still done manually, and the use of parametric tools is often too time-consuming. Functional concepts can thus be created before they are subjected to digitally supported analyses. However, the results are structured in such a way that they would be directly transferable into a parameterised environment and thus provide a good basis for a further digital development and analysis.

The work also deals with thermophysical effects of architectural design measures, such as surface geometries, positioning of elements or layered structures and the adaptability of geometric configurations. The importance of this approach is to provide evidence that architectural design can offer a variety of performing measures for dynamic processes in façade constructions. Enabling adaptive functionality in façades should not be a '*one plus one plus one plus one plus one...*' path as it is now by assembling active components. Self-adaptive functionality can also be initiated by a smart geometric design. This can result in technical simplification of adaptive solutions without reducing its functionality. The integrative aspect of this approach also accounts to the aesthetics of an adaptive system, as the assemblies often result in aesthetic compromises. Further architectural requirements, such as flexible configurability or modularity, may also be achieved easier.

1.5.2 Societal relevance

Nature offers a remarkable variety of solutions for diverse tasks. The variables to be taken into account are comparable to many technical solutions, such as temporal and spatial criteria, limitations by local conditions or material sources. But the interaction of these parameters in biological systems is much more sophisticated and sustainable than in technical systems. Looking systematically into the processes of biological role models should contribute to the understanding of how we can use resources sufficiently but effectively.

The results of this work should not only show novel concepts to the urgent need of passive cooling design measures in buildings, but also stimulate the application of such systematics to other challenges in the construction sector. The results should provide insights into how a performative functionality in a system can be generated by design principles. This *function-oriented art inspired by biomimetics* is not only an exciting eye-opener for meaningful design, but also aims to reduce the discrepancy between design and functionality.

The intention of this dissertation is also to empower discussions on how seemingly disadvantageous external influences can be transformed into strengths by design in order to achieve a functional goal. The transfer of (thermo)physical principles is an example for this. Physics is hereby the design guide to develop adaptive solutions with little but cleverly placed, valuable material. This idea can be employed to any challenge and thus the findings can also contribute to the discussion about sufficiency in the context of sustainable use of finite resources.

1.6 Determining framework and constraints

Along the process, several constraints had to be defined, either due to scope limitations, lack of knowledge, resources or information, or limiting possibilities in the transferability of biological characteristics. As these constraints are of different nature and discovered along the process, they are mentioned directly in the corresponding chapters.

The author is aware of the fact that some assumptions are incomplete or vague and could be criticised as inappropriate. The main challenge in this work is to allow for these uncertainties, but to discuss them critically despite or because of the transdisciplinary framework and the complexity of the project.

The intention of the work is to develop a systematics that serves as a function-oriented design guide for the translation of biology into façade construction. The developed systematics itself is critically examined, but the validation of the proposed functional models is beyond the scope of this thesis. Numerical simulations or calculations would be necessary to validate the functional models, which requires mathematical modelling of the processes, function(s) and dependencies. A correct mathematical-physical representation of the models with all parameters is a major task due to the complexity. It needs a restriction to the analysis of single models and the support of experts from the relevant fields. This is therefore considered as a future activity based on this work.

The primary goal is to identify strategies that allow a functional transfer of thermally adaptive processes. These should positively influence summer conditions, i.e. contribute to the reduction of cooling energy. Due to the application of known design strategies in façade engineering for the development of the biomimetic models, many limitations arise: functionality, especially in thermally relevant modulation processes of biological systems, are tightly bound to scales – many play out on the nano or micro scale. These can only be transferred indirectly to a limited extent or not at all considering the defined system boundary of this work - unless materials with the corresponding characteristics are already available. Since functionality is sensitively to scale, great care must be taken here in the selection of biological principles to ensure that they function when the scale is changed. Some models can therefore not be pursued further, although they possess a high potential. This also applies to biochemical processes that often influence thermal energy flows in nature - these must also be omitted from this work.

The interaction and acceptance of adaptive façade measures by the users and economic optimisation of the measures are not examined. Nor are production processes considered. Aspects dealing with architectural quality, safety or realisation of the models would also need to be considered at a later stage of the development. All these are subsequent steps after the validation of the models and part of future work.

1.7 Structure of work

The structure of this work is developed along the three phases, as described in Section 1.4 and has eight chapters in total. Figure 1.4 presents the structure with the related purposes and applied methods in each chapter:

After an general introduction of the context in *Chapter 1*, *Chapter 2* starts with the analyses of the framework conditions, targets, and needs for highly energy-efficient buildings to set up the scope for thermally high-quality building envelopes. It also introduces the measures and parameters used to assess the buildings´ performance. The chapter concludes with the defined search fields and a developed parameter specification list, comparable to a checklist, that describes the important design measures in a structured form.

Chapter 3 zooms deeper into the defined search fields and sets the search scope. It provides the State-of-the-Art of adaptive façades and shows their potential for increasing energy efficiency on the basis of thermal adaptation targets. It emphasises the current mechanisms of adaptiveness and leads through some examples for thermally adaptive façades. Based on the evaluation of selected cases, design criteria for thermally adaptive façade are extracted and systematically arranged into a list. This criteria list serves as a support tool for the whole analogy process, from the search for adaptation strategies in nature, to the identification and selection of potential principles and the development of functional models. As a further result of the evaluation, the studied cases are grouped into purpose groups, which are evaluated in regards to their design effectivity. From this evaluation, use cases are extracted which later serve as comparison cases for the generated biomimetic models in Chapter 7.

Observations of unknown fields need a '*navigation tool*' to guide through. *Chapter 4* provides this by discussing the links between the domains façade design and biology: it provides an overview of about thermo-physical processes and influencing factors, design rules and characteristics for adaptation. This information is then reflected and relevant rules for the translation process are established. The chapter completes with the summary of search key words and evaluation tools that form the translation systematics.

Chapter 5 leaves the engineering field and enters life sciences via the analogy search in biological databases and sources. The identification and qualitative selection of suitable biological role models are provided in this chapter, as well as information about this identification and selection process. The identified role models are clustered into groups of similar functional purposes and evaluated in regards to some criteria that have been defined in the previous chapter 3. It concludes with a list of suitable potentials from nature.

The functional principles of the selected role models are in the focus of *Chapter 6*. The selected biological strategies of chapter 5 are then investigated in regards to their applied main principles for thermal adaptation. These principles are not yet linked to the engineering language. By analysing the biological strategies, a qualitative description including the functionality of the identified principle(s) and their dependencies, but also information about the role of geometry and physical attributes, is provided. These descriptions are summarized in a semantic form as *biological concepts* for two examples.

Chapter 7 is engaged with the development of functional models that transfer the biological concepts of the previous chapter to conceptual façade designs. Thus, this chapter provides the transfer work that guides back to the origin domain of façade engineering and design. Exemplary functional models are described using sketches and parametric information about the system (physical design) and functional settings (adaptation mechanisms). The chapter concludes with the evaluation of the design effectiveness and adaptation mechanisms of the generated functional models by comparing them with the prepared use cases of Chapter 3. The aim is to identify the similarities and differences between the use cases and the functional models to judge whether the transfer process is beneficial for innovations and meets the objectives. This evaluation is done by a qualitative analysis using the defined evaluation criteria of Chapter 4.

Finally, *Chapter 8* reflects the research questions, including the developed systematics and results of the transfer work. It critically reviews both and further provides recommendations and an outlook to future work.

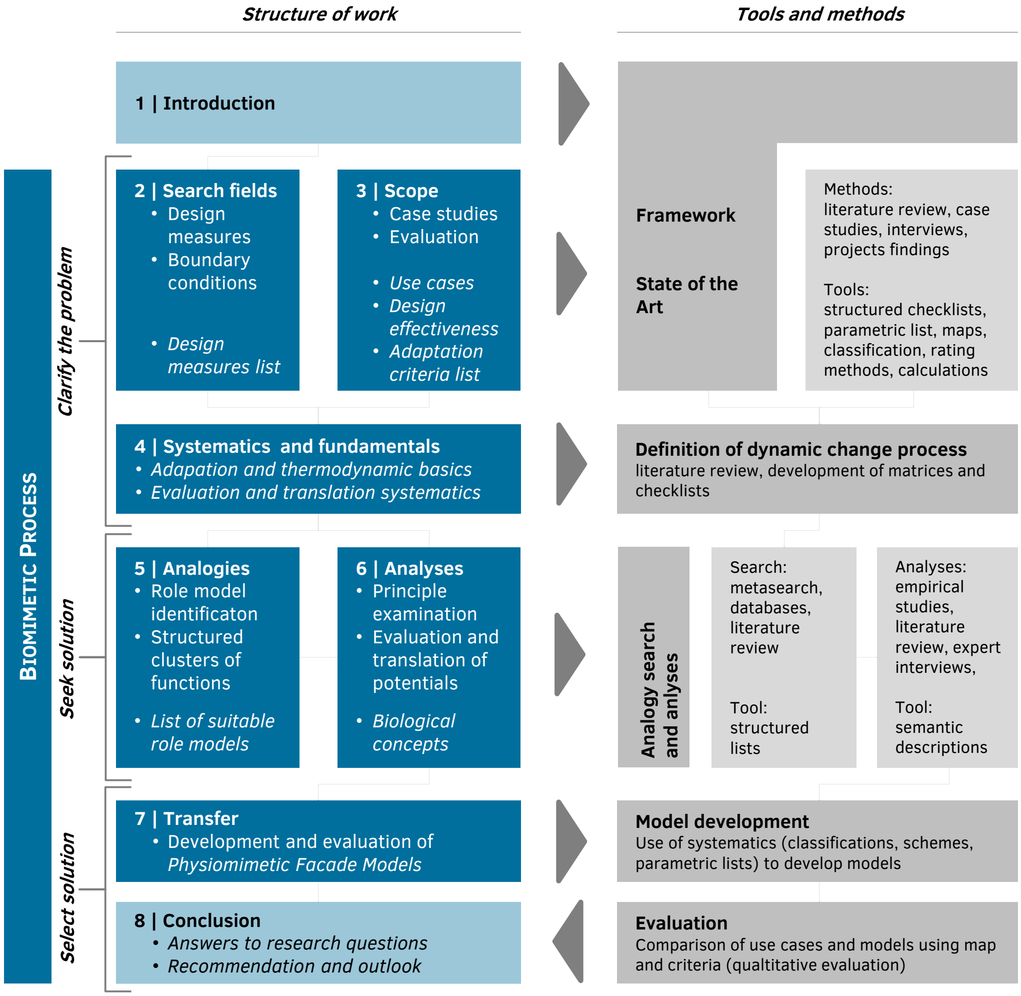

FIG. 1.4 Structure of work with the assignment of the chapters to the respective purpose and methods

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2 [Search fields] Thermally related façade design measures

This chapter sets out the framework necessary to identify the search fields. For this purpose, the requirements and tasks for achieving good summer performance of buildings are surveyed, focusing on thermally related measures in façades. To understand the effectiveness of the measures, their interdependencies and the physical processes are presented using the standardised performance indicators.

The current thermal adaptability of these design measures is then evaluated. To clarify the boundary conditions for summer performance, the main environmental influences and the criteria for achieving good indoor thermal comfort are further reviewed. With this information, a rough definition of the search field can be made.

Along the process of the review and evaluation of the measures, their design parameters, dependencies and influences are systematically recorded and transferred to a parametrically created list. This list will be extended in the next chapter to include thermal adaptation criteria. This approach should facilitate a systematic recording of the problem and enable the modelling of biomimetic concepts and the comparison with existing systems, because the parameters and dependencies become comparable.

After an introduction about the performance challenges of façades in Section 2.1, Section 2.2 presents their thermally relevant design measures, with a particular focus on cooling targets and the respective performance indicators for each measure. It concludes with a classification proposal of the functional principles from the identified measures. The design measures are subsequently assessed by a multi-stage evaluation process in Section 2.3. For this purpose, both the current and potential adaptability of each measure are estimated, and the influence and conflicts of certain parameters are assessed. In addition, the influences of the boundary conditions are explored in Section 2.4: the thermal indoor comfort and the external climate factors. Finally, the results from the evaluation steps are summarized to identify search fields for the tasks '*thermal measures for cooling*' and '*adaptability*'. The chapter concludes with a list of selected design measures that contribute to the summer performance. This forms the general search fields.

The information compiled in this chapter results from extensive screening of publications and European building standards. This information is supplemented by scientific building project reports and the author's existing knowledge. Targeted quantitative parameter studies are carried out in Section 2.3.4. to evaluate the dependency between geometric and material properties. A qualitative weighting method is used to evaluate the measures and the parameters in Section 2.3.

2.1 Introduction

The origin of modern performance-driven façade design can be traced back to the developments in climate-sensitive architecture, '*bioclimatic'* design or respectively solar passive design, as well as to the evolving energy efficiency regulations for the building sector since the 1970s. Since then, European countries have been following standards and technical specifications for measures in buildings to reduce energy demand while maintaining a high level of indoor comfort.

Already in the late 1960s, publications about the interrelation between climate and building design measures illuminated the traditional knowledge of vernacular architecture and upgraded this for modern design actions by adding new knowledge from architecture, engineering, meteorology and physics. One of the well-known works in this regards is the book from Victor Olgyay about '*Design with Climate*' (Olgyay, 1963), in which he explains critical design strategies such as orientation, aerodynamic shapes or the physical utilization of materials. With this and many other publications on passive design that followed, the trend began to systematically re-incorporate environmental boundary conditions into the design framework.

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2.1.1 The assets of bioclimatic design

'*Bioclimatic*' design is generally seen as a planning strategy that combines environmental conditions, indoor comfort targets and constructive measures with the aim of achieving a good balance between architecture, comfort, energy and resource efficiency. Supporting design approaches have been developed to facilitate the use of analytical tools for design processes, such as the revised bioclimatic charts by Givoni (1992). The bioclimatic design strategy is nowadays better known as 'sustainable design strategy' or as '*Integrated Design Process*' (IDP) (Larsson, 2009). It is applied in energy certificates, such as e.g. in the Passive House standard (iPHA, 2016) or in worldwide known sustainability labels, such as LEED (USGBC, 2019), BREAAM (BRE Group, 2017), Green Star (GBCA, 2017) or DGNB (DGNB e.V, 2018), among others (Tam et al., 2018).

The core idea of the IDP is to relate environmental parameters and building parameters by applying standardized assessment processes along the design phases. Environmental parameters include regional, meteorological and geographical information about a site, while building parameters range from geometric design tasks to physical material attributes. The IDP provides calculation and evaluation tools that work with these parameters in such a way that the environmental resources are used in the best possible way for an energy-efficient operation of the building. The choice of the building shape, material and construction details determines how well this goal is achieved on the 'passive' side; and it determines the need and type of building technologies to be needed for the 'active' supply side.

Bioclimatic design developments and the development of thermal performance assessments are closely linked to the economic significance of energy efficiency in building construction. It was driven in particular by the rise in oil prices in the 1970s and the resulting development of thermal insulation. Although thermal insulation as a heat protecting measure has historically been of importance since early times (Bozsaky, 2010), it was not until this economic crises that it was recognised as a necessary benchmark for energy consumption. Thermal quality became comparable by the introduction of performance parameters, such as the thermal resistance (R-value) or respectively heat transfer coefficient (U-value). Other parameters, such as e.g. the solar heat gain to assess overheating risks, were of secondary importance at that time and were taken into account later due to the increasing glazing share in buildings and resulting higher cooling demand. Today, the consideration of energy-related building design is an obligatory part of the planning and implementation process in most so-called industrial nations. The supporting process of modelling and analysing the energy transfer effects between the building and its surrounding, and thus its energy efficiency, is a specified in the national building standards. It reveals the importance of the passive design measures, the construction parameters, to achieve high energy efficiency. Therefore this chapter focuses on the constructive design measures for building envelopes, respectively façades, and their assessment indicators.

2.1.2 Thermal performance and building envelope

The European Union's '*Energy Performance of Buildings Directive*' (EPBD/2018/844/EU) states that the building envelope "*has a significant impact on the energy performance*" (EU EPBD, 2018, p. 19). The focus of the performance evaluation of façade components is on the cold (winter) period: high thermal insulation, efficient glazing and air tightness of the building envelope account to this. The last update of the EPBD, which has been issued in June 2018, also addresses now measures for the warm (summer) period. Thus, recommendations for the prevention of overheating by shading devices and, preferably passive, cooling strategies (thermal mass activation and night-time ventilation) are provided.

The EU member states and non-member states, such as Switzerland, agreed to the implementation of the targets in the EPBD, although the execution differs from country to country (UNECE, 2018). Austria, for example, defined the nearly Zero-Energy Building (nZEB) standard as a minimum for new built construction with a heat energy demand ranging below 25 kWh/(m²a) and a max. U-value for external walls of 0.35 W/(m²K) (OIB, 2019). Germany follows similar targets with a maximum U-value for external walls of 0.28 W/(m²K) (Tuschinski, 2020). Sweden defines differing primary energy consumption limits for a whole building according to four different climate zones in the country, with respective max. heat energy demand for each zone ranging from 5 to 15 kWh/(m²a) (Boverket, 2019). Specific maximum U-values for the external walls are not provided in Sweden, but a maximum average U-value for the total building envelope for various building types from 0.4 to 0.33 W(m²K) (CA-EPBD, 2020). Switzerland and The Netherlands applied similar strategies like Austria towards nearly Zero-Energy Buildings, but ask for lower U-values for external walls: Switzerland limits it to a maximum of 0.17 W/(m²K) (EnDK, 2018) and The Netherlands ask for a maximum of 0.22 W/(m²K) (Bouwbesluit, 2020). International applied energy efficiency labels, such as the Passive House (PH) standard target at values for a primary energy consumption of 120 kWh/(m²a) for conventional constructions, space heat demand ≤ 15 kWh/(m²a), heating load of ≤ 10 W/m² and air tightness n50 ≤ 0.6 /h at 50 Pa (N/m²). The maximum limit for the U-value for external walls is 0.15 W/(m²K). These examples show that the performance quality of building envelopes is most often measured by the static U-value, usually calculated for the winter period.

The performance effectiveness of buildings, however, is based the assessment of the energy balance for a whole year, including the summer period. The calculation is based on average annual climate data and standardized indoor thermal comfort ranges. The psychrometric chart of Figure 2.1 displays the thermally relevant climatic conditions of a year in Central Europe, divided into three climate zones (Cfa, Cfb, and Dfb) according to the Köppen-Geiger classification (Beck et al., 2018). To stay within the thermal indoor comfort ranges as described in the EN ISO 7730 (2005a), mainly heating energy is required as temperature drop below beyond the comfort zone for over most of the year in all zones.

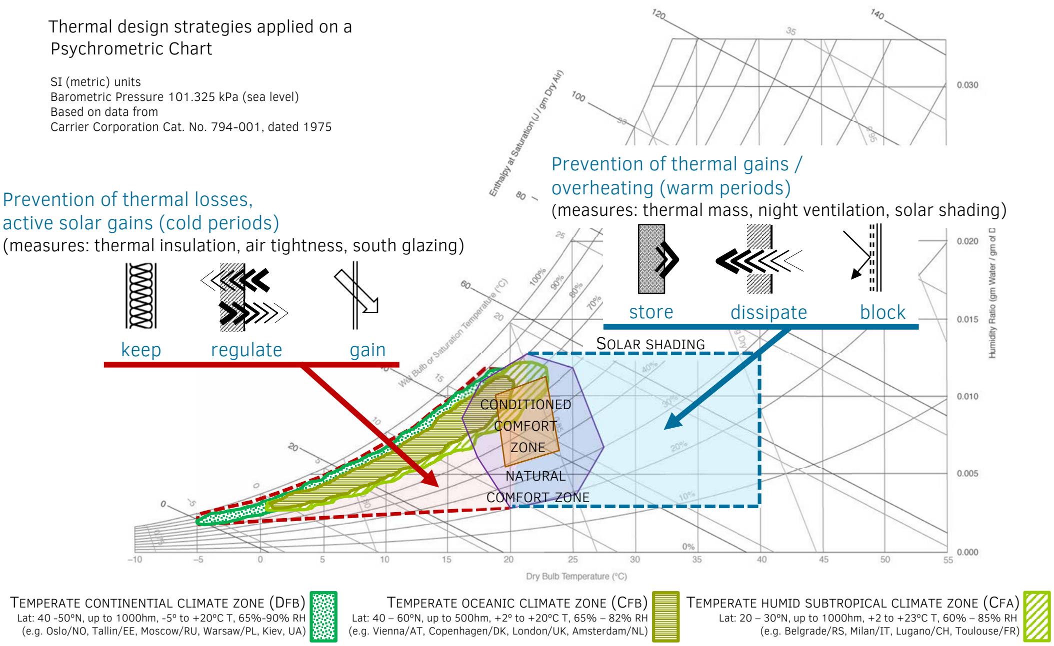

FIG. 2.1 The psychrometric chart presents the passive design strategies applied for winter and summer in the major Central European climate zones (Dfb, Cfb, Cfa).
Thermal insulation, avoidance of thermal bridges, air tightness to prevent heat losses and solar gains through glazing's are obligatory passive measures to keep the thermal comfort in winter. Solar shading, thermal mass use and active night ventilation are needed measures in summer, whose efficiency is strongly influenced by the measures designed for winter.
Source: Data basis of climate regions from Köppen-Geiger climate classification (Kottek & Rubel, 2017), thermal comfort zones according to ISO EN 7730 (2005), psychrometric chart is licensed under CC BY-SA 3.0 provided by Ogawa (2009).

Passive design measures applied in the cold period are to prevent thermal losses and to use solar gains (marked red in Fig. 2.1). Thus, 'keep' heat (thermal insulation), 'regulate' the air exchange to reduce heat losses (air tightness, ventilation), and 'gain' solar heat (glazing) are the major tasks to consider. For the warm period, measures must be taken to prevent overheating by 'dissipate' internal heat (night ventilation), 'block' external heat (shading) to enter and 'store' cooler heat gained by night ventilation (thermal storage capacity) (marked blue in Fig. 2.1).

The package of design measures for the winter target points to a conflict: the glazing on the south-oriented building surface area is optimized for maximum solar gains (and thermal quality with low Ug-values) in winter, which worsens the comfort situation in summer. The resulting need for shading lowers the daylight level, and the low U-values hinder the dissipation of internally stored heat in summer.

The tasks 'block' and 'gain' solar radiation as well as 'dissipate' and 'keep' heat are conducted by the same components throughout the year. This eventually led to the development for adaptive components in the façade.

2.1.3 The need for cooling

While global warming causes slowly a decrease of heating energy demand (-27% in the '2070 to 2100' long period versus -5% in the '2020 to 2050' short period), cooling energy demand increases drastically by 44% in the short period according to Kitous and Després (2018). Studies warn that the "*increases in cooling energy demand due to global warming will be outweighed by reductions in the need for heating energy.*" (Aebischer et al., 2007, p. 859) and that "*space cooling demand is increasing faster than any other household energy consumption*" (Jakubcionis & Carlsson, 2017, p. 235).

In addition, overheating has become a social issue, as health risks and well-being in the event of overheating result in major economic expenditures (Lomas & Porritt, 2017). For example, the frequency of accidents increases significantly at room temperatures above 25°C, whereas work performance and mental ability drop significantly (Hausladen et al., 2003, p. 18). Even in cooler climatic regions of Europe, such as in the UK, overheating risks increase dramatically due to the better insulated quality of buildings that shall meet the NZEB (Nearly Zero Energy Building) strategy of the EU (McLeod et al., 2013). For the same climate, the importance of behavioural patterns to reduce the risk of overheating was also studied: the way in which occupants open/close windows and shadings significantly affects overheating (Mavrogianni et al., 2014).

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Thus, the need for energy-efficient cooling solutions is increasingly becoming a focus of interest.

Studies like the above indicate that the cooling energy demand increases due to the improved thermal quality of the building envelope. In addition to heating and cooling needs, the demanding thermal comfort requirements ask for an almost continuous regulation task of the indoor climate (Fig. 2.2).

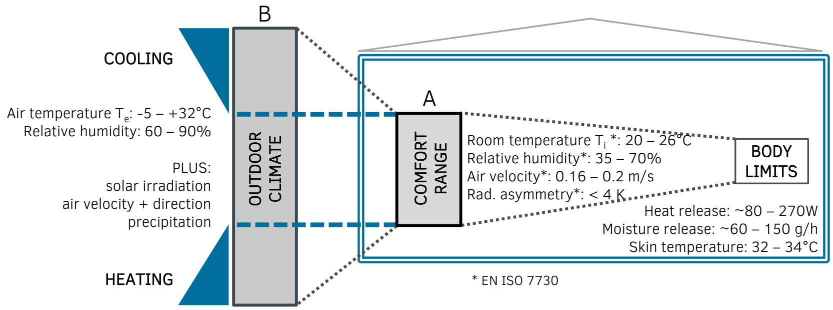

FIG. 2.2 Environmental deviations with which a building envelope has to deal.
The needs of the human body are directly influenced by the thermal indoor climate and thus form its basis (A). On the other hand, there is the local climate (B), which deviates from the thermal indoor comfort zone over longer periods. The building envelope is an important player in balancing and modulating these climatic deviations. If the passive design strategies cannot maintain thermal comfort limits, building service technologies must provide cooling or heating to achieve this (Graphic is adapted from Fig. 1 in Moser, 2006).

The reduction of the cooling energy demand or the avoidance of its increase still ask for solutions in the construction field. The possible potentials provided by passive measures are still not fully explored. This, in turn, means that the building envelope would have to play a bigger role by adapting dynamically in order to achieve the objectives for both winter and summer.

In this context, the façade as part of the building envelope with additional aesthetic and visual comfort tasks becomes particularly interesting. Adaptive façade systems are supposedly recent developments to address this conflict. Their potential to dynamically regulate the energy flow for either cooling or heating has just been rediscovered. It stands in contrast to the rigid performance benchmarks that demand a steady-state behaviour over the whole year. Thus, the permanently installed design measures related to thermal performance are still based on the winter case.

2.2 Passive façade design measures

Guidance for the right choice of passive design measures is provided by various tools: while voluntary certificates, such as those mentioned in 2.1.1, usually provide checklists, legally supported energy certificates offer a step-by-step procedure to calculate the performance quality. These then refer to the respective national building code with some additional benchmarks. Many of these tool's target nowadays sustainability aspects that go far beyond specific planning criteria. The International Initiative for a Sustainable Built Environment (iisbe), for example, recommends a tool called '*SBTool*' as a generic framework for the assessment of sustainable buildings. The SBTool asks for rather comprehensive information, targeting the location and site characteristics, environmental issues, social and economic aspects, up to material and operation impacts. The building envelope is only addressed by rather general attributes, such as "*material efficiency (B3.3)*", "*noise*" and "*adaptability constraints imposed by building envelope and technical system (E.4.4)*" (master list of criteria iisbe, 2020).

Exemplarily for worldwide applied sustainability certificates, the LEED™ (Leadership in Energy and Environmental Design) rating system by the Green Building Council (USGBC, 2019) started originally as a motivation tool and is now used as an award and sales system for sustainable buildings. It appears to emphasize global measures beyond the construction of a building, including rainwater use, transportation or the ecological footprint. Its relationship to the role of the building envelope is rather general but at least a bit more detailed compared to the SBTool: it mentions basic attributes of the building envelope, such as thermal insulation values, window-to-wall ratios, glazing characteristics, shading and window operability (rating system v4, USGBC, 2019). Furthermore, it is mentioned that some façade-related criteria are to be assessed with regards to the quality and operation of important components, such as glazing and shading.

The most detailed information about the needs to avoid overheating in summer are provided in the European standards.

2.2.1 Methodology

In order to identify passive design measures for the façade in the above-mentioned context, a literature study is conducted. The aim is to obtain information on the most applied passive measures that regulate thermal flow. Their functionality is briefly described and the most critical parameters and indicators to assess the performance is discussed.

Identification of design measures

The sources for the literature study are publications addressing energy efficiency and the impact of façade-related design measures over the last ten years, such as exemplarily Juaristi et al. (2020), Planas et al. (2018), Ihara et al. (2015), Konstantinou (2014), Knaack et al. (2013), Pacheco et al. (2012), or Sadineni et al. (2011). Additionally, scientific reports about built projects and expert knowledge gained by the author herself is considered. Amongst these sources are façade refurbishment studies provided for the Swedish refurbishment initiative in 2016 (Gosztonyi et al., 2017), the prototyping of a multifunctional plug and play façade (Mach et al., 2015), a scientific pre-design study for a plus energy office building (Preisler et al., 2012), or a studies on energy efficiency strategies for buildings (Amtmann et al., 2012) (Gosztonyi, 2007).

Based on this review, a classification for applied façade design measures in context with thermal performance has been set up, as shown in Table 2 1, in which relevant parameters are assigned for each measure.

TABLE 2.1 List of thermal performance related design measures associated with the façade
The list is structured by a classification ID [PXX: Physical description]. The table shows furthermore the identified constructive and adaptive characteristics.

ID	Class	Constructive integration	Current adaptability
P01	Thermal insulation	Part of façade structure	None, rigid
P02	Thermal mass	Part of building structure	None, rigid
P03	Glazing	Part of façade structure	None, rigid
P04	Shading	Added component	Flexible
P05	Air tightness	Part of façade structure	None, rigid
P06	Openings (ventilation)	Added component	flexible
P07	Thermal boundary layer	Part of façade structure	None, rigid
P08	Passive cooling	Part of façade structure	None, rigid
P09	Form and shape	Part of building structure	None, rigid

This list complies well with the common state-of-knowledge on energy-efficient passive design measures, as feedback from interviewed planners and experts in the field confirmed. In the following, these design measures are introduced in brief.

Identification of performance indicators

As mentioned in Section 2.1.2, the European Commission has established a systematic set of European building standards for assessing the *Energy Performance of Buildings (EPB)*. For this purpose, the standard ISO 52000-1 (2017) defines the systematic approach for the assessment, which is implemented in the national building codes. The assessment procedures also address, among others, the energy flow effects through the building envelope components. This is considered in the review in order to extract performance indicators, which are then assigned to the list of design measures (cf. Table 2.1). The assignment is intended to display the importance of both physical properties of materials (e.g. thermal mass capacities, thermal conductivity, reflectance) and structural attributes (e.g. thickness, volume, length).

Additionally, threshold values of various national building specifications and certificates in a few Central European countries, including Austria, Switzerland, Germany and the Netherlands, are studied to obtain key values for comparison.

The following Sections 2.2.2 to 2.2.8, the findings of the review are presented together with the functional purposes, tasks, influencing parameters and key performance indicators.

2.2.2 Thermal insulation

The quality of thermal insulation materials depends primarily on their ability to reduce heat flow transmission. The most important benchmark is therefore the thermal resistance (R-value) or respectively the thermal conductivity (λ) of the materials. The development for insulation materials is thus driven by the goal to reach higher efficiency while reducing the thickness in order to reduce costs, resources and needed space. This goal is set by the requirements for highly insulated buildings to achieve the NZEB standard (EU EPBD 2010) or beyond and the need to reduce the resulting large thicknesses of external walls with total depths of up to 500 mm or even more. For example, to achieve the Passive House standard, Uw-values must remain below 0,15 W/(m²K) (Passipedia, 2019), with insulation thicknesses ranging from approx. 40 mm to 250 mm, depending on the material (Fig. 2.3).

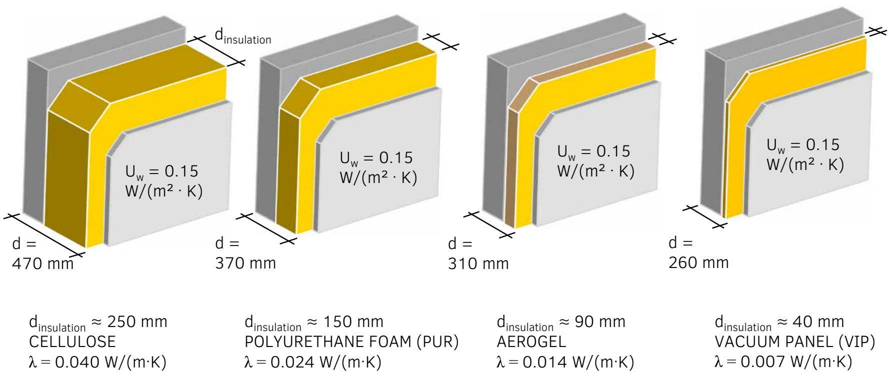

FIG. 2.3 Comparison of thermal insulation materials with regard to their thicknesses.
To reach the U_w = 0.15 W/(m²K), the thicknesses of the materials cellulose, polyurethane foam, aerogel and vacuum insulation panels vary between 250 mm to 40 mm.

With this in mind, a whole range of solutions is available – from conventional materials, such as polystyrene or rock wool (Schiavoni et al., 2016) to super-insulating materials targeting at very thin thicknesses, such as silica aerogels (Kapsalaki, 2017) or Vacuum Insulation Panels (VIP) (Kalnæs & Jelle, 2014).

Another group of thermal insulation materials follows sustainability aspects using natural or recycled raw material, such as cellulose, cork or sheep wool insulation (Asdrubali et al., 2015), although the optimization for slim thicknesses cannot be reached by these materials.

The overall thermal quality assessment of external walls includes furthermore possible thermal bridges that should be avoided. Thermal bridges can occur due to poor material or construction assembly. The avoidance of thermal bridges is regarded an obligatory task of the thermal insulation(O'Grady et al., 2017), as well as the considerations of the dynamic hygrothermal behaviour of materials, which is calculated by the standard EN ISO 13786 (2017). Moisture transport occurs by capillary forces and diffusion, and to the air by convection where the properties of the thermal boundary layer become important. This effect is described in the standard EN 15026 (2007) through the state variables ϕ, p_v, p_{suc}, T and the moisture content of the building material, which are related by the moisture storage function. No adaptability needs are associated with moisture transport in materials. For lightweight metal façades, the hydrothermal behaviour can be neglected; instead, possible condensation must be avoided. Here, too, there is no need for adaptation.

A final decision on the right thermal insulation material also depends other criteria, such as the chemical (e.g. flammability, moisture resistance), ecological (e.g. energy use for production) and constructive (e.g. weight, space, durability, etc.) attributes. Some studies, such as those by Ihara et al. (2015), also state that a reduction in the U-value can lead to an increase in cooling energy demand under certain circumstances (buildings with higher internal load, warmer climate regions and/or periods).

Performance metrics

To assess the overall U-value for external walls, the specific U-values of all components (windows, walls, frames, glazing) must be known. The calculation procedures for the U-values of opaque façade components (Fig. 2.4) is defined in the standard EN ISO 6946 (2017), and of frames in the standard EN ISO 10077 (2017). The U-value for curtain wall façade systems must be calculated using the standard EN 12631 (2017). The calculation method provided in EN 6946 is also applicable for external monolithic walls (with mineral materials), although hygrothermal conditions must then be considered.

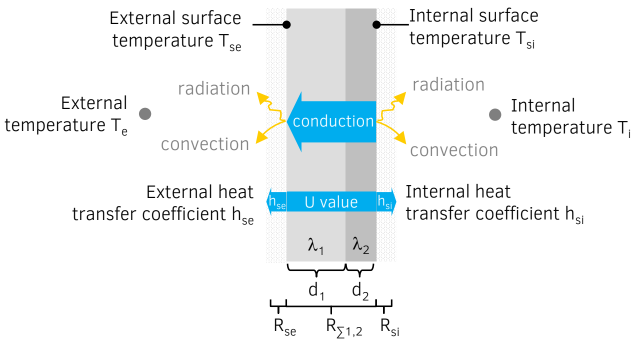

FIG. 2.4 Heat transmission parameters through a monolithic wall construction
The figure shows the physical parameters for heat transmission (U-value) by the thermal resistances (R) of each layer k and heat transfer from matter to air (hs).

The thermal resistance R [m²K/W] of opaque components depends on the thermal conductivity λ [W/m K] of the material, which is independent of material geometries, and the material thickness d [m], a dimension factor. The thicker a material, the higher gets the thermal resistance R. The thermal resistance R, as shown in [2-1], only considers conduction through a matter, not the heat transfer from solid matter to gaseous air.

TOC

$$R = \frac{d}{\lambda} \quad [(m^2 \cdot K)/W] \qquad [2\text{-}1]$$

$$U = \frac{1}{\sum R_k} \quad [W/(m^2 \cdot K)] \quad \textit{(for monolithic walls)} \qquad [2\text{-}2]$$

where $\sum R_k$ is the sum of thermal resistances of all layers and to the air (R_{se} and R_{si})

The U-value [2-2] considers this transition by including the thermal transfer resistances R_s [2-3], or its reciprocal values h_s [2-4] in the calculation, for which the heat flow q is related to the temperature difference between the surfaces $T_{se,\, si}$ and environment T_e or T_i.

$$R_s = \frac{1}{h_s} \quad [(m^2 \cdot K)/W] \qquad [2\text{-}3]$$

$$h_{si} = \frac{q}{(T_i - T_{si})}, \quad h_{se} = \frac{q}{(T_e - T_{se})} \quad [W/(m^2 \cdot K)] \qquad [2\text{-}4]$$

The U-values of components and systems, such as for windows (U_w-value [2-5]) or for curtain walls (U_{cw}-value [2-6]) also consider heat flow changes between material intersections and assemblies (expressed by heat bridges). Heat bridges are herein expressed by the linear heat transmission value ψ along edges and by possible point-related heat transmission value χ, according to the standard EN ISO 10077 (2017).

$$U_w = \frac{\sum A_g \cdot U_g + \sum A_f \cdot U_f + \sum l_g \cdot \psi_g}{\sum A_g + \sum A_f} \quad [W/(m^2 \cdot K)] \quad \textit{(for windows)} \qquad [2\text{-}5]$$

$$U_{cw} = \frac{\sum A_g \cdot U_g + \sum A_p \cdot U_p + \sum l_{TJ} \cdot \psi_{TJ}}{\sum A_g + \sum A_p} \quad [W/(m^2 \cdot K)] \quad \textit{(for curtain walls)} \qquad [2\text{-}6]$$

The earlier mentioned heat transfer coefficients (h) is simply said the sum of the convective and radiative share [2-7]:

$$h = h_r + h_c \quad [W/(m^2 \cdot K)] \tag{2-7}$$

According to EN ISO 6946 (2017), h_r and h_c calculations are simplified with predefined emissivity values, provided for the main heat flow directions (horizontal, vertical). h depends on the inclination (α°, flow direction of heat) and the wind velocity (v).

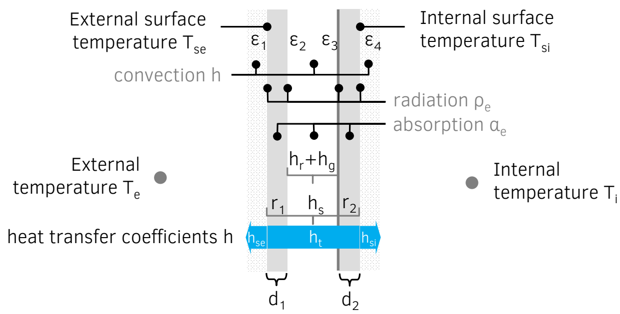

FIG. 2.5 Heat transmission parameters through glazing's.
The figure shows the physical parameters radiation and convection in the glazing system, and the importance of the heat transfer coefficients (h) for the total heat transmission (Ug-value).

The heat transfer coefficients (h) become particularly interesting at transparent components. The cavities in the glazing system create further thermal effects and introduce additional convection and radiation processes (Fig. 2.5), which are calculated according to standard EN 673 (2011). Applying formula [2-7] on glazing's cavities leads to the heat transfer coefficient of the gas cavity $h_{s,k}$ [2-8] for each layer *k*, which is the sum of the radiant value $h_{r,k}$ [2-9] and the heat transfer coefficient of the gas $h_{g,k}$ [2-10].

$$h_{s,k} = h_{r,k} + h_{g,k} \quad [W/(m^2 \cdot K)] \tag{2-8}$$

TOC

$$h_{r,k} = 4\sigma\left(\frac{1}{\varepsilon_{1,k}} + \frac{1}{\varepsilon_{2,k}} - 1\right)^{-1} \cdot T_{m,k}^3 \text{ [W/(m}^2\text{·K)]} \qquad [2\text{-}9]$$

where $T_{m,k}^3$ is the absolute median temperature in the gas cavity,

$\varepsilon_{1,k}, \varepsilon_{2,k}$ are the effective emissivity's of the glass surfaces.

$$h_{g,k} = Nu \cdot \frac{\lambda_k}{s_k} \quad [W/(m^2 \cdot K)] \qquad [2\text{-}10]$$

where λ_k is the thermal conductivity of the gas cavity,

s_k is the width of the cavity and Nu the Nusselt-Number.

The glass properties, such as reflectance ρ, transmission τ, and absorptance α of the glass panes, are also adding to the thermal quality. Furthermore, added coatings on a pane influence the emissivity ε of the respective surface.

According to the standard EN 673 (2011), the total thermal resistance for the glazing is then the sum of the heat transfer coefficients of all cavities (h_s), the thermal resistances of the glass panes and the heat transfer coefficients to the surfaces (h_{se}, h_{si}) [2-11][2-12].

$$\frac{1}{U} = \frac{1}{h_{se}} + \frac{1}{h_t} + \frac{1}{h_{si}} \; [W/(m^2 \cdot K)] \qquad [2\text{-}11]$$

$$R = \frac{1}{h_{se}} + \sum_1^{kn} \frac{1}{h_s} + \sum_1^{km} d_k \cdot R_k + \frac{1}{h_{si}} \quad [(m^2 \cdot K)/W] \qquad [2\text{-}12]$$

where d_k is thickness of each glass pane,

R_k is the thermal resistance of each glass pane,

the index *k* presents the type/number of layers,

the index *m* refers to material and the index *n* to gaseous layers

A further influence on the thermal transmission of transparent components is provided by shadings. Its influence depends on the thermal properties of the material and the air permeability P_e [2-13]. This factor describes the interspaces between the wall and the shading system and is an important value, as it affects the heat flow resulting in an adapted ΔR. P_e is calculated by EN 13125 (2001).

$$P_e = e_{tot} + 10_p \quad [mm] \tag{2-13}$$

where p_e is the surface area ratio of the interspaces (shading to wall) to shading area in [%],
e_{tot} is the sum of all interspace' widths within this area [2-14] (Fig. 2.6)

$$e_{tot} = \sum e_1 + e_2 + e_3 \quad [mm] \tag{2-14}$$

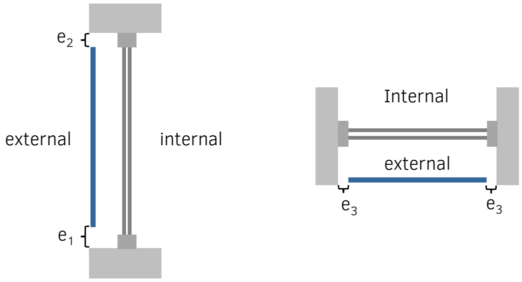

FIG. 2.6 Geometrical influence of shading gaps on the heat transmission
The interspaces e1 to e3 decide over the air permeability and thus, over the additional thermal resistance of the shading.

EN 13125 (2001) provides tables with standard values for the interspaces (e) and ΔR for various opening types. ΔR is needed to calculate the reduced thermal coefficient U_{ws} [2-15] considering a fully applied shading according to EN ISO 10077 (2017).

$$U_{ws} = \frac{1}{\frac{1}{U_w} + R} \quad [W/(m^2 \cdot K)] \tag{2-15}$$

TOC

2.2.3 Thermal mass

The influence of the thermal mass (inertia) or thermal storage capacity on the energetic quality of a building is another important passive design criteria that is particularly considered in the performance assessment for the summer period (Verbeke & Audenaert, 2018), but also influences the energetic quality in winter periods. Thermal storage capacity is used to reduce the risk of overheating, provided that heat dissipation is possible and thus, contributes to passive cooling strategies.

Thermal inertia depends on the dynamic thermal properties of a material depending on the time required for heat energy to pass through a material. Additionally, it also depends on the thermal energy supplied, which causes the temperature to rise: a system that requires a lot of energy per Kelvin temperature rise is more thermally inert. An important parameter of thermal inertia is its density. The higher this is, the higher the thermal storage capacity becomes.

The effectiveness of the thermal inertia in the built context depends also on the (natural) air ventilation strategy (to dissipate heat), as well as on surface area and temperature differences between material and surroundings.

As traditional solutions with high thermal inertia, dense materials can be named, such as concrete, natural stones or sandstone. For modern buildings, prefabricated curtain wall constructions, have become increasingly attractive. Such constructions are usually lightweight to save space and costs. But thus, both the advantages of passive storage of solar radiation in winter and thermal storage capacity in summer cannot be used with lightweight constructions. Recent developments try to compensate this the integration of latent storage materials or PCM (phase change materials). The storage density of latent storage materials is 7 to 10 times higher than the storage capacity of traditional heavy building materials due to possible temperature fluctuations (Mehling, 2002). They offer the possibility of providing higher thermal inertia with lower mass or space requirements, although the design of the proper PCM for an application is rather complex (Mavrigiannaki & Ampatzi, 2016). PCM enables also a dynamic behaviour by modulating actively the dissipation and storage of heat energy (Sun et al., 2019) (de Gracia & Cabeza, 2015).

Performance metrics

The thermal inertia is usually linked to the summer case assessment evaluating overheating risks with operative temperatures > 26°C. It depends, as well as the thermal insulation, also on the moisture content of materials that can take up water vapour. There are various performance models existing for the calculation of thermal inertia or the thermal storage capacity according to Balaras (1996).

The physical process describing thermal inertia is the ability to absorb, store and release heat with its surroundings. A few values are used in this context: thermal effusivity, thermal diffusivity, TTC value, effective heat capacity, etc. Only some of them are presented here.

An often-used value is the material-related value thermal effusivity (β-value) [2-16]. The thermal effusivity measures the ability to exchange thermal energy with the surroundings.

$$\beta = \sqrt{\left(\lambda \cdot \rho \cdot c_p\right)} \ [\mathrm{J/(m^2 \cdot K \cdot \sqrt{s})}] \qquad [2\text{-}16]$$

where c_p is the specific heat capacity, λ is the thermal conductivity, ρ is the density. The product of ρ and c_p is the volumetric heat capacity.

The influencing factors are the thermal conductivity λ [W/(mK)], the density ρ [kg/m³] and specific heat capacity c_p [J/[kg K)] of the material, as well as the heat penetration depth δ_{th} [mm]. The heat penetration depth δ_{th} defines the depth where temperature fluctuations occur in a certain time period. It indicates at which depth in the material the temperature variation amplitude balances out. The thermal storage capacity is calculated for a certain time period of 24h, considering also the thermal resistance values (R_{se}, R_{si}).

Another value, the thermal diffusivity α_{th} is a measure to analyse the flow speed of the heat energy in a material. It influences the penetration depth in a diurnal heat wave within a material. "*Materials with higher thermal diffusivity values can be more effective for cyclic heat storage at greater depth than materials with lower values*" (Balaras, 1996, p. 2).

The relevant factor for the thermal storage capacity is the TTCA value (Thermal Time Constant of an area) [2 17]. It is the product of the thermal resistance R_i and the heat capacity per unit area Q_{AI} of the material layer k, also depending on the heat penetration depth δ_{th}. Is the TTC high, the thermal inertia of a building envelope is high and the ability to store heat for longerr.

$$TTC_A = \sum \left(C_{A.k} \cdot R_k \right) \quad [2\text{-}17]$$

where $C_{A,k}$ is the heat capacity per unit area of each material layer. It is calculated as:

$$C_A = d \cdot \rho \cdot c_p \, ,$$

R_k is the thermal resistance of each layer, including also the layers to the air

Some countries offer in their national standards a simplified calculation for the thermal storage capacity, such as e.g. Switzerland in the standard SIA 380/1 (2016). Herein, the thermal storage capacity C_R per unit area of an building envelope can be taken as simplified value C_R/A_E from a table, divided into "*heavy*" (which is e.g. for CH 0.15 kWh/(m²K)), "*medium*" (in CH: 0.08 kWh/(m²K)) and "*light*" (in CH: 0.03 kWh/(m²K)) constructions. A general method to evaluate the dynamic behaviour of the thermal inertia is provided by the European standard EN ISO 13786 (2017).

2.2.4 Glazing

JJust as thermal insulation ranges from conventional to highly efficient quality, there is a similar variety for insulated glass units (IGUs). Their efficiency depends on the cavity attributes between the glass panes, the glass attributes and the coatings on the panes. The winter suitability is assessed by the U_g-value, which ranges between ~1.5 to 1.0 W/(m²K) for modern double glazing's and between ~0.9 to 0.5 W/(m²K) for triple glazing's. Triple glazing supports the highest thermal quality standard, the Passive House standard, and must achieve a very low U_g-value of less than 0.8 W/(m²K). The JRC Science report on the implementation progress of the Nearly Zero Energy Building standard in the EU countries indicates U_g-values between 1.5 to 0.6 W/(m²K) as implemented standard (D'Agostino et al., 2016).

In order to assess the thermal quality of glazing's, not only the Ug-value but also the solar heat gain (g-value) must be known. The g-value is the main indicator for the summer suitability of a glazing and indicates the proportion of (solar) energy that passes through the glazing. Decisive for the g-value are the number and property of glass panes, particularly their coating properties. Low-E coatings are used to transform glazing into thermo-protective or sun-protective systems: the metallic coatings influence the reflectance of the glass pane, and thus the absorptance or emissivity. The higher the reflectance of the glass, the more it becomes a highly effective solar control glass.

Low U_g-values and g-values do not only increase thermal efficiency in the respective period, but also decrease the daylight transmission (T_v). Particularly sun-protective glass is problematic, as it causes very low visible light transmission of around 0.17 to 0.40 in comparison to a normal triple glazing with about 0.82 to 0.50. This is one of the conflicts of highly efficient glazing's: the better the thermal quality, the worse is the visual quality. In the competition for maximum energy efficiency, however, thermal requirements are often given priority over visual aspects. Once defined, a compromise must be found for the visual comfort.

Another conflict also becomes apparent within the thermal quality goals of glazing's: while solar gains are desirable in cold periods and thermal losses shall be kept minimal, this is reversed in warm periods. Solar gains are then unwanted and thermal losses shall be maximized – particularly during cooler night-time (Fig. 2.7). The spectral properties of glass panes create hereby a specific problem: while short-wave, energy-intensive solar radiation can penetrate the glass panes, long-wave thermal radiation cannot pass through and is kept in the room, causing the so-called greenhouse effect. Trade-off approaches particularly between desired solar energy gains and avoidance of overheating are therefore a central topic in recent developments of adaptive transparent materials.

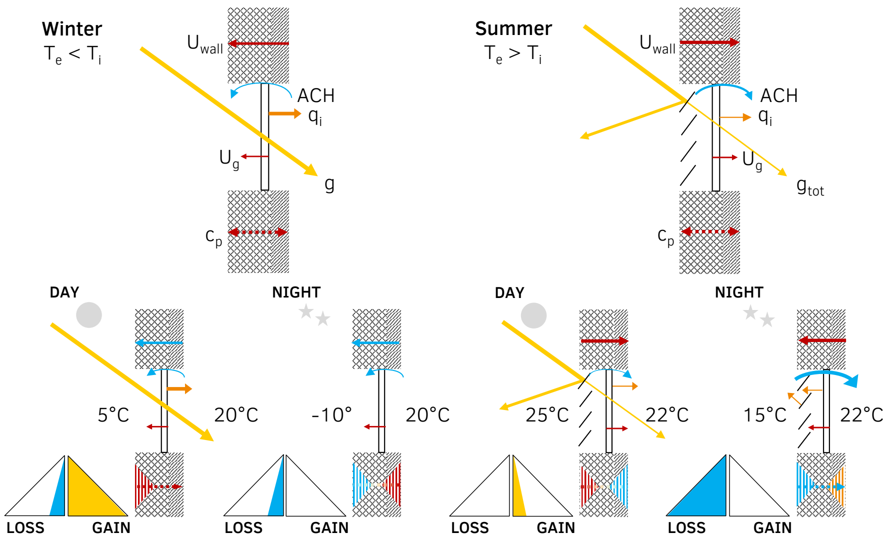

FIG. 2.7 Winter (left) and summer scenario (right) with indicators for thermal energy flow.
The conflict of glazing tasks is revealed on daily and seasonal scale: in winter, the goal is to maximize solar gains (g-value) and minimize thermal losses (U-value). In summer, solar gains (g-value, q_i-value) must be avoided and heat dissipation during night-time is required by night ventilation. During night, however, thermal inertia influences the heat dissipation in summer, and solar heat gains through walls in winter.

Performance metrics

The performance assessment for the heat transfer coefficient U_g-value has been already introduced in Section 2.2.2. Thus, the focus is laid on the solar characteristics of glazing's and its calculation. The relevant parameters to assess the solar characteristics are the reflectance ρ_e, transmittance τ_e as well as the absorptance α_e and thermal emittance ε of the surfaces. These characteristics usually do not behave adaptive, although in recent years a way has been found via switchable glazing's to change this and respond to the conflict.

The solar characteristics are assessed by determining the solar heat gains (g-value), which is defined in the EN 410 (2011) (Fig. 2.8).

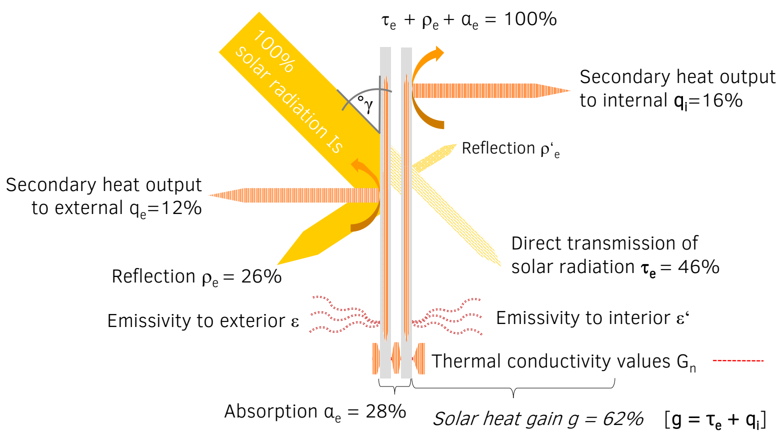

FIG. 2.8 Scheme for the solar heat gain factor, g-value.
The g-value is the sum of the direct solar transmission and the secondary heat output to the inner side of the glazing.

The g-value [2-18] describes the solar energy gain by the sum of the transmitted solar radiation (τ_e) and secondary heat output (q_i) (Fig. 2.8). The secondary heat output (q_i) captures the inward energy generated by long-wave IR radiation and convection, while τ_e considers the share of direct irradiation.

TOC

$$g = \tau_e + q_i \quad [-]$$ [2-18]

where τ_e is radiant transmission,
q_i is the secondary heat output towards inside.

The radiant transmission (τ_e) depends, like all spectral values, on the wavelength of the radiation, it would be correctly named $\tau_{e,(\lambda)}$. Standard values are provided by manufacturers or can be found in the standard EN 410 (2011). The secondary heat output (q_i) depends on the heat transfer coefficients (h_{si} and h_{se}), and the emissivity (ε) of the glass panes towards interior, with which the h_{si} is corrected. It furthermore depends on the absorptance (α_e) of all glass panes and heat transfer coefficient of the glazing. To determine the absorptance, the data about the reflectance (ρ) and transmission (τ) must be known [2-19] or the secondary heat output to both sides of the glazing [2-20].

$$\alpha_e = 1 - \left(\tau_e + \rho_e\right) \quad [-]$$ [2-19]

or: $$\alpha_e = q_i + q_e \quad [-]$$ [2-20]

The secondary heat output (q_i) is calculated differently according to the EN 410 (2011) depending on the various glass units, whether single, double or triple glazing.

For the calculation, the total energy flow through the layers, including the spectral parameters on both sides of each layer, must be considered (Fig. 2.9). Furthermore, in the standardized calculation, the solar radiation angle is assumed perpendicular to the panes. In reality, however, the spectral values depend on the incident angle of the solar radiation.

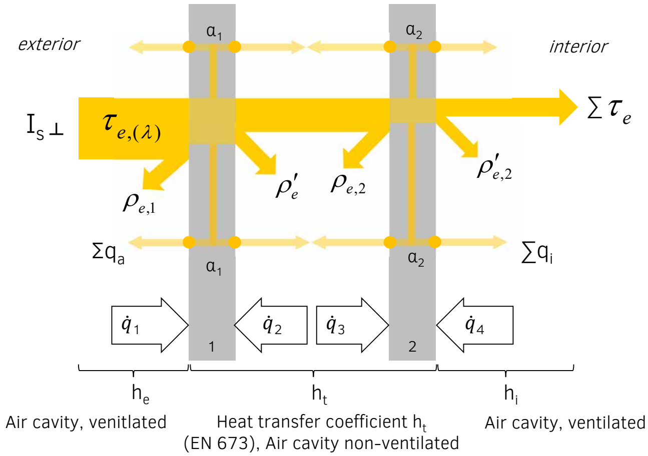

FIG. 2.9 Visualisation of the solar calculation model as provided in the standard EN 410:2011.
The figure shows the spectral parameters of both sides of each glass pane (backsides of solar irradiation path are marked with single quotation marks).

2.2.5 Shading systems

Shading systems have the major task to prevent solar irradiation through glazed components of the building envelope. By this, they are designed to be highly adaptive. However, they are also used as glare protection, which, as with glazing's, leads to conflicts between daylight availability and shading.

Shading systems also influence the aesthetic, visual, and thermal quality of buildings and must meet structural requirements. Conventional (additive) shading systems are considered and assessed as independent physical components. There are many design variations of shading systems, which can be generally divided into movable (e.g. slats) or fixed (e.g. Brise soleil) types. Moveable shading systems represent the majority of the implemented systems – and also the majority of the so-called "*adaptive façades*" according to the COST project '*Adaptive Façade Network*' (Aelenei et al., 2015) (cf. Chapter 3). Since their function is to block direct incident solar radiation, the local course of the sun must be known before planning to identify appropriate solutions (e.g. lateral geometry at structural solutions or horizontal louvres on the south, vertical louvres on the west and east).

Modern systems are normally controlled automatically (usually activated by either a certain solar radiation maximum or operative indoor temperature maximum) and thus the control strategies receive special attention.

The role and performance impact of shadings has been addressed in many publication, such as e.g. by van Hoof et al. (2016) investigating their effects on the cooling demand. The energetic performance related to the (static) geometry of shading elements have been investigated in the course of biomimetic analogy studies by Fiorito et al. (2016), Helfman Cohen et al. (2014) and Pesenti et al. (2015). Gosztonyi (2018) has analysed their kinetic typology and deducted design-oriented criteria supporting the definition of adaptive design criteria. Overall, the importance of a smart adaptiveness has been gradually increased in the last two decades - not least because the balance of cooling energy requirements and daylight availability is becoming more central.

Performance metrics

Just like the solar characteristics of glazing's, the shading quality is also determined by the solar heat gain: the total solar heat gain (g_{tot}-value) expresses the reduction of the incident solar radiation by the combination of glazing and shading systems and is calculated according to EN ISO 52022 (2017).

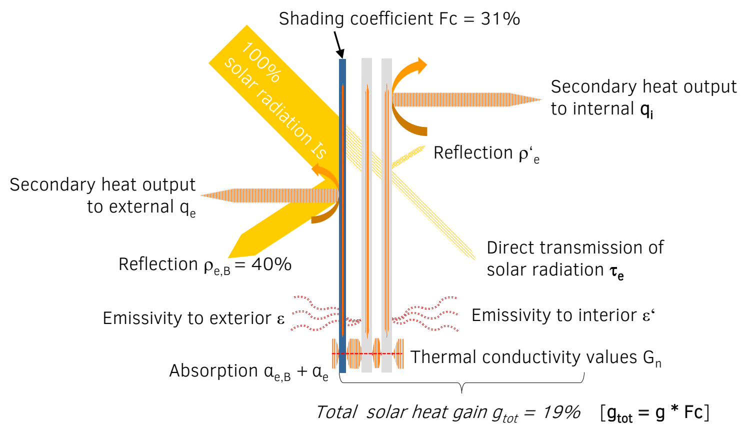

FIG. 2.10 Scheme for total solar heat gain factor, g_{tot}-Value.
The g_{tot}-value considers the g-value and the reduction by the shading (factor F_c).

TOC

A rather simple calculation of the g_{tot}-value is based on the shading factor F_c proposed by the European standard EN 14501 (2005) (Fig. 2.10). The shading factor F_c shows the ratio of the solar gain (g_{tot}) passing through the combination glazing and shading to the solar gain (g) passing through the glazing without shading [2-21]. The shading is in full (closed) position.

$$F_c = \frac{g_{tot}}{g} \quad [-] \tag{2-21}$$

The ratio, however, does not consider the thermo-physical processes on the shading system and between the shading and glazing.

These influences are included in the more precise g_{tot} value calculation of the standard EN 52022 (2017), which provides two procedures: the simplified calculation of part 1 provides formulas for the three installation positions and defines maximum deviations of +0.10 to -0.02 compared to the detailed calculation of part 3. For this g_{tot} calculation, various parameters about the glazing (U_g, g), the shading ($\rho_{e,B}$, $\tau_{e,B}$, $\alpha_{e,B}$) and predefined heat flow parameters (G_{ext}, G_1, G_2) are required. The different positions of the shading lead to three formulae, of which the external position is shown in [2-22].

$$g_{tot} = \tau_{e,B} \cdot g + \alpha_{e,B} \cdot \frac{G_{ext}}{G_2} + \tau_{e,B}\left(1-g\right) \cdot \frac{G_{ext}}{G_1} \quad [-] \text{ (for external shading)} \tag{2-22}$$

In part 3 of the standard EN 52022 (2017), the g_{tot} value is determined most accurately by numeric simulation. The detailed calculation considers the thermo-physical effects of the shading material and in the glazing system (Fig. 2.11), equal to the detailed glazing calculation in EN410. The solar intensity also relates to the specific geographic location and the orientation of the façade surface.

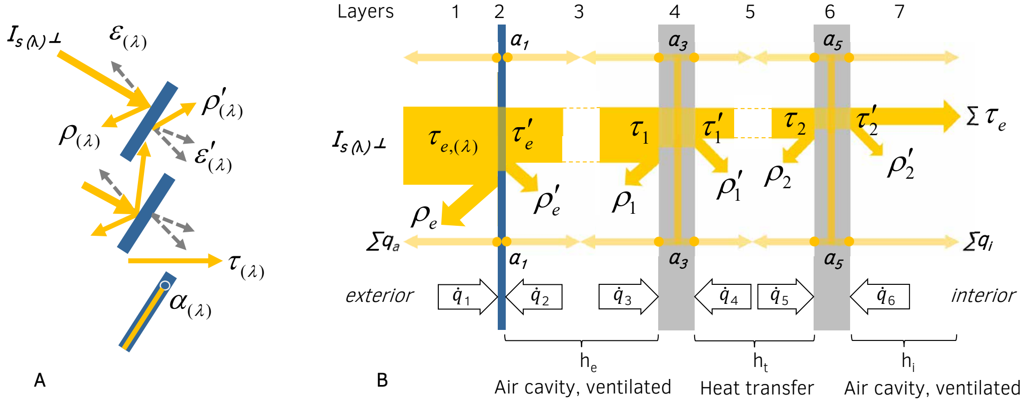

FIG. 2.11 Visualisation of standardized models for solar shading slats (A) and for the solar heat gain calculation (B). The scheme of A shows the spectral parameters of both sides of the slat material (the backside of the solar irradiation path is marked with single quotation mark) as provided in the standard EN 14500, and scheme B shows the spectral parameters for the solar transmission through the combination of shading and glazing as provided by the standard EN 52022-3:2017.

2.2.6 Air flow related measures

Air flow related measures include air tightness and air infiltration, controlled air exchange and air flow close to a surface (Fig. 2.12, A).

Air tightness of a building envelope is, like thermal insulation, a design strategy that is already considered in vernacular architecture. Attempts to achieve the lower air permeability have been made by stuffing cracks and joints with moss, straw or clay. Plaster claddings were added later as an effective option. Finally, windows have become tight and sealings were established after the oil crisis in the 1970s. Air tightness is now seen as a measure to control the air infiltration rate and avoid air leakages through the building envelope.

Air infiltration and air leakage depend on the air pressure and air temperature differences between inside and outside, as well as geometric effects (Younes et al., 2012). The shape of a building or of the cavity geometry in multi-skin façades is a critical design factor for air infiltration, as the example of the wind pressure profile on a building, the stack effect (thermal buoyancy, Fig. 2.12, B) or changes in the cross-section of a defined volume (Bernoulli effect) (Nave, 2005) show. The highest level of air tightness is defined by the Passive House standard with an air exchange rate of < 0.6 ACH at 50 Pa air pressure (iPHA, 2016).

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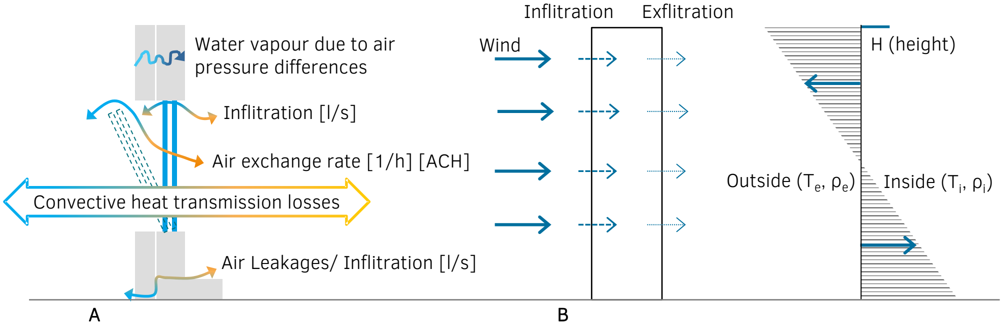

FIG. 2.12 Air exchange types through the building envelope.
Air exchange is either controlled by window opening, or uncontrolled by infiltration or air leakages in the construction (A). Two main influencing factors need to be considered: the thermal buoyance (stack effect)(B) and the wind pressure profile on the building surface as well as its distribution and exfiltration rate that determines the flow pattern and speed (C). (*Graphic A own work, graphics B and C are adapted from Younes et al., 2012, p. 271-272).*

Free air flow or intentional air exchange is linked to controlled natural or mechanical ventilation. Planning measures related to controlled air exchange through the building envelope become particularly relevant if the air is to be precooled or heated by double skin façades or the use of thermal buffer zones in front of façades (Gosztonyi et al., 2017). Ventilation is actively used, especially in summer, to discharge the charged thermal storage of walls and ceilings at night. The cooler air temperature at night times is then used to flush the building and dissipate heat. This strategy is a typical measures in Central Europe (Zimmermann & Glauser, 2003).

Both, air tightness and controlled air exchange are not only critical parameters to modulate the heat storage, but also to reduce construction damages due to moisture. It also impacts the level of harmful substances (from inside and outside), CO_2 level and generally fresh air quality. Thus, the air exchange rate influences the hygienic and thermal comfort quality likewise.

Measures involving controlled air exchange must be automatically adaptable, which is usually made possible by mechanical ventilation systems or by opening mechanisms of windows. A general recommendation of the fresh air exchange (ACH) is provided in most building codes, but control recommendations are rather generalized (Mavrogianni et al., 2014). There are no ready-made solutions with inherent adaptability of materials used for air exchange in buildings. However, there are some conceptual prototypes that use smart memory alloys or hydromorphic properties of cellulosic materials for this purpose.

Depending on the airflow velocity, the airflow along a surface can create a passive cooling effect by reducing the surface temperatures. That micro-region near the surface where air pressure and air velocity are affected is called the thermal boundary. Thermal boundary effects are influenced by the viscosity of the air flow forces close to the micro-structure of a material's surface. Basically, any heat transfer from matter to air is influenced by this effect. To characterize the thermal boundary layer, the temperatures of the surface and air, the kinematic viscosity and the freestream velocity are needed to calculate the effective thickness of the layer. It can be assumed that the thermal boundary layer influences the heat flow losses and air infiltration likewise. Intentional design measures to generate a thermal boundary layer are hardly found. An example that addresses this effect is found in a PhD thesis about black tents (Pfeifer, 2015): Pfeifer mentioned the creation of a thermal boundary effect due to the micro-structure and weaving of the goat-hair fabric of the tent. The effect depends on the moisture content of the fabric, the air temperature differences between inside and outside, and the tent shape and opening. Unintentionally such effects occur with any surface structures under certain circumstances. In nature, however, role models use geometries intentionally to generate thermal boundary layers, such as e.g. plants in particularly extreme climate regions.

Performance metrics

According to EN ISO 9972 (2015), the air permeability of a building envelope is based on the standardised parameter qa_{50} or n_{50}. This parameter describes an air exchange that occurs because of leakages (infiltration) through the building envelope at the defined pressure difference between inside and outside of 50 Pa. The units are 'air exchange rate per hour' [1/h] or [ACH], or [m^3 Air/h/m^2 floor area], and as infiltration rate [l/s].

There are different limits in each European country for natural and mechanical ventilation, and infiltration. For natural ventilation, the values for e.g. Germany are 3.0 [1/h] or 7.8 [$m^3/h/m^2$] and 3.0 [$m^3/h/m^2$] leakage rate per façade area. In Austria, for example, the infiltration rate is calculated by the value n_x for which simplified approaches are provided in the national building code (e.g. $n_{50} < 0.60 – n_x = 0.04$; $n_{50} > 1.50 – n_x = 0.11$).

The performance evaluation of air flow related measures are carried out in the field of aerodynamics and / or in building services engineering, where technical units or passive measures (openings, surface geometries) are dimensioned. Since this work focuses on passive measures and since aerodynamic analyses have to be excluded due to their complexity, the details of the performance evaluation will not be discussed in more detail.

2.2.7 Passive cooling at surface

Passive cooling measures at façade surfaces may be divided into those measures that 'passively' reduce heat uptake, such as highly reflective coatings or paints, and those that 'actively' deal with heat dissipation, such as evaporative cooling or use of conditioned air flows. In general, both cooling effects are not intentionally applied in building envelopes in Central Europe, because they require high heat transmission through the construction, which should be low in well insulated buildings.

The microclimate surrounding the outside of the façade plays an increasingly important role in passive cooling strategies. If the outer surface temperature of a façade could be lowered, this would have a positive effect on the thermal comfort despite the high insulation, as less warm air would enter the interior at the supply air openings.

The effect of radiative cooling by façades, a passive strategy, seems to be relatively small and strongly dependent on the environmental conditions and radiation-related factors (irradiation angle, wavelength, intensity). Ultra-white or 'cool' coatings and paints are nowadays mainly applied at flat roofs to reduce the solar absorption. These are designed with a high infrared emittance and high solar reflectance, which lowers the surface temperature by emitting long-wave radiation and reflecting short-wave radiation to a possible maximum (Hossain & Gu, 2016). Newer developments of this field achieve nearly 5°C below ambient temperature by applying photonic structures that increase the reflectance and emittance of the material without heating up (Raman et al., 2014) (Zhu et al., 2015). Cool paints are more effective on surfaces facing directly to the sky than on 90° declined façades. A less common type of radiant cooling is night radiation. The use of the long-wave infrared (IR) radiation is the main factor in this strategy: the objective is to emit energy to the clear night sky, an infrared atmospheric window between 8 – 13 µm, which causes highly effective emission if faced to the cold spot in the atmosphere. This effect depends on the surface attributes (orientation, area) and atmospheric conditions (Hossain & Gu, 2016).

The atmospheric conditions are best if the air is dry and unpolluted and the right angle to the cold spot can be reached. Thus, in urban or areas with polluted air, radiative cooling might not work effectively.

'*Active*' strategies for passive cooling need heat sinks and cooler sources, regulated air flows or components to change the enthalpy of the air. The major active strategy for passive cooling is air ventilation, but also evaporative cooling is included. Evaporative or adiabatic cooling uses water to change the relative humidity of the air.

This process depends on the respective air temperature and its capability to take on water (saturation of vapour content X in air [g/kg air]).

Evaporative cooling is one of the major measures of vernacular architecture in arid climate regions. In regards to façade-integrated solutions, exemplarily ceramic water cooling jars integrated in the window can be mentioned (Schiano-Phan, 2004).
Its effect is rather small in the tempered climate zone of Central Europe, as the necessary conditions (hot dry air) is not given. Modern applications are found in Southern Europe using actively wetted surfaces, such as e.g. the British pavilion of the Expo 1992 in Seville, Spain, designed by Grimshaw Architects (1992).

And finally, applied again in the hot dry climate mainly by vernacular architecture, the cooler soil or water temperature of ground water is utilized either to protect from overheating (passive direct coupling) or to enforce earth ducts through which air flows and cools down before it enters the building. This effect depends on the duct length, thickness of the walls and diameter of the ducts, as well as air speed and surface parameters of the wall. It needs long distances to work effectively, because air-based systems deal with a lower thermal conductivity as water-based systems.

Performance metrics

Evaporative cooling effects can be best evaluated by the psychrometric chart (also called Mollier or h-x diagram). This chart shows the enthalpy of air and respectively the thermodynamic changes of the stages of humid air when heated or cooled, humidified, or dehumidified (Fig. 2.13, left pictogram). Enthalpy is a state variable and describes the internal energy of air at a certain pressure and volume change. It depends on the air temperature (dry bulb temperature) and water content in the air at a given air pressure. The dependencies are illustrated in Figure 2.11. Such charts are used in building services technology to design HVAC systems, but are also used to evaluate passive design measures such as adiabatic cooling. The change potential is determined by the magnitudes of the states within limits defined by the physical process. If air is already warm and humid, adiabatic cooling would no longer work, because the saturation vapour content of air is almost reached.

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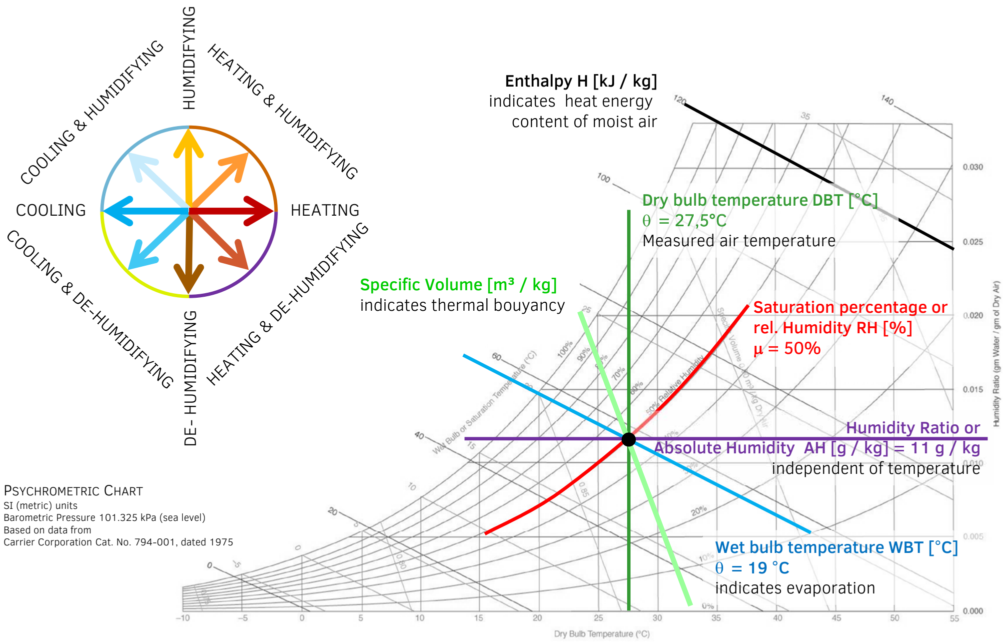


FIG. 2.13 The psychrometric chart indicates the thermodynamic states of humid air
The chart displays parameters such as air temperature, water content in air, relative humidity, the specific air volume and energy content (enthalpy H). It is used to identify the need for heating and cooling with or w/o (de-)humidifying to achieve thermal comfort targets *(Graphic on the upper left is reproduced from Figure 4.3 in Košir, 2019, p. 122).*

What is special is that such measures are applicable to short periods of time, e.g. within a day or hour. They must furthermore be adaptive and reversible.

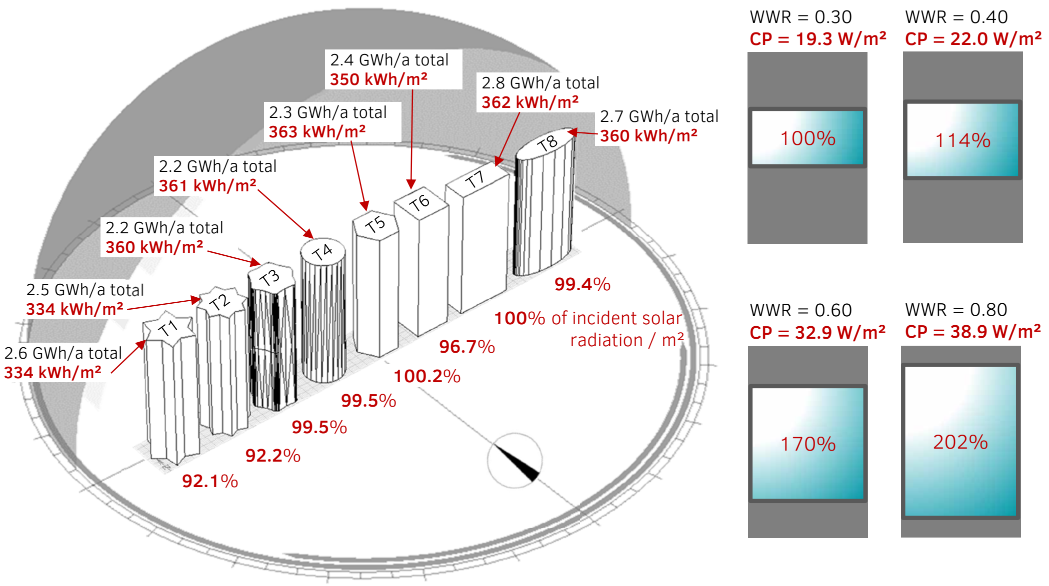
No specific, standardised performance evaluations have been found for such passive cooling strategies in the field of building technology. They are taken into account in the standardized assessments via material parameters for heat transfer, radiation or air flow rate. In specific projects, numerical or experimental tests on radiation emission or evaporation processes are carried out.

For active cooling strategies, dimensioning methods can be found in the field of building services engineering, such as for DEC (Desiccant Evaporative Cooling) devices. For these technical devices, the psychrometric diagram is again applied.

2.2.8 Building form and façade geometry

Optimising the building form to reduce the solar radiation area or to create a useful thermal boundary layer is a supporting strategy for controlling thermal energy flows through the building envelope. Sensitive site design, including self-shadowing forms and use of shading from neighbouring objects, as well as well-designed orientation of glazing to the sun's path are design strategies of this measure. On the façade level, optimising surface geometry can influence the surrounding microclimate and support passive cooling strategies. The following considerations characterise these optimisation options:

- The A_S/I_S ratio indicates the relation of the surface area of the façade to its direct solar exposure at a specific time. The total solar energy impact (kWh/m²) on the respective surface is influenced by the form (Fig. 2.14, left),
- orientation and inclination of façade elements and self-shading structures of the building envelope, i.e. fixed shading elements or offsets, in order to increase the self-shading share,
- The WWR or WFR ratio (window-to-wall/window-to-floor ratio) of transparent elements is directly linked to the energy performance levels, i.e. the needed cooling power (CP) (Fig. 2.14, right).



GWh/a total:	total absorbed radiation per year (including reflected radiation of surfaces)	WWR:	window-to-wall ratio
kWh/m²:	incident direct solar radiation on surface per square meter	CP:	cooling power

FIG. 2.14 Energetic influence of the As/Is ratio and the WWR ratio as a function of geometric shapes.
The A_s/I_s ratio of various building shapes on the left shows, starting from the rectangular shape T7 (100 %) that the direct irradiation (given as kWh/m²) decreases for polygonal shapes if they are partly self-shaded (cf. T1 and T2). However, the total absorbed solar energy per year (given as GWh/a) is higher for the polygonal shapes because the proportion of reflection between the surfaces increases. On the right, the schemes show that with increasing WWR ratio, the cooling power CP also increases massively (assumptions: unshaded, south-facing, office room with a volume of 40m³, U_g = 0.8 W/(m²K), 1 person with standard operation).

The main interest in geometric design measures in the façade lies in optimising the solar radiation surface. This measure is defined in the early design phase of planning and is not considered adaptive. In Central Europe, shape-optimising measures are also only considered for the winter case in order to reduce heat loss by a balanced surface/volume ratio (A_s/V). The same objective applies to the window-to-wall ratio, which relies on larger glass areas in the south than in the other orientations to gain solar heat.

In summer, this objective is disadvantageous, as solar gains are to be avoided. Figure 2.14 shows how surface variations and window-to-wall ratio variations affect solar gain and, as a result, cooling energy in summer.

The conflict of either gaining or avoiding solar gains can be resolved by adjusting the surface form (or by adding adaptive elements, such as shading devices). Specifically designed façades that aim to solve this conflict are for example folded façades, such as those of the Endesa Pavilion in Barcelona (IAAC, 2011) or the office building Energy Base in Vienna (Rauhs et al., 2009). In both cases, vertically folded façades allow optimal use of solar gains in winter and avoidance of direct solar irradiation in summer. Thus, the need for shading devices is redundant.

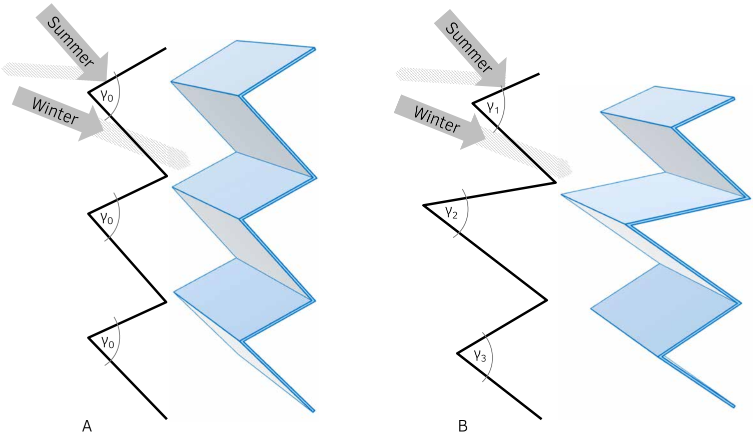


FIG. 2.15 Schemes of folded façades as a solution to the conflict in using solar radiation in summer and winter.
Scheme A (left) shows the regular folded version as applied e.g. to the Energybase building in Vienna (Rauhs et al., 2009). Scheme B (right) shows an irregular folded façade in its principle similar to the Endesa Pavilion (IAAC, 2011). Both versions block solar radiation in summer and allow transmission in winter.

A dynamic adaptivity of the shape is currently being explored e.g. in studies by Reichert et al.(2015), Pesenti et al. (2015) or Fiorito et al. (2016) by using SMA (shape memory alloys) to change the solar exposure area.

Performance metrics

The geometric parameters thickness (d, [m]), length (l, [m]), area (A, [m²]), volume (V, [m³]) or number of layers or panes (k, [-]) are used as parameters in all measures, but there is no standard for optimising the shapes. This is more or less considered in the design process. The role of geometry for the thermal efficiency is continuously evaluated and discussed in this work (cf. Chapter 4).

2.2.9 Conclusion

Summarizing the functions and objectives of the identified design measures for façades following can be stated:

- The task of reducing heat transfer through the building envelope makes thermal insulation the key indicator for the performance assessments of buildings in Central Europe. However, with the increase in insulation quality and warmer climate periods, this task also bears potential disadvantages. The higher the efficiency of the thermal insulation, the longer the gained heat is kept inside. This circumstance makes thermal insulation a design measure that is indispensable for the winter but would have to be more flexible in the summer - especially at night.

- The use of thermal storage capacity is particularly important in summer when lower temperatures are to be stored during night ventilation and overheating during the day can thus be delayed. However, this effect is hardly performed by façades, especially curtain walls, as they possess only little thermal mass, or the wall materials are heated up strongly during daytime. The use of intelligent storage materials in curtain walls, such as phase change materials, shows potential for delaying temperature absorption but also limits in its efficiency (Wüest et al., 2020).

- Solar radiation, especially short-wave radiation passing through transparent components, is highly relevant in both cold and warm seasons, albeit in opposite ways. Glazing's are faced with a seemingly insoluble conflict, as they must adapt to the needs in the warm and cold seasons and, in parallel, deal with a deterioration in visual quality. Switchable glazing attempts to resolve this conflict by modifying its transmission properties but causes another conflict as it affects the colour quality of daylight. The influence of glazing's ultimately depends on the window-to-wall ratio and orientation, but the consideration of these criteria is increasingly neglected in modern buildings. Glazing's and its properties are thus rather challenging façade components whose efficiency depends on their adaptability.

- Shadings are also aiming at the modification of solar irradiation and are per se adaptive. Many design solutions are available on the market, for which the control and automation optimization is the main current challenge, also in respect to the user perception.

- Heat loss is also related to unwanted air infiltration and air exchange. Therefore, a controlled heat flow through the building envelope is a declared goal, which must be considered equally throughout the year. While air tightness is a static task, controlled ventilation through openings has a highly dynamic goal that must behave almost more adaptive than shading. A thermally modifying integration of the air flow in the façade construction is enabled by in multi-layered façade constructions (double skin façades). The pre-tempered air cavity acts then as a heat buffer. This can contribute to reducing the heating energy demand. Adaptability is also possible, although the control mechanisms have more to do with fresh air supply than temperature control.

- Passive cooling strategies can be implemented due to certain surface properties and geometries by influencing natural air flow along the surface. Furthermore, these surface attributes can also modify incident solar radiation for the same purpose, as shown by e.g. higher reflection of 'cool' paints (although these do not cool but reduce the absorption of thermal radiation). Optical and geometric properties of the surface also play a role in heat dissipation by thermal emission. And the surface (and its direct surroundings) can be ‘actively’ cooled by evaporation effects of the surface. Many of these approaches have certain limits to their effectiveness due to local conditions (dry climate, clear skies) or design constraints of the building (exposed surface, thermally insulated outer skin). This must be considered when adaptive approaches are considered.

- Finally, the shape of a building, its positioning in the local environment and the degree of transparency of the skin influence the thermal quality. None of these factors are generally considered adaptable, except of few innovative materials that can e.g. adapt the transparency share (switchable glazing’s) or the shape (shape memory effects).

From this conclusion and the inspection of the performance assessment procedures, the main functional principles and their sub-principles are derived for each design measure (Fig. 2.16).

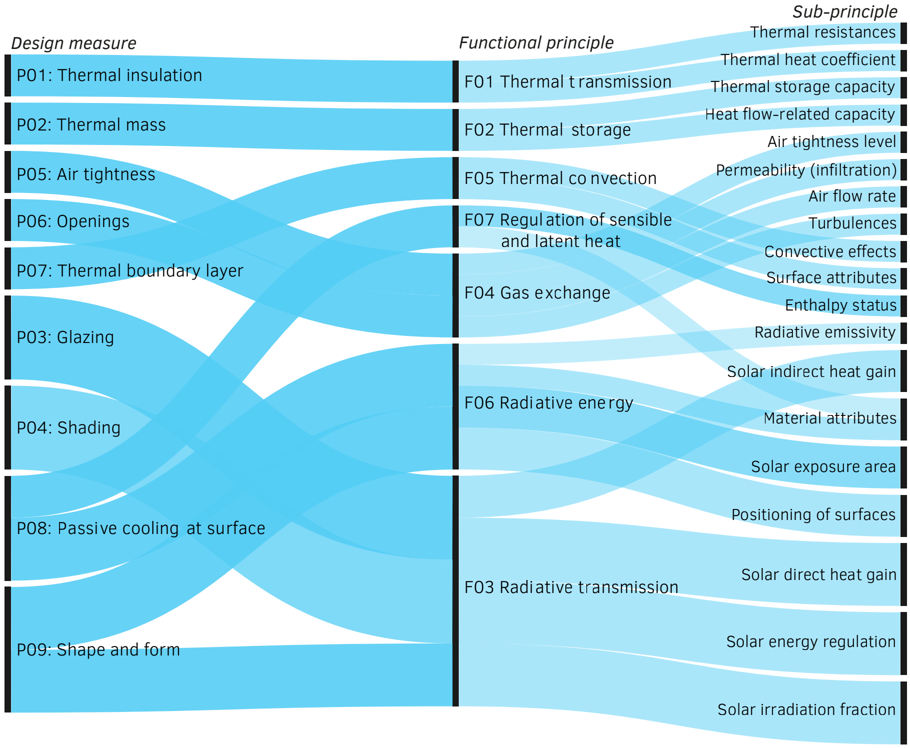


FIG. 2.16 Classification of functional principles of the design measures.

The list of Table 2.2 presents this information as a systematic classification list showing following items: for each passive design measure (ID class: P0x), the most important design components (ID Sub-Class: P0x.x) are presented. The main functional principle of each design measure (ID: F0x) is added as rows, and their functional purposes (ID: F08.x) as well as assumed influence on the cooling goal are added as additional columns. The assumptions are based on the findings in the literature review.

This table serves as a basis for the development of a parametric list that provides a systematic structure for the search and evaluation process. A complete list of all identified parameters is provided in Appendix 3-2.

TABLE 2.2 List of thermal performance-related design measures associated with assumed influences on cooling. The sub-classes (ID: P0x.x) describe main design factors of each measure (ID: P0x). The blue fields highlight possible search fields. The functional principles (ID: F0x) provide additional information about the physical process.

ID	Class	ID	Sub-Class	Functional purpose [F08]	Assumed influence to cooling target
P01	Thermal insulation	P01.1	System design	*F08.1 Heat loss prevention, F08.2 Thermal energy control*	Conflict measure: designed for cold periods, no supportive function for cooling
		P01.2	Material properties		
		P01.3	Hygrothermal material properties		
F01	**Thermal transmission**				
P02	Thermal mass	P02.1	System design	*F08.2 Thermal energy control F08.5 Overheating prevention*	Supportive measure: seldom applied in façades (except PCM)
		P02.2	Material properties		
F02	**Thermal storage**				
P03	Glazing	P03.1	System design	*F08.2 Thermal energy control, F08.3 Solar gain*	Conflict measure: must be supplemented by shading, depends on size
		P03.2	Material properties		
F03	**Radiative transmission**				
P04	Shading	P04.1	System design	*F08.5 Overheating prevention*	Established measure: designed for overheating prevention
		P04.2	Material properties		
F03	**Radiative transmission**				
P05	Air tightness	P05.1	System design	*F08.1 Heat loss prevention*	Minor relevance
		P05.2	Material properties		
F04	**Gas exchange**				
P06	Openings	P06.1	System design	*F08.2 Thermal energy control, F08.4 Heat dissipation, F08.6 Energy exchange*	Established measure: relevant for natural ventilation strategies
F04	**Gas exchange**				
P07	Thermal boundary layer	P07.1	System design	*F08.2 Thermal energy control, F08.4 Heat dissipation*	Supportive measure?: unclear role for cooling
		P07.2	Surface properties		
F05	**Thermal convection**				
P08	Passive cooling at surface	P08.1	Radiative cooling – system design	*F08.4 Heat dissipation, F08.5 Overheating prevention, F08.6 Energy exchange*	Supportive measure: designed for specific locations (night radiation)
		P08.2	Radiative cooling – material properties		
		P08.3	Evaporative cooling – system design		Supportive measure: designed for specific locations (arid climate)
		P08.4	Evaporative cooling – material properties		
F06 **F07**	**Radiative energy** **Regulation of sensible and latent heat**				
P09.	Shape and form	P09.1	Solar exposure - system design	*F08.3 Solar gain F08.5 Overheating prevention*	Supportive measure: designed for specific locations (solar exposure, orientation, etc)
		P09.2	Transparency share / design		
F03 **F06**	**Radiative transmission** **Radiative energy**				

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2.3 Evaluation of design measures

In the following, some aspects of the reviewed design measures of Table 2.2 are examined more in detail through qualitative and quantitative evaluations to select suitable search fields for the further investigation.

2.3.1 Methodology

Three evaluation rounds are established for the selection of the search fields, using a qualitative procedure based on weighting factors and a quantitative parameter analysis. The qualitative evaluation is done by a personal estimation based on the findings in the review. This approach supports the identification of the needed adaptability and of the role of selected parameters.

1. In a first round, the evaluation focuses on the thermal adaptability of the design measures. Three criteria are defined for which a weighting indicates the current and potential need for adaptability of the design measures. The result selects potential search fields for thermal adaptability (Section 2.3.2).

2. In a second round, the influence of various physical parameters on a few selected functional goals, which are important for summer behaviour, is evaluated. The physical parameters were identified as important performance indicators in the literature review. This evaluation applies again a weighting factor to indicate how often each parameter is considered for the respective goal (Section 2.3.3). The aim is to identify the likely role of the parameters in the potential search fields).

3. For the assumed conflicting objectives of some design measures (cf. last column in Table 2.2), quantitative parameter studies are carried out. The intention is to understand the impact of changing geometric and physical parameters for the selected design measure (Section 2.3.4).

2.3.2 Adaptability potential

The intention of the assessment, as shown in Table 2.3, is to evaluate all design measures regarding their assumed current and potential adaptability to prevent overheating in summer. The criteria to be evaluate are as following:

A Short-term adaptability, for which 'short-term' is defined < 1 day,
B Degree of embedment of the adaptation in the façade system,
C Degree of functional contribution to support the thermal performance targets in summer.

For the evaluation, a simplified weighting method that provides only estimated tendencies is applied. It was submitted to a review by colleagues and selected experts in the field of energy-efficient building design.

- The weighting is divided into four levels:
  - 0: not applicable,
  - 1: low or neglectable,
  - 3: considerable,
  - 5: critical.

The values are subject to a certain uncertainty due to the qualitative assessment approach. The weighting factor (last column) indicates the considered share of an assumed maximum number of points per design measure, which is defined as five points.

The lower two rows in Table 2.3 show the assumed adaptabilities of each design measure: the first row presents the '*current adaptability*' to support cooling tasks in summer and the second row the '*potential need for adaptability*' of the design measures. The numbers present the mean values of the weighted results of criteria A and C.

Those results, which are marked with 'x' are considered potential search fields, measures marked with 'o' are considered established solutions. The threshold value for potential search field is set to > 10. Measures marked with '(x)' already display adaptive behaviour and are not classified as urgent for solution seeking.

TABLE 2.3 Qualitative evaluation of the passive façade design measures.
The current and potential role for adaptability, embedment level in the façade construction and functional contribution to support the thermal performance targets in summer are weighted. The weighting factors are set as: 0: not applicable, 1: low or neglectable, 3: considerable, 5: critical. The mark 'x' indicates the potential search fields, the mark 'o' indicates established solutions, and mark '(x)' indicates search fields with lower indication for solution seeking.

Criteria		P01 Thermal insulation	P02 Thermal storage	P03 Glazing	P04 Shading	P05 Air tightness	P06 Air exchange	P07 Air flow /surfaces	P08 Passive cooling	P09 Form /shape	Weighting factor [%]
A. Short-term adaptability*	actual	1	1	5	5	0	5	1	1	0	18
	potential	5	3	5	5	3	5	3	5	0	32
B. Embedment of adaptation	actual	0	3	3	5	0	5	1	1	0	17
	potential	5	5	5	5	0	5	3	5	1	32
C. Functional contribution to cooling°	actual	0	3	3	5	0	5	0	1	3	19
	potential	5	5	5	5	3	5	3	5	3	37
Assumed current adaptability° in %		3	10	21	26	0	26	3	5	8	
			o	o	o		o				
Assumed need for adaptability° in %		14	11	14	14	8	14	8	14	4	
		x	(x)	(x)	(x)		(x)		x		

** < day*
° Support of thermal performance targets in summer

The table shows that shading devices (P04) and air exchange (openings for natural ventilation, P06) are considered established design measures in both categories '*current adaptability*' and '*need for adaptability*' for cooling contribution. The second category indicates in this context optimization needs in the control strategies. In this work, due to the established adaptability, their targets are considered but they are not chosen as search fields.

Glazing's (P03) can only be assessed if new developments are included: switchable glazing's target at dynamic adjustments of the shading function. Thus, they fulfil a dynamic adaptation of light transmission while maintaining the view to the outside. This embedment of adaptive functions in transparent materials is a relatively recent development. Certain technologies are now established on the market, so this measure is not considered urgent for the definition as search field.

Air tightness (P05) is linked to the function of ‘heat loss prevention’ and therefore not considered for cooling purposes. Furthermore, it is also not considered to function adaptive. ‘Shape and form’ (P09), i.e. geometric adjustments to the overall building shape are not considered desirable and feasible, but shape-changing behaviour of individual façade elements may inherit some potential (cf. P04).

Thermal mass (P02) behaves adaptive from a physical point of view, but not necessarily within the building envelope. Thermal storage capacity is more often considered in other building parts (interior walls, floors, etc.), as the effect conflicts with thermal insulation being an integrated function of the building envelope. However, with the use of smart material, such as PCM, the potential of façade-integrated thermal storage regains attention. The reason why it is not chosen as search field, even though it shows potential, is that it is more material related with assumed little connection to design tasks.

The same is assumed for the regulation of air flow at surfaces (P07), which has received little attention in design developments so far and is only considered as heat transfer coefficients and resistances to air. It also promises some potential to influence the thermal performance, particularly as a passive cooling supportive measure. From the literature review, however, it can be assumed that this potential is limited due to the indirect contribution (again, conflict with thermal insulation).

Passive cooling strategies (P08) show no adaptability in current projects but are applied as static measures, such as cool paints on roofs. Its potential for the vertical façades has been hardly tested in modern projects. However, since it is known that colour (more precisely its reflectance) indirectly influences thermal conductivity, such measure has been used for a long time already. Passive cooling strategies are found in vernacular buildings located in arid climatic regions – evaporative cooling should also be mentioned here as another measure in the group. The potential for such passive cooling of modern buildings is unclear, but a similar conclusion as for P07 can be drawn. A particular passive cooling strategy is night radiation, which is recently applied as a supportive measure in combination with solar thermal systems, mounted on roofs. The possibility of overcoming the barrier of thermal insulation through such a combination makes this group a potential field of search.

A special focus of this investigation is laid on the potential for seemingly static measures that should become adaptable due to its conflicting objectives for summer and winter: thermal insulation (P01) is not adaptive but plays a crucial role in the thermal behaviour of the building throughout the year. Thus, potential for adaptation is sought. To understand the dependencies of its geometric and physical attributes, parameter studies are conducted in Section 2.3.4.

2.3.3 Influences of parameters

To understand the dependencies between geometric and material-physical parameters, another qualitative assessment is done, using the same weighting method as for the first evaluation. The aim is to identify the significance of the parameters for the respective functional principle of the design measure. It shall be assessed how often these parameters are considered and how important they are in the performance assessments.

From the list of the design measures in Table 2.2, only those functional principles are chosen which are assumed to contribute to the summer performance (cf. Table 2.2, ID: Fx):

- thermal transmission (F01), thermal storage (capacity) (F02), radiative transmission (F03), gas exchange/ air flow rate (F04.3), thermal convection (F05), radiative energy/ radiative emission (F06.1), solar exposure of surfaces (F06.2). positioning of surfaces to the sun (F06.3), regulation of sensible and latent heat/ evaporation (F7.1).

For better reading, the collected parameters of the assessment procedures are clustered into following groups:

A heat flow,
B material-related properties,
C geometric properties,
D climate and time.

Table 2.4 shows the parameters in the rows and the functional principles in the columns. Two factors are defined in the evaluation:

- The weighting factor in the right column of the table indicates the tendency to the overall use of the respective parameter, i.e. how much it is considered in total, assuming that 5 is the maximum rating and the maximum count is 50.

- The distribution factor presents the share of the design critical group '*material-related parameters*' and '*geometric parameters*' to visualize their assumed role in each principle. The distribution factor is a mean value of the material-related group B and the geometry-related group C. 50% is defined as threshold value where a parameter group is considered essential for the performance of the measure.

TABLE 2.4 Qualitative evaluation of the role of parameters in the assessment procedures for the selected design measures.
The weighting ranges from: empty field: not applicable, 1: low or neglectable, 3: considerable and 5: critical.
Two factors are shown: the weighting factor shows the intensity of occurrence of each parameter (how often a parameter is applied). The distribution factor on the bottom of the table presents the share of the design critical group pf parameters: 'material-related parameters' and 'geometry-related parameters' for each design measure
.

	Parameters		ID	F01 Thermal transmission	F02 Thermal storage	F03 Radiative transmission	F04.3 Air flow rate	F05 Thermal convection	F06.1 Radiative emission	F06.2 Solar exposure area	F06.3 Positioning of surfaces	F07.1 Evaporation	Weighting factor 1 [%]
A. heat flow	conduction	ϕ	W	5	5	3		1	1			1	42
	convection	ϕ	W	3	1	3	5	5	1			5	48
	radiation	ϕ	W	1	1	5		1	5	5	5	1	50
	mass transport air	ACH	l/s				5	3				3	22
	mass transfer material	k	-	1	3			3				1	26
B. material-related properties	thermal conductivity	λ	W/mK	5	5	3		1	3			1	46
	density	ρ	kg/m³	3	5	1		1	1				32
	specific heat capacity	cp	J/(kg K)	3	5	1		1	3				32
	kinematic viscosity	v	kg/(m s)	1	3	1		5	3	1		1	32
	heat penetration depth	δth	mm		5			1	1			1	22
	permeability	P	cm³cm/cm² s Pa				5	1				3	18
	emissivity	ε	-	3	1	3		5	5	1			38
	reflectivity	ρ	-			5			3	1			18
	absorptivity	α	-		5	5		5	3	1		1	40
	transmissivity	τ	-			5					5		20
	water vapour diffusivity	η	-	1	1							3	20
C. geometric properties	Surface area	A	m²	3	3	5	3	5	5	5	5	5	88
	Volume	V	m³	1	1		3	1					14
	mass	m	kg	3	3	1							20
	length	l	m	5		1	5	3		3	3		40
	thickness	d	m	5	5	5	3	1					48
	angles	x,y	° degree			3		3	5	5	5		42
	layer	k	-	5	3	5	1	1	1				38
	air cavity width	s_k	mm	3	1	5	3	3	3			1	44
D. climate and time	temperature difference	ΔT	K	5	5	3	5	3	5			3	64
	enthalpy	H	kJ/kg air	1	1			1				5	26
	solar radiation	Is	W/m²	1	1	5		5	3	5	5	1	54
	air pressure	p	Pa				5	5				1	24
	velocity	v	m/s				5	5	1			3	30
	time / time lag	t, ϕ	s	3	5	1		1	1			1	34

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TOC

TABLE 2.4 Qualitative evaluation of the role of parameters in the assessment procedures for the selected design measures.
The weighting ranges from: empty field: not applicable, 1: low or neglectable, 3: considerable and 5: critical.
Two factors are shown: the weighting factor shows the intensity of occurrence of each parameter (how often a parameter is applied). The distribution factor on the bottom of the table presents the share of the design critical group pf parameters: 'material-related parameters' and 'geometry-related parameters' for each design measure
.

	F01	F02	F03	F04.3	F05	F06.1	F06.2	F06.3	F07.1
Distribution factor [%]	Thermal transmission	Thermal storage	Radiative transmission	Air flow rate	Thermal convection	Radiative emission	Solar exposure area	Positioning of surfaces	Evaporation
Material-related parameters	39	65	49	22	54	61	24	28	62
Geometry-related parameters	61	35	51	78	46	39	76	72	38

The table shows that solar radiation and thermal temperature differences are considered in almost all calculations for the selected functional principles. The parameters radiant emissivity and thermal absorptivity play an equally important role in the physical processes of transparent and opaque components and are considered more frequently in the assessments than reflectivity and transmissivity. Thermal conductivity also appears in most assessments of the principles.

As for the geometric characteristics, surface area is considered important in all principles' assessments. Furthermore, length and thickness, as well as layers and cavity widths are considered in the assessment approaches of many principles.

The weighting of the two groups 'material-related properties' and 'geometric properties' on the bottom of Table 2.4 shows that geometry-related parameters play a decisive role for thermal transmission, radiative transmission (through glazing), air exchange processes and geometry-related principles (shapes).

2.3.4 Conflicting objectives

As mentioned in Section 2.3.2, one of the rigid design measures, thermal insulation, has a particularly difficult objective, as it would have to reverse its main function depending on the season or even day. Therefore, adaptability might be beneficial for this measure. While this conflict is already addressed for the other conflict measure, glazing's, by smart glazing's, there are few or no approaches to solve the conflict for thermal insulation.

To understand the thermal behaviour of thermal insulation and the role of geometry and material properties, parameter studies are performed. The intention is to understand the performance of current insulation materials and to identify those parameters that could possibly influence adaptive behaviour.

Shading systems (P04) and air exchange (P06) might also generate conflicting objectives: the conflict of shading systems occurs between thermal and visual requirements, and in the case of air exchange the conflict lies in the different requirements for hygienic and thermal comfort. The analysis focuses on thermal processes only, and, for reasons of necessary distinction of the scope, does not consider these aspects.

Parameter studies on thermal insulation

Currently, conventional thermal insulation requires larger thicknesses to achieve the needed U-values. These thicknesses are increasing with sustainable (natural) insulation materials and decreasing with highly efficient materials. In general, developments aim to reduce the thickness while increasing the insulating properties.

If thermal insulation is to be able to dynamically regulate the heat flow, the material must be able to *reduce* or *increase* its thermal conductivity. For example, in winter this should be reduced over the whole day, in summer it should be increased, particularly at night. Adaptivity in this context will probably have to deal with the variability of the material thickness or system arrangement, if known materials are used.

Questions arise such as which insulation material properties with which material thickness currently achieve the highest efficiency standard, the Passive House standard? And how do natural, sustainable insulation materials perform in this regard? To what extend does the material thickness influence the performance? These questions are considered in the following parameter studies.

The principle of thermal insulation is to slow down the energy flow through the wall construction to minimize heat losses. The physical factor behind this effect, the thermal conduction, is influenced by the thermal conductivity (λ) of the material and the flow path (d) through the material [2-23]. The lower the thermal conductivity of a material, the better it insulates. While the thermal conductivity of a material itself is independent of dimensions, the overall thermal transmittance or U-value [2-24] of a building envelope is dimension- and composition-depending.

Based on these facts, a simple base case presenting a massive brick wall is composed (Fig. 2.17) and its thermal resistance, respectively its thermal transmittance, are calculated: the base case is composed of a 1 mm thin plaster on both sides, and a 18 cm thick brick wall.

$$R_n = \frac{d_k}{\lambda_k} \quad [(m^2 \cdot K)/W] \qquad [2\text{-}23]$$

$$U = \frac{1}{R_{se} + \sum R_n + R_{si}} \quad [W/(m^2 \cdot K)] \qquad [2\text{-}24]$$

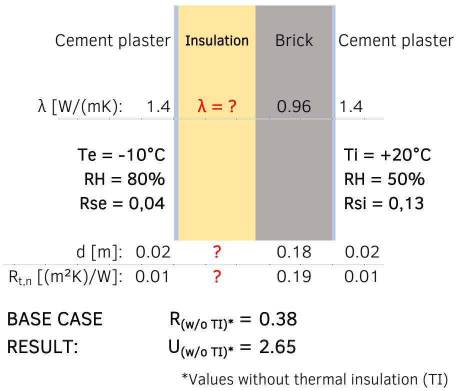


FIG. 2.17 'Base case' of a plastered brick wall. The construction of the 'base case' is 0,22 m thick without thermal insulation and has an U-value of 2.65 W/(m²K).

Thermal insulation parameters:
Vacuum insulation panels (VIP): λ = 0.007 W/(mK), ρ = ~180 kg/m³
Aerogel (A): λ = 0.014 W/(mK), ρ = ~100 kg/m³
Polyurethane (PUR): λ = 0.024 W/(mK), ρ = ~35-100 kg/m³
Rock wool (RW): λ = 0.034 W/(mK), ρ = ~40-100 kg/m³
Cellulose (C): λ = 0.040 W/(mK), ρ = ~50-80 kg/m³
Cork: λ = 0.060 W/(mK), ρ = ~170-210 kg/m³

Six commercially available insulation materials are selected for the study: Vacuum insulation panels (VIP), Aerogel panels (A), Polyurethane (PUR), Rock Wool (RW), Cellulose (C) and cork panels (Cork).

The U-values and R-values of the various insulation materials are calculated as a function of thicknesses between 0.12 and 0.38 m (Fig. 2.18). The target is to understand the dependence of material thicknesses and thermal conductivity.

Additionally, the required thickness to achieve the Passive House standard with a U-value of 0.15 W/(m²K) is shown in Figure 2.18.

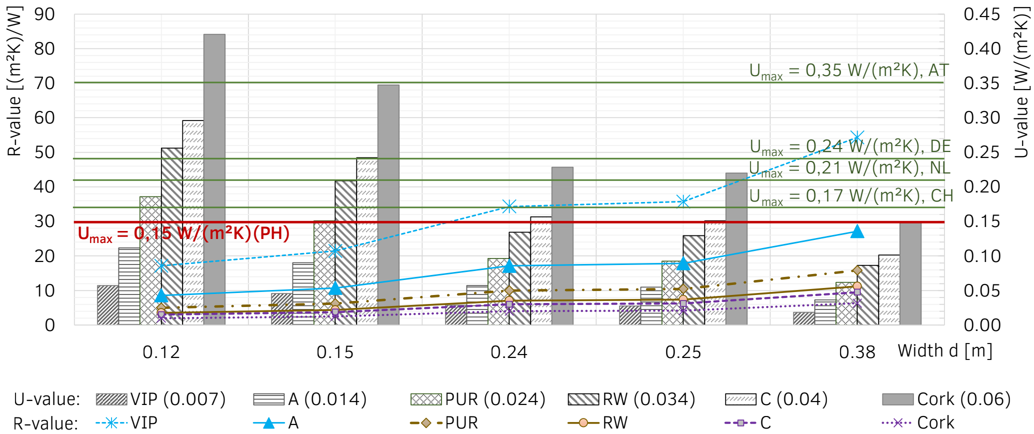
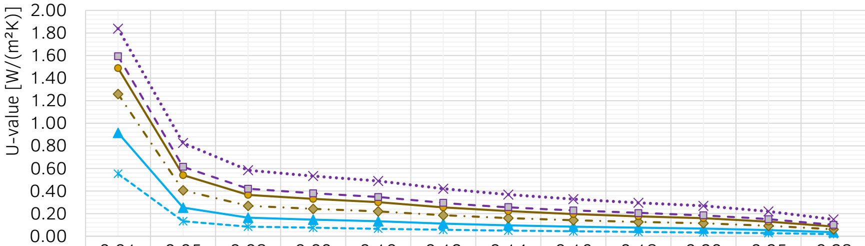


FIG. 2.18 Parameter study results on the influence of thickenesses on various thermal insulation materials. To reach the Passive House standard with the base case construction: Vacuum insulation panels (VIP, 0.007 W/(mK)) need minimum ~5cm thickness, aerogel panels (A, 0,014 W/(mK)) need ~9 cm, polyurethane (PUR, 0,024 W/(mK)) needs ~15 cm, rock wool (RW, 0,034 W/(mK)) needs ~22 cm, cellulose (C, 0,040 W/(mK)) needs ~25 cm, and cork panels (Cork, 0.060 W/(mK)) needs 38 cm thickness. The national max. U-values in the building codes of the Netherlands, Austria, Switzerland and Germany as well as the limits for the Passive House standard are added as benchmarks.

Insulation materials with a thermal conductivity λ of around 0.024 W/(mK) or less, such as PUR, need a minimum insulation thickness of around 15 cm to reach the benchmark of U = 0.15 W/(m²K). The same benchmark at lower insulation thicknesses can only be achieved by highly efficient materials, such as aerogels (λ of 0.014) at approx. 9 cm or VIP (λ of 0.007) at approx. 5 cm.

Common insulation materials with a λ between 0.024 and 0.038, to which mineral wool, rock wool or polystyrene (EPS) belong, require minimum insulation thicknesses between 15 cm and 24 cm. Natural, sustainable insulation materials, such as cellulose (λ of 0.040), require a minimum insulation thickness of around 25 cm, cork even around 38 cm. A detailed comparison of thicknesses and material types is provided in Figure 2.19.



	0.01	0.05	0.08	0.09	0.10	0.12	0.14	0.16	0.18	0.20	0.25	0.38
Vaccum Insulation (VIP)	0.55	0.13	0.08	0.08	0.07	0.06	0.05	0.04	0.04	0.03	0.03	0.02
Aerogel (A)	0.92	0.25	0.16	0.15	0.13	0.11	0.10	0.08	0.08	0.07	0.05	0.04
Polyurethane (PUR)	1.26	0.41	0.27	0.24	0.22	0.19	0.16	0.14	0.13	0.11	0.09	0.06
Rock wool (RW)	1.49	0.54	0.37	0.33	0.30	0.26	0.22	0.20	0.18	0.16	0.13	0.09
Cellulose (C)	1.59	0.61	0.42	0.38	0.35	0.30	0.26	0.23	0.21	0.19	0.15	0.10
Cork	1.84	0.83	0.58	0.53	0.49	0.42	0.37	0.33	0.30	0.27	0.22	0.15

Thickness [m]

FIG. 2.19 Results on the dependencies between thickness and thermal heat transfer efficiency.
The diagram reveals that insulation materials with very low thermal conductivity reach maximum efficiency quite quickly. The worse the thermal conductivity gets, the more the thickness comes into account.

As an environmentally friendly material, cellulose can keep up well with conventional materials. This material is particularly of interest, as it is similar to biological insulation material used in nature.

Conclusion

The following conclusion can be drawn for the question of which insulation material properties with which material thickness currently achieve the Passive House standard - provided that market-ready insulation materials are used: for an 18 cm brick wall, insulation materials with very low thermal conductivity, such as Aerogels or VIPs, reach the benchmark already with about 5cm. Common plastic materials, such as PUR, perform better than mineral or natural materials.

This means, that highly efficient insulation material with low thicknesses target at materials that efficiently trap air. However, their manufacturing asks for an energy-intensive production effort: Aerogels are made from silica through supercritical drying from a gel. Vacuum insulation requires an equally complex process to embed structures in a high-density envelope system that can withstand the vacuum pressure. Both are also cost-intensive and highly fragile.

The detailed calculation of the parameter studies on thermal insulation can be viewed in Appendix 2-1.

2.4 Boundary conditions

In order to refine the search field objectives, the boundary conditions must also be known. As mentioned in 2.1.3, deviations between indoor and outdoor climate are first regulated by the building envelope. Therefore, both indoor and outdoor conditions need to be clarified to understand which façade parameters must be adapted to create a comfortable situation.

2.4.1 Methodology

The influencing factors from inside (comfort) and outside (environment) are surveyed through literature studies, particularly in standards. The identified criteria for both environments are structured, analogue to the design measures, into classes and sub-classes with unique IDs.

Finally, the findings are evaluated for their role in the façade environment. For this purpose, the general influencing factors (regionally determined) and the local influencing factors that directly affect the façade are examined and linked to the corresponding design measures. The aim of this analysis is to find out which factors can be directly influenced by or react on local measures from the façade.

2.4.2 Comfort-related factors

In European countries within the temperate climate zone, the needed energy to maintain a comfortable thermal indoor climate is mainly related to heating. Climatic changes in recent years, such as e.g. re-occurring heat waves (IPCC, 2018) and generally increasing temperatures, ask now for energy for heating AND cooling, and force the use of active cooling systems (OECD/IEA, 2013, p. 90). Poor construction quality in the existing building stock and the transparent designs of new constructions are further reasons for increasing cooling energy demand (van Hooff et al., 2016). The high thermal insulation quality and air tightness of modern buildings also requires consideration of how excess energy can be dissipated during warm periods. One option is to create adaptive concepts.

The thermal comfort benchmark, which is the target for all energy related tasks, was first investigated by Ole Fanger (1970) and later developed further into the '*standard comfort model*' that is used nowadays. Other studies at that time, such as those conducted by Humphreys & Nicol (1998) on the human perception, resulted in the '*adaptive comfort model*'.

The *standard comfort model* is based on the heat balance model, which assumes that thermal comfort is proportionally depending on the thermal load of defined physiological factors of the body (metabolic rate): the energy, which a body produces (metabolism) and loses to the environment (= thermal load) is put in relation to defined thermal factors of the body (clothing, activity, length of stay, number of persons in a room), technology-related factors (heat from devices, electricity, lighting, etc.) and indoor climate-related factors (temperature, humidity, etc.). The more (human) energy is needed to keep the same comfort perception (thermal sensation), the less comfort quality is given (dissatisfaction degree). This model uses empirical data from laboratory studies by Ole Fanger. It became the most applied standard for building designs, provided in the EN ISO 7730 (2005).

The EN ISO 7730 provides two evaluation indices to assess the degree of thermal dissatisfaction of people exposed to thermal environments: the PMV (Predicted Mean Vote) and the PPD (Predicted Percentage of Dissatisfied). The standard also provides equations to assess the local discomfort, such as draught, vertical air temperature differences, floor surface temperature and radiant temperature asymmetry. The perceived indoor air temperature T_{op} that relates air temperature and radiant temperature of the surfaces is a further value that is noted in the standard.

The EN 7730 approach is based on a standardized human perception. Thus, its heat balance model is quite stringent to meet three defined comfort classes (A with T_{op} 21 – 23.5°C, B with T_{op} 20 – 26°C, and C with T_{op} 19 – 27°C). The model does not include any adaptive behaviour according to Olesen & Parsons (2002) and de Dear (2011), who extensively investigated thermal comfort issues. Their studies already informed long time ago that the acceptance and behaviour of occupants differs a lot to the calculated predictions of the heat balance model. Particularly, with the use of concrete core thermal activation, natural ventilation or environmental heat sinks, the model become less reliable (de Dear & Brager, 1998).

The standard EN ISO 7730 also mentions the difference between steady and unsteady conditions. The unsteady conditions point to three types that influence the indoor climate perception: temperature cycles that occur time-depending, temperature drifts that occur due to temperature differences Δt, and transitions of the operative temperature that combine the above types. Time and drifts are considered as time-weighted averages in the standard.

Buildings without mechanical cooling are thus evaluated according to the *adaptive comfort model*. A suitable approach for the model was first proposed by Nicol and Humphreys in 1972 and further developed by de Dear and Brager (1998). It takes the human dynamic interaction (e.g. opening windows, activating solar shading) and changes in the outdoor climate into account and considers some passive adaptation capability of the building itself, namely the thermal storage capacity. The model allows a broader acceptable temperature range than the static model. It is defined in the standard ASHRAE 55:2017 (*Thermal Environmental Conditions for Human Occupancy*) (ASHRAE, 2017) and with some more aspects such as lighting and acoustics in the newly established standard EN ISO 16798-1 (2019) that replaced the former EN ISO 15251.

Vernacular buildings and some modern building concepts that intend to minimise energy consumption while taking sustainability and costs into account through less strict thermal indoor comfort goals follow the adaptive comfort model. The standard EN ISO 16798-1 also provides occupancy schemes and further dynamic parameters for the design of the building envelope, and for the heating, cooling, ventilation, and lighting. This standard currently offers the most holistic approach for thermal comfort assessments.

Both standards, the EN ISO 7730 and the EN ISO 16798-1, include assessment criteria for the general indoor thermal comfort and local thermal discomfort. Those parameters that are considered to create a good thermal comfort in summer are as following:

- General comfort parameters:
  - Indoor air temperature T_i (Summer: 23-~26°C; max. 28°C)
  - Operative Temperature T_{op} (Winter: 22 +-2°C; summer: 24 +-1,5°C)
  - Mean radiant temperature $T_{s,r,m,i}$ (<4K)
  - Relative humidity Rh (35 - 70%; < 12 g H_2O/kg air)
  - Indoor air velocity v_i (Summer: 0,12 m/s at class A; 0.19 m/s at class B)

- Local comfort parameters:
  - Surface temperatures T_s (particularly on the inside of façades)
  - Floor surface temperature $T_{s,floor}$ (19 – 28°C)
  - Vertical air temperature distribution T_v (max. 3K at 0.10 – 1.10m diff.)
  - Radiant temperature asymmetry Δt_{pr}:
    - Ceilings: < 14 – 18 K (cold), < 5 – 7 K (warm)
    - Walls: < 10 – 13 K (cold), < 23 – 35 K (warm
  - Air draught rate DR (10% at class A, 20% at class B, 30% at class C)
  - Degree of turbulence Tu

Summarising the above, it can be said that there are two levels of thermal comfort: one level is the thermal comfort in the room, which has a bandwidth that is relatively defined by average values for a period (summer, winter) and targeted quality classes. The other level deals with the area adjacent to the façade, which influences the local thermal comfort and is relative to a position in the room. Particularly the temperature differences of a façade surface to the interior, the air flow along the inner surface and the direct irradiation into the room contribute significantly to the local thermal sensation of a person.

With regard to adaptive measures, following parameters are considered relevant:

- Surface temperature (T_s): The surface temperature influences not only the subjective thermal sensation but also the heat flow efficiency and is therefore an essential factor for both assessments, the thermal comfort quality and physical behaviour of the exterior walls.

- Radiant asymmetry (Δtpr): Radiant asymmetry is caused by radiative temperature differences from the surfaces to a point of reference, in case of thermal comfort to a defined position in the room. The allowed maximum for radiation asymmetry can be up to 35K for warm walls (class III), which means a significantly higher deviation tolerance than for cold walls (in winter).

The influencing factors of the façade construction for these two parameters are the thermal transmittance of the walls (U-value) and radiative transmission share (g-value and g_{tot}-value), which define the surface temperatures, as well as the façade area, transparency share and distance from the façade surface to the measure point.

These comfort-related factors are added to the parameter list using category 'T 'for '*thermal comfort*'. The complete list of parameters is provided in the adaptive façade criteria list in Chapter 3 (Appendix 3-2).

2.4.3 Climate-related factors

Initial thermal considerations for a building project are usually linked to a general evaluation of the local climate conditions in which the building will be placed. The climate zones, as proposed by the Köppen-Geiger climate classification (Kottek & Rubel, 2017), provide general information about the climatic conditions of a region and indicate whether heating or cooling, humidifying or dehumidifying would be required to meet a certain comfort level.

Central Europe is mainly located in group C (temperate or mesothermal zone) and group D (continental zone) of the Köppen-Geiger classification (as shown in Fig. 2.1). The climate zones are allocated between ~20° to 60° northern latitude. The average temperatures vary between -5°C to +23°C with relative humidity ranging between nearly 90% in the continental hemiboreal zones to 60% in the oceanic zones (Kottek & Rubel, 2017). Vegetation shows a high diversity but without particularly characteristics. In some areas of this zone, endemic species emerged, such as on the islands of the Mediterranean, or in South America and New Zealand. Seasonal migrations of some species like birds are found as well as hibernating animals.

The analysis of climate data reveals the framework conditions for applying appropriate passive design strategies. In the course of a planning process, specific climate data from meteorological measurements of a site or from prepared reference climate databases such as Meteonorm (Meteotest, 2021) are used to assess the energetic performance of a building. Together with other site-depending parameters such as topography, vegetation and built neighbourhood, these factors are called 'non-influenceable' boundary conditions. The analysis of the climatic factors is also the first step in understanding biological processes for thermoregulation.

Following meteorological data play a decisive *primary* role in thermal-energetic assessments and the passive design of buildings:

- ambient air temperature (T_e)
- (mean) radiant temperature of environmental surfaces ($T_{s,r,m,e}$)
- solar radiation (I_s)

Less influence on the thermal-energetic design decisions is attributed to the *secondary* design factors, such as:

- wind speed and wind direction (v_e),
- relative humidity of the external air (Rh) and
- air pressure (p).

The secondary design factors have a bigger impact than is often considered in current design processes, as studies on the influence of wind velocity on thermal losses through thermal bridges (O'Grady et al., 2017) or the influence of moisture content on the thermal conductivity of materials (Liu et al., 2017) demonstrate. These factors are partly considered in later design phases to e.g. assess the hydrothermal material behaviour or the convective attributes of a constructive detail but are not seen as primary factors for energy performance optimization. However, the more adaptable building envelope elements become or the more sophisticated their responsiveness is, the more these secondary factors gain in importance.

Interestingly, it is often these secondary factors that play an important role in nature for the thermal adaptation capability. While buildings are more or less static structures that are sealed off and isolated from external changes like closed systems, biological systems use these secondary climatic changes to their advantage; exemplarily for this ability is the hydromorphic behaviour of coniferous cones (Reyssat E. & Mahadevan L., 2009). In extreme climate zones, organisms evolved various strategies to utilize the secondary factors on daily, hourly or even shorter time basis in the best way. For example, high solar radiation combined with high temperatures throughout the year, typical of semi-arid and arid climate zones, means that measures can only be taken at the remaining, changing secondary level to prevent overheating and loss of water. Organisms in this climate zone evolved strategies to use the morning dew or radiant surface differences that cause air motion. The biomimetic analyses of e.g. termite structures (Soar, 2016) or cacti structures (Lewis & Nobel, 1977) reveal that they initiate passive ventilation and thermal convection through changes in air or surface temperatures and air pressure differences. Other species use locally changing humidity conditions to adapt their colour, such as the Hercules beetle (Rassart et al., 2008). Both adaptations have a fast response time and are reversible.

The climate-related factors are added to the parameter using category 'E' for '*Environmental factors*'. The complete parameter list is provided in the adaptive façade criteria list in Chapter 3 (Appendix 3-2).

2.4.4 Evaluation of influencing boundary conditions

The interrelation between climatic and thermal comfort factors regulated by the façade can be considered on two levels (Fig. 2.20):

- The first level is the macro level (A), which considers annual average temperatures and solar radiation to define generic measures for the provision of the thermal comfort. This level considers the seasonal climate fluctuations. For the temperate climate zone in Central Europe, with cold winters and mild summers, the maintenance of the thermal comfort meant so far focusing on the energy consumption in the cold seasons, which is longer than in warm seasons. The passive measures must also consider local factors such as vegetation and topography. The results are static and long term, such as the defined shape a building and its orientation, the thermal quality of the building envelope or the positioning and size of the windows. For the warm season, certain disadvantages are accepted: shadings of the transparent components prevent overheating but also reduce daylight availability the building. A highly thermally insulated building envelope keep the heat inside and thus reduces a rapid dissipation of heat energy to the outside.

- A compensation of the disadvantages of level A may occur on the second level, the micro level (B). The climate analysis of the micro level focuses on significantly shorter time intervals. The fluctuations take place in the course of a day or hours. Appropriate passive design measures must therefore be taken that can react to these time span. These are usually fast adapting kinetic systems, such as shading systems or ventilation openings. The difference to the macro level lies in the needed reactivity and the reversibility.

MACRO LEVEL (A)

→ Primary factors: temperature, solar radiation

	A1	Non-influenceable parameters
	A.1.1	Climate changes on annual/seasonal level (climatic region)
	A.1.2	Location (topography, environmental factors, surroundings)
	A2	Design parameters related to climate
	A.2.1	Orientation, A/V ratio, zoning, WFR/WWR, thermal insulation, air tightness, thermal heat capacity, etc.
Adaptability	A.2.2	Material properties (emissivity, reflectivity, absorptivity, thermal conductivity, etc.)
Response time	↘	Passive design measures on system level applying the approbiate material to meet the structural and physical needs
Adaptation	↘	
Reversibility	—	

MICRO LEVEL (B)

→ Secondary factors: humidity, wind, pressure

B1	Non-influenceable parameters
B1.1	Climate changes at short-time interval (sec, min, hour, day) (irradiation, relative humidity, etc.)
B2	Parameters influencing the local climate
B.2.1	Thermodynamic processes on micro level (turbulences on surface, radiant surfaces, etc.)
B.2.2	Dynamic design measures, such as shadings, openings for ventilation, etc.
B.2.3	Material behaviour alteration based on their properties (conductivity change, etc.)
↑	Passive design measures using components or materials with adaptive behaviour and focus on short-term adjustment.
↑	
↑	

FIG. 2.20 Summary of the environmental factors on the macro and micro levels.
The macro level (A) deals with the primary climate parameter and the related design measures to meet the annual climatic requirements. The micro level (B) deals with the secondary climate factors and their related adaptive or dynamic design measures.

2.4.5 Conclusion

Climatic influences on the building envelope occur on two levels, the macro and the micro level. Both are relevant for adaptive façade measures, whereby the micro level is the one to be influenced. Thermal boundary layers, radiation asymmetry or material behaviour due to thermal effects can only be felt at the micro level.

Climate and comfort form the framework and the cause for optimisation tasks of a building. The deviation from a defined target plays hereby the decisive role. This criterion is included in the parameter list, as well as the climatic data for monitoring the actual and target conditions.

The complete parameter list is provided in Chapter 3 (cf. Appendix 3-2).

2.5 Definition of search fields

The definition of the search fields is based on the assumed adaptability of the identified design measures. The aim is to define those fields whose potential has not yet been exhausted and which could make an important contribution to the cooling tasks of façades.

The list of Table 2.5 provides the evaluation result of Section 2.4 on the potential and actual adaptability of the passive design measures, and is thus a continuation of Table 2.2 . It shows the identified design measures (classes), their relevant design-related components (sub-classes) and functional purpose (F08.x). The results of the evaluation regarding the current adaptability and potential adaptability are added: those measures that were assessed as already being adaptive are rated positive (green ample with 'y' for 'yes') or likely (yellow ample with 'm' for 'maybe'). All others are rated negative (red ample with 'n' for 'no'). As a concluding column, the arguments for the rating are added.

If both evaluation results are rated positive, the are considered established and are not selected as search fields. If the current adaptability is rated negative and its potential adaptability positive or likely, the measure is defined as either high level search field ('yes') or supportive search field ('maybe').

TABLE 2.5 List of selected design measures, based on the evaluation results.
The results of the evaluation are shown by traffic lights symbols with 'n' for negative, 'm' for maybe/likely, and 'y' for positive. Excluded search fields in the right column are marked grey, high potentials are marked green, possible potentials are marked yellow. Those fields that are marked red are considered established with no need for biomimetic solutions.

ID	Class	ID	Sub-Class	Functional purpose	Results from evaluation		
					Current adaptability*	adaptation potential*	Selection as search fields
P01	Thermal insulation	P01.1	System design	F08.1 Heat loss prevention F08.2 Thermal energy control	n	y	Potential field: designed for cold periods, but high influence on cooling – no solutions established.
		P01.2	Material properties				
		P01.3	Hygrothermal material properties				
P02	Thermal mass	P02.1	System design	F08.2 Thermal energy control F08.5 Overheating prevention	m	m	Supportive measure: seldom applied in curtain wall systems (except PCM) and probably little effect due to thermal insulation and/or small useable area.
		P02.2	Material properties				
P03	Glazing	P03.1	System design	F08.2 Thermal energy control F08.3 Solar gain control	y	y	Established measure: adaptive smart glazings, solar glazings.
		P03.2	Material properties				
P04	Shading	P04.1	System design	F08.3 Solar gain control F08.5 Overheating prevention	y	y	Established measure: adaptive overheating prevention.
		P04.2	Material properties				
P05	Air tightness	P05.1	System design	F08.1 Heat loss prevention	n	n	Not expected to be adaptive.
		P05.2	Material properties				
P06	Openings (ventilation)	P06.1	System design	F08.4 Heat dissipation F08.6 Energy exchange	y	y	Established measure: adaptive passive ventilation strategies.
P07	Thermal boundary layer	P07.1	System design	F08.2 Thermal energy control	n	m	Possible relevance: not yet applied as a design measure in modern buildings. Appears complex.
		P07.2	Material properties				

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TABLE 2.5 List of selected design measures, based on the evaluation results.
The results of the evaluation are shown by traffic lights symbols with 'n' for negative, 'm' for maybe/likely, and 'y' for positive. Excluded search fields in the right column are marked grey, high potentials are marked green, possible potentials are marked yellow. Those fields that are marked red are considered established with no need for biomimetic solutions.

ID	Class	ID	Sub-Class	Functional purpose	Results from evaluation		
					Current adaptability*	adaptation potential*	Selection as search fields
P08	Passive cooling at surface	P08.1	Radiative cooling – system design	F08.4 Heat dissipation F08.5 Overheating prevention	n	y	Potential field: radiant cooling is not yet applied on façades, although has controllable potential; it might contribute to cooling in urban settings.
		P08.2	Radiative cooling – material properties				
		P08.3	Evaporative cooling – system design	F08.7 Energy conversion F08.5 Overheating prevention	n	n	Potential unlikely for evaporative cooling; it is successfully applied in vernacular architecture in dry hot climate regions, but not applicable in Central Europe.
		P08.4	Evaporative cooling – material properties				
P09	Shape and form	P09.1	Solar exposure ratio - system design	08.3 Solar gain control F08.5 Overheating prevention	n	m	Supporting measure: shape and proportion optimisation of a building envelope is partially taken into account for solar buildings, but not as an adaptive measure.
		P09.2	Positioning transparent parts - system design				

** results from Table 2.3*

The relationship between material and geometry properties to achieve the performance objectives has been qualitatively evaluated for the functional principles of the selected design measures (cf. Table 2.4, Section 2.3.3). The evaluation indicates the assumed role of these parameters based on their use in the standardized performance assessments. Figure 2.21 links these results with the selected design measures to present the search fields and related main functional principle.

The figure shows that for the measure '*thermal insulation*', the material properties (thermal conductivity) play an important role in current solutions, but strongly depend on the geometric properties (thickness). Existing adaptive thermal insulation solutions in façades are further investigated in Chapter 3. The functional principle is then used for the analysis and selection of potential role models in nature.

Geometric parameters are also the decisive criteria for '*passive cooling* measures *at surfaces*' and the supporting measure '*shape and form*' in relation to the shapes of the building envelope (proportion of exposed surface, angle of surfaces to each other) or in relation to the degree of transparency of the façade surface. Possible approaches for adaptive façades that consciously use radiant energy of the surface to cool are also explored in the next chapter. The principle of radiant energy at surfaces is taken into account in the search for potential solutions in nature.

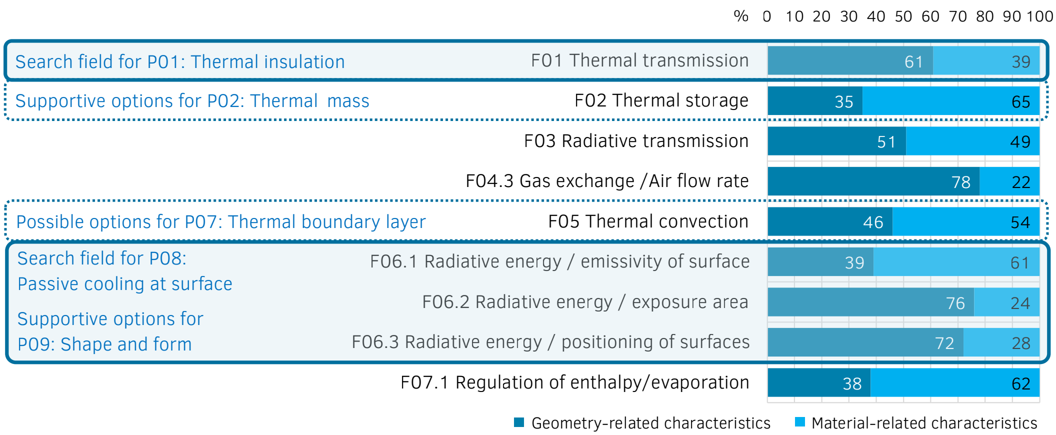

FIG. 2.21 List of search fields and their functional principles (F.x).
The list shows the selected search fields with the assumed relation between geometry and material properties. The dashed fields are supportive measures, the coloured fields are the main selected search fields.

For '*thermal mass*', '*passive cooling / emissive attributes of surfaces*' or '*passive cooling / evaporation*', material parameters play a bigger role than geometric parameters. It equals nearly for the supportive measure '*thermal convection*'.

This evaluation of the relationship between geometry and material attributes is repeated for the selected biological role models in Chater 6 to examine similarities or deviations.

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2.6 Summary

In order to identify the search fields, target objectives are initially set for the review of façade-related design measures: only passive façade design measures that contribute to the thermal performance of buildings are sought with a focus on cooling demand.

The design measures are then discussed to extract their role in the performance assessment. Thermal insulation and glazing are the most controversial measures. Their purposes result in contradictions regarding the energy efficiency targets, as each fulfil one objective very well while worsening another. However, both play a fundamental role in the design measures for energy-efficient buildings and are therefore in the focus of high-tech developments. While market products already exist for adaptive glazing, there are no applied solutions for adaptive thermal insulation. This is the reason for the conduction of a parametric study on the dependencies of the geometric and the material properties of current thermal insulation materials. The aim is to classify the influence of these parameters on energy efficiency and also to investigate their benchmarks for achieving a high level of energy efficiency, the Passive House standard.

Other design measures such as thermal boundary layers and passive cooling strategies on the outer surfaces of façades may possibly contribute to cooling, but their influence has not been clarified – especially in the context of highly insulated envelopes, which limit the effect of such measures. The same applies to shape optimizations of buildings, although the effect of transparency proportions and building orientation is well known and considered in practice. A finetuning of the façade shape to reduce cooling energy is, however, not applied in practice. Some of these design measures prove some influence on cooling in vernacular architecture where they reach a higher effect (such as e.g. reflective colours).

The identified design measures are also qualitatively assessed for their current and potential adaptability. It shows that most of the current measures – with exception of shading and opening functions – are not intended to react dynamically. However, potential for improving thermal tasks through adaptivity is attributed to most of them. It is assumed that particularly thermal insulation, passive cooling and shape optimization could positively influence the thermal performance in hot periods if they become adaptive. Shading and glazing are established as adaptive measures. Thermal storage and thermal boundary layers in front of the façade surface are considered to be supportive, but not sustainably influencing measures, as they already behave adaptive. These assumptions are further investigated in the following chapters.

Finally, the criteria of the boundary conditions, comfort and climate, are examined. It can be assumed that there are two influencing levels for both the indoor and outdoor climate: the macro level, which reacts to long-term changes and the dynamic micro level, which adapts to short-term changes. It reveals that the micro-climate influences particularly the thermal behaviour of thermal transfer and evaporative cooling measures. Effects of glazing's and air exchange measures tend to include those factors related to the macro level. These findings are considered when evaluating biological role models and their influencing factors.

Following main search fields are selected:

- **Thermal insulation (P01)** to find adaptation strategies for thermal transmission (F01),
- **Passive cooling (P08)** to find adaptation strategies for the modulation of radiant attributes of surface materials (F06.1),

The main search fields are complemented by assumed supportive search fields:

- Thermal mass (P02) to find *supportive* strategies to increase the thermal mass effects,
- Thermal boundary layer (P07) to find *supportive* strategies to cool the outer surface of façades,
- Passive cooling (P08) to find *supportive* strategies for the regulation of the enthalpy in air (evaporative processes) (F07.1)
- Shape optimization (P09) to find supportive strategies for the modulation of heat energy by the adaptation of exposed surfaces (F6.02) or their orientation and positioning (F6.03).

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Appendices

Apendix 2-1 Parameter study results on thermal insulation

PHASE 1: CLARIFY THE PROBLEM (I: Define framework of investigation and search fields)

Uw-values [W/(m²K)]														
	Vaccum Insulation (VIP)		Aerogel (A)		Polyurethane (PUR)		Rock wool (RW)		Polystyrene, exp.(EPS)		Cellulose (C)		Cork	
	0.007	λB [W/(mK)]	0.014	λB [W/(mK)]	0.024	λB [W/(mK)]	0.034	λB [W/(mK)]	0.038	λB [W/(mK)]	0.040	λB [W/(mK)]	0.060	λB [W/(mK)]
d	R (TI)	**Uw**	R (TI)	**Uw**	R (TI)	**Uw**	R (TI)	**Uw**	R (TI)	**Uw**	R (TI)	**Uw**	R (TI)	**Uw**
[m]	[(m²K)/W]	**[W/(m²K)]**	[(m²K)/W]	**[W/(m²K)]**	[(m²K)/W]	**[W/(m²K)]**	[(m²K)/W]	**[W/(m²K)]**	[(m²K)/W]	**[W/(m²K)]**	[(m²K)/W]	**[W/(m²K)]**	[(m²K)/W]	**[W/(m²K)]**
Base Case (R + Uw)														
	0.38	2.65	0.38	2.65	0.38	2.65	0.38	2.65	0.38	2.65	0.38	2.65	0.38	2.65
0.01	1.43	**0.55**	0.71	**0.92**	0.42	**1.26**	0.29	**1.49**	0.26	**1.56**	0.25	**1.59**	0.17	**1.84**
0.04	5.71	**0.16**	2.86	**0.31**	1.67	**0.49**	1.18	**0.64**	1.05	**0.70**	1.00	**0.73**	0.67	**0.96**
0.05	7.14	**0.13**	3.57	**0.25**	2.08	**0.41**	1.47	**0.54**	1.32	**0.59**	1.25	**0.61**	0.83	**0.83**
0.08	11.43	**0.08**	5.71	**0.16**	3.33	**0.27**	2.35	**0.37**	2.11	**0.40**	2.00	**0.42**	1.33	**0.58**
0.09	12.86	**0.08**	6.43	**0.15**	3.75	**0.24**	2.65	**0.33**	2.37	**0.36**	2.25	**0.38**	1.50	**0.53**
0.10	14.29	**0.07**	7.14	**0.13**	4.17	**0.22**	2.94	**0.30**	2.63	**0.33**	2.50	**0.35**	1.67	**0.49**
0.12	17.14	**0.06**	8.57	**0.11**	5.00	**0.19**	3.53	**0.26**	3.16	**0.28**	3.00	**0.30**	2.00	**0.42**
0.14	20.00	**0.05**	10.00	**0.10**	5.83	**0.16**	4.12	**0.22**	3.68	**0.25**	3.50	**0.26**	2.33	**0.37**
0.15	21.43	**0.05**	10.71	**0.09**	**6.25**	**0.15**	4.41	**0.21**	3.95	**0.23**	3.75	**0.24**	2.50	**0.35**
0.16	22.86	**0.04**	11.43	**0.08**	6.67	**0.14**	4.71	**0.20**	4.21	**0.22**	4.00	**0.23**	2.67	**0.33**
0.18	25.71	**0.04**	12.86	**0.08**	7.50	**0.13**	5.29	**0.18**	4.74	**0.20**	4.50	**0.21**	3.00	**0.30**
0.20	28.57	**0.03**	14.29	**0.07**	8.33	**0.11**	5.88	**0.16**	5.26	**0.18**	5.00	**0.19**	3.33	**0.27**
0.22	31.43	**0.03**	15.71	**0.06**	9.17	**0.10**	6.47	**0.15**	5.79	**0.16**	5.50	**0.17**	3.67	**0.25**
0.24	34.29	**0.03**	17.14	**0.06**	10.00	**0.10**	7.06	**0.13**	6.32	**0.15**	6.00	**0.16**	4.00	**0.23**
0.25	35.71	**0.03**	17.86	**0.05**	10.42	**0.09**	7.35	**0.13**	6.58	**0.14**	6.25	**0.15**	4.17	**0.22**
0.28	40.00	**0.02**	20.00	**0.05**	11.67	**0.08**	8.24	**0.12**	7.37	**0.13**	7.00	**0.14**	4.67	**0.20**
0.30	42.86	**0.02**	21.43	**0.05**	12.50	**0.08**	8.82	**0.11**	7.89	**0.12**	7.50	**0.13**	5.00	**0.19**
0.38	54.29	**0.02**	27.14	**0.04**	15.83	**0.06**	11.18	**0.09**	10.00	**0.10**	9.50	**0.10**	6.33	**0.15**
0.50	71.43	**0.01**	35.71	**0.03**	20.83	**0.05**	14.71	**0.07**	13.16	**0.07**	12.50	**0.08**	8.33	**0.11**

3 [Scope] Adaptation and façades

This chapter deals with adaptive façades and the factors that come into play when implementing adaptability. Thermal adaptability of façades is conventionally not included in design specifications - except for shadings to avoid or openings to exchange air flow. Conventional façades are planned with static thermal properties designed for specific conditions, as discussed in Chapter 2. The deliberate adaptability of material or system properties is a goal that has been pursued in the last years on the rise of intelligent *adaptive* façades. Within this context, adaptability as a planning task is a particular challenge. There are neither established planning nor evaluation procedures. Many performative features of adaptive façades can only be described qualitatively or assess by huge efforts (dynamic simulations or experimental testing). These challenges, the objectives, and the potentials of adaptive façades, in particular of thermally adaptive façades, and the definition of criteria to describe the adaptation are the aim of this chapter.

Façade applications with adaptive features are investigated in published case studies and projects, their attributes are presented in clustered groups of similar types. The result is a collection of various adaptive solutions and the investigation of the mechanisms and components used to ensure adaptive functions. In addition, design criteria for adaptation are extracted from this investigation to serve as input for the paramteric classification used for the biomimetic transfer process later in this work.

After a brief introduction to the definition approaches of 'adaptive' façades in Section 3.1, Section 3.2. provides the methodology for the identification and evaluation of adaptive façade cases. Section 3.3 shows then the state-of-the-art by presenting cases of different types of *adaptive* façades and their peculiarities. Furthermore, examples of thermally adaptive façades, available on the market or as concepts, are examined. The results of this case study analysis and the examination of various publications and projects leads to a list of use cases: similar approaches are grouped together to get an overview of the various approaches and characteristics of adaptive façades.

The advantages, disadvantages, and technical challenges of adaptive façades from the perspective of various stakeholders in the construction sector are discussed in Section 3.4. to define the most important 'design effectivity criteria' for successful adaptive façade implementations. From this review, the needed design benchmarks are derived, which are later used to evaluate the use cases. In the same section, also implementation barriers and assessment challenges are discussed to get an insight into the challenges of developing adaptive façades.

The literature review leads furthermore to the identification of functional criteria for the development of adaptive features, which are examined in detail in Section 3.5. From the collection of existing '*adaptive façade classification*' approaches, an own systematic criteria list is created. This '*adaptive façade criteria list*' serves, together with the '*design effectivity criteria'* as a selection and evaluation tool for the later search and transfer process.

Finally, the use cases are evaluated against the developed by three evaluation rounds, which is presented in Section 3.6: '*functional purpose and design effectivity*', '*implementation frequency*' and '*strengths and weaknesses*'. For the last round, a graph is created showing the deviations between intended and achieved design effectivity goals for the use cases. This graph is later taken to compare the use cases with the developed functional models. Section 3.7 concludes with refined search fields (from Chapter 2) based on the findings from this chapter. The refinement narrows down the search to those fields that possess a need and potential for biomimetic search. The outcome are the two criteria lists for the search and evaluation and use cases.

3.1 Introduction

Climate-sensitive design strategies are a traditional craft in architectural design and engineering, although they reach new prominence in today's sustainability context. Climate adapted building structures can be found in all climate zones, civilisations and cultural contexts throughout human history, such as the wind catcher in the arid, hot climate of the Middle East to cool the house (Foruzanmehr, 2012), the naturally ventilated houses in tropical climates to get a fresh breeze into the house (Tantasavasdi et al., 2001) or the well covered, heavy stone houses in the alpine area of Central Europe to increase thermal storage capacity and decrease thermal losses. However, with the rise of the industrial revolution and the gain of independence from local sources through building services technologies and energy supply systems, architectural solutions focused less and less on perfomative tasks. Only daylight design strategies remained an architectural design goal.

Since the goals for energy-efficient buildings can no longer be achieved solely by mechanically supplied building machines, as was the target in the 1960-90s, passive design strategies are once again gaining importance. Todays's goal is not only to provide sufficient thermal insulation and airtightness to reduce energy losses, or applying solar design rules, such as orientation of the building or optimization of the window-to-wall (WWR) ratio of the building envelope. It shall now also include measures that control solar radiation and thermal energy flows. Thus adaptability of the building envelope or parts of it become more and more standard. Even static design measures regained a role in this context, such as e.g. smart building forms that positively influence performative behaviour (e.g. thermal zoning by specfic spaces, self-shading forms). Design strategies from vernacular (traditional) architecture now provide inspiration for modern solutions targeting at natural ventilation or shading. Dynamic design measures currently gaining the market are smart materials and elements with embedded dynamic behaviour such as e.g. smart glazings or thermally adaptive storage materials (phase change materials).

3.1.1 Multifunctionality of façades

The façade or external wall, being the largest surface area of a building envelope, comprises many tasks: it not only needs to fulfil performance-related criteria, but is also has to meet aesthetic, constructive and economic expectations, (urban) environmental issues and individual identity values. Even more so, building envelopes mirror the knowledge-based, individualistic and communal expressions of societies, which always required a rethinking of constructions – whereby the façade is the expression of its state-of-the-art (Knaack, Klein & Bilow, 2008).

Conventionally, adaptability of façades is associated with moveable elements and apertures, such as doors, windows, shading devices or ventilation flaps. Originally only providing the option for manual control, adaptive façades are nowadays operating as highly automated systems that regulation of the energy flow of light, heat or gas (air) (Arkin & Paciuk, 1997) (Klein, 2013) (Fig.3.1).

Modern façades features are intelligently performing interfaces, which are designated to interact with continuously changing environments and needs in order to achieve a pleasant indoor environment whilst operating on high energy efficiency levels. A central feature of such systems is their reversible adaptation ability that alters the morphological and/or physiological properties. The development of appropriate concepts and solutions for such an ability puts a major challenge on design and engineering skills (Klein, 2013) (Derek & Clemens-Croome, 1997).

A B C

FIG. 3.1 Evolvement of adaptive façade components from manual towards intelligent.
The evolvement is exemplarily shown by shading devices: (A) traditional shutters (building from 19th century) (Image by author),(B) automated shading elements of oval office by Sauerbruch & Hutton, Colonia (DE) (Image licensed under CC0 Public Domain), (C) intelligent kinetic skin of ThyssenKrupp Q1 Headquarter by JSWD Architekten and Chaix & Morel et Associés, Essen (DE) (Image courtesy of Günter Richard Wett).

3.1.2 Design and operation complexity

Adaptation became a matter to high-tech engineering and materials, advanced computational and control techniques. About fifteen years ago, the design of mechanical alteration of some single components has been transformed into intelligent acting systems regulating many parts in the façade structure (Heiselberg, 2006). Due to the increasing design complexity and maintenance of such systems, next generation solutions aim now at a higher degree of embedded intelligent functionality calling them '*living building skins*', as referring to biological skins (Loonen, 2015).

Such façades are complex in their interaction and require a good understanding of the adaptation processes and goals (Attia et al., 2015) (Böke et al., 2020). Many developments can be found in the engineering field, focusing on technical realization of smart controls to enable communication with the building control system. This is required to coordinate the energy performance of the façade components with the building services. To increase their reliability and flexibility, a transdisciplinary planning approach was demanded from the very beginning of the developments, incorporating the strengths of architecture, engineering and many other disciplines to achieve well-functioning solutions (Fernández, Rubio & González, 2013).

3.1.3 Definition approaches

Various terms have been introduced in the last 20 years to describe the specific façade type that dynamically and automatically '*adapts*' its properties or functions as a response to environmental needs and changes: "*climate-adaptive*" (Loonen, et al., 2013) (van Timmeren, 2009), (Braun & Bader, 2013), "*advanced (integral)"* (Aschehoug & Andresen, Eds., 2008), (Klein, 2013) *"kinetic"* (Kirkegaard & Foged, 2011) (Sharaidin, 2014), *"responsive"* (Arkin & Paciuk, 1997), "*intelligent"* (Wigginton & Harris, 2002) (Derek & Clemens-Croome, 1997) or "*autoreactive*" (Persiani et al., 2016) (Braun & Bader, 2013). More recent design concepts applying biomimetic approaches call it "*living*" skins or envelopes (Badarnah-Kadri, 2012) (Lieverse, 2009). This brief listing of terms has no claims of completeness, but indicates the ambiguity in regards what is seen adaptive. All terms are designated to adaptation abilities of façades on various levels of intervention, without a conform approach to the functional implication.

In principle, any façade can be considered *adaptive*, because some elements are always actively adaptive (e.g. windows, shading) and some are passively adaptive (e.g. heat transfer and storage properties of solid walls depending to temperature gradient). Therefore, by the use of the terms, the functionality shall be described. Some may be associated with purely technical adaptability (e.g. auto-reactive, intergral, intelligent), others with holistic adaptability including material or design (e.g. climate-adaptive, responsiver, living). The terms leave the type of adaptation in material or system open to speculations.

A commonly accepted description for adaptive façades is that they are able to change their morphological or physiological attributes dynamically and intentionally. The intention is driven by e.g. energy and indoor comfort optimization of a building or by communication targets (e.g. media façades). Thus, realized adaptive façade examples vary largely in their objectives. This is considered to be one of the reasons, why the concept of an adaptive façade must be carefully linked to the contextual framework. As far as the context is energy and thermal comfort optimization, following attempts for describing '*adaptive façades*' are surveyed:

- In the first comprehensive summary about the State-of-the-Art of adaptive façades, the IEA ECBCS Task 44 '*Integrating environmentally responsive elements in buildings*' described a "*responsive building element (RBE)"* as a "*building construction element that assists to maintain an appropriate balance between optimum interior conditions and environmental performance by reacting in a controlled and holistic manner to changes in external or internal conditions and to occupant intervention*" (van der Aa et al., 2011). Façade-integrated RBEs were then basically all types of smart materials or devices, including kinetic systems or even manually adaptive components.

- The '*Adaptive Building Initiative*' developed this further towards experimental explorations of highly intelligent, movable elements in the façade system that are responsive to changing environment (Drozdowski, 2011). They called their adaptive solutions "*Intelligent Surfaces*", as to refer to systems that continuously change their visual surface appearance (pattern, opacity, geometry) according to a goal definition (e.g. daylight optimization).

- Kirkegaard and Foged pointed out at the same time that "*architecture may benefit from the integration of computing power into built spaces and structures*" (Kirkegaard & Foged, 2011, p. 3). Herein, adaptation respectively the "*intelligence*" of façades is an engineering task and strongly confined to considerations of intelligent computation technologies (ICT). Thus, sensors, actuators, signal processors and smart controls systems are enabling an adaptive behaviour of façades, as they provide a transformation of a physically static state into an intelligent acting performance.

- In the report about "*plusFASSADEN*" of Haselsteiner et al. (2011), built solutions dealing with adaptive properties are classified according to their targets. Hereby, adaptive façade are either "*hybrid"* utilizing smart materials like aerogels to provide adaptive thermal insulation, "s*torage façades"* utilizing thermal inertia and smart materials to store and dissipate thermal energy, "*multifunctional intelligent façades"* utilizing intelligent controls, integrated devices and smart materials to turn façades into communicating systems, or "g*reen façades"* that adapt according to the specific plant physiology and season passively.

- In one of the most recent publications about the definition of adaptive façades, R. Loonen took in his dissertation thesis "*Approaches for computational performance optimization of innovative adaptive façade concepts*" an engineering perspective and described an adaptive façade with the "*ability to repeatedly and reversibly change some of its functions, features or behavior over time in response to changing performance requirements and variable boundary conditions, and does this with the aim of improving overall building performance in terms of energy use and IEQ*." (Loonen, 2018, p. 18). He also noted in a preceding article that multi-functional façades are not necessarily adaptive: "*Multi-ability differs from adaptability in the sense that multiple objectives can be fulfilled consecutively, not concurrently*" (Loonen et al., 2013, p. 486). Hence, the sole integration of active technologies, such as energy converting technologies (building-integrated solar technologies) or building services technologies (HVAC devices) do not provide automatically adaptive functionality.

- Perino & Serra identified a paradigm shift in the role of façades and suggested that "*opaque and transparent components become a 'living' membrane*" that manage "t*he external environmental parameters to satisfy the internal needs*" by "*modify*(ing) *the mass and heat fluxes*" (Perino & Serra, 2015, p. 150).

These non-exhaustive examples provide approaches for the definition of adaptive façades, which can be described by three characteristics:

- Operation system: setup to enable the adaptation (material – system settings, operation and activation type and carrier),
- Intelligence of automatization: type of control and actuation (intrinsic or extrinsic sensors, actuators, and controls), response behaviour (manual to self-reactive), system intelligence,
- Level of physical embedment of the adaptive function on surface, in matter; material – component – system, visibility, robustness.

While the operation system is linked to the degree of intended and influenceable change behaviour (or ability to self-react to user inputs up to fully self-learning and self-activating processes), automatization describes the technical setup of the adaptation processes. The physical embedment finally points to the physical design setup, ranging from kinetic systems to inherent smart materials, as well as from full façade to component level.

In general, it can be observed that recent adaptive façade concepts are more and more associated with artificial intelligence approaches (ICT) where controllability is seen as an inherent feature of the system (Böke, 2020).

3.2 Methodology

The applied method in this chapter is a literature study, respectively cases study analysis, based on surveying various publications about built adaptive façade solutions and designed prototypes and concepts (Fig. 3.2, left). The main sources for the case study analyses are the publications of the international program COST TU1403 "Adaptive Façades" (COST TU1403, 2019), particularly the "*Case Studies*" booklet to which the author also contributed. About 165 case studies have been

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collected in this booklet regarding adaptive façade solutions (Aelenei et al., 2018). The COST source is complemented by individual publications found in a metasearch using the search words "*thermal performance*" AND "*adaptive*" AND "*façades*". The sources for this search are research databases, such as e.g. national research funding websites (FFG, 2020), or European commission websites (CORDIS-EC, 2020) (EC-EASME, 2020) and related publications found in ScienceDirect or Google Scholar, like from Favoino et al. (2018), Modin (2014), Basarir & Altun (2017) or Kuru et al (2018) just to name a few.

Furthermore, a supplementary literature study is conducted to identify two types of describtive criteria: evaluation criteria to judge the effectiveness of adaptive façades and design criteria for the development of adaptive façades. For this purpose, articles from scientific and trade journals are added to the main source (Fig. 3.2, right).

This literature study is dedicated to the identification of the most important criteria for a successful implementation and operation of adaptive façades. The findings from the case studies is considered in this step. Special attention is paid on discussed technical challenges and operational experiences of built façades. The aim is to identify the essential characteristics for an effective design from a market perspective and develop 'design effectivity criteria', which should help to evaluate the current effectiveness of adaptive façade cases in this chapter and be able to compare these to the functional models in Chapter 7.

Furthermore, technical criteria for the design of adaptive façades are derived from the review of current classification approaches that functionally describe adaptive façade features. The identified classification approaches are merged to identify missing criteria that are found in the earlier review. The outcome is an 'adaptation criteria list' that lists all features that must be considered when developing an adaptive façade solution. This list serve as a search and selection tool for the further process in this work.

By analysing the cases, similar ones can be grouped together in order to generate 'use cases' (Fig. 3.2, middle). Two evaluation rounds are then applied to these cases, using the same qualitative rating method as for the evaluation in Chapter 2.

In a final step, the search fields from chapter 2 are re-evaluated and concretised with the insights gained in this chapter. For this purpose, Table 2.5 is revised with the results of this chapter in order to obtain selected search fields and create a scope for the biomimetic analogy search.

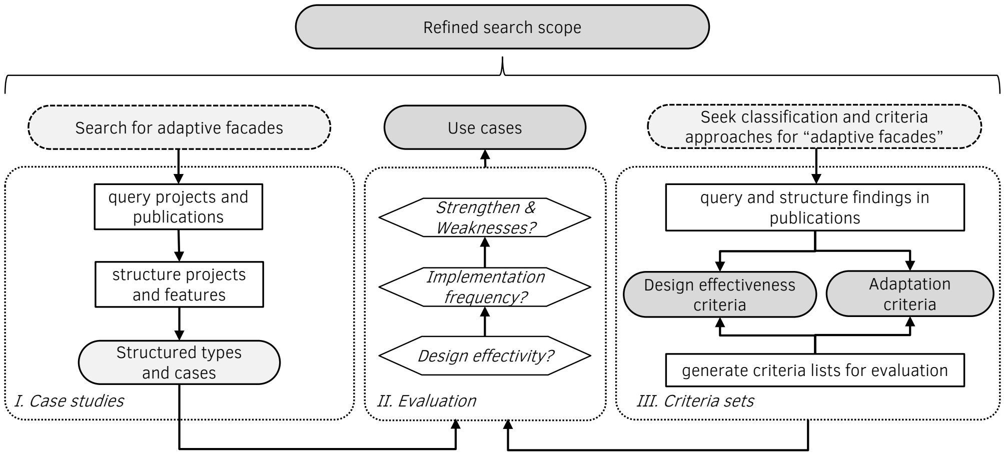

FIG. 3.2 Scheme of the applied process to identify and evaluate adaptive façade solutions

3.3 Case studies on adaptive façades

In the following, various cases featuring adaptive prototypes and built adaptive façades are collected and analysed to identify their characteristics and technical maturity (by adding the Technology Readiness Level as defined by the EU (Wikipedia, 2020).

The authors of the main source, the COST case studies booklet concluded that about 29% percent of the reviewed case studies provide adaptive measures related to thermal comfort issues, 24% are related to visual comfort, 16% to mass transfer control (air exchange), 7% to energy conversion and about 9% are linked to energy management (Aelenei et al., 2018). Only those cases targeting thermal comfort issues have been screened and exemplary representatives selected.

3.3.1 List of studied cases

The identified cases are grouped into types of similar features in order to structure the solutions to create use cases. Each type respectively subgroup within one type is then reviewed and following information is collected:

- Types showing the type of adaptation and containing various examples,
  - Type A Modulation of kinetic system,
  - Type B Modulation of hybrids combining smart materials and kinetic motion,
  - Type C Modulation of material properties,
  - Type D Modulation by multi-layered systems,
  - Type E Modulation by structures.

- case name and case No., featuring groups of similar examples within one type,
- example No. presenting projects within the cases,
- main feature for adaptation,
- short description,
- examples' name (displaying two representative examples),
- keywords, describing the examples.

The COST sources are referenced in the list as following: "*COST ('Code in booklet'_No')*". If some cases have the same code in the booklet, only the numbers are added. Example: "*COST (FS_92/17/24)*". The other sources are added as normal references.

The total list of selected cases and their description can be found in Appendix 3-1 (provided online). In Table 3.1 only the types, the cases and a short description and two examples are shown.

TABLE 3.1 List of reviewed case studies clustered according to their functional type.
Main source is the COST TU1403 case studies report (Aelenei et al., 2018) and individual publications. A detailed list is provided in Appendix 3-1, provided online.

Type	Case No.	Case name	Description	Examples (max. 2)
Type A: Modulation of kinetic systems	Case 01	moveable shades, 1-dim	Various moveable shadings in 1-dimension by shift, roll, rotate by shift, roll, rotate within a façade system, or with little spatial extension	1: Institute du Monde Arabe, 2: Tesselate™ - Adaptive Building Initiative, Hoberman Associates . Happold.
	Case 02	moveable shades, 2-dim	Various moveable shadings in 2-dimension by fold, rotate in front of façade insulation layer	1: Oval Office (Cologne), 2: Kiefer Showroom (Bad Gleichenberg).
	Case 03	moveable shades, 3-dim	Various moveable shadings in 3-dimensional motion in front of façade insulation layer	1: Al Bahar Towers (Dubai), 2: Thyssen Krupp Headquarter (Essen).
	Case 04 Case 05 Case 06	Moveable ventilated curtain walls targeting adaptive U-value	Moveable lamellas / layers allow adaptive insulation effect (air and energy flow adaptation); moveable insulation for daytime cooler system	1: thermocollect (Austria), 2: Palazzo Lombardia (Milano).
	Case 07	kinetic components self-activated by wind forces	Autoreactive shading screens activated by wind forces	1: Ned Kahn projects, 2: KFW Westarkade (Frankfurt).
Type B: Modulation of material properties (hybrids combining smart materials and kinetic motion)	Case 08	Pneumatic modulation of system	Pneumatic adaptive system of ETFE influencing radiative transmission by changing printed layers to each other	1: Media-Tic (Barcelona), 2: Cylcebowl (Hannover).
	Case 09	Self-reactive material (SMA, BI-metals)	SMA metal sheets as envelope	1: BLOOM pavilion, D.K. Sung (Los Angeles)
	Case 10	Electro-active polymer (EAP), SMA, Piezo-electric, etc. as actuators for kinetic systems	Kinetic shading devices, membranes changing their permeability (breathing walls), motion organic structure with SMA converts electric energy into kinetic	1: Kumorigami, Nitinol project, 2: The Living Glass.
	Case 11	hygromorphic shape changing materials	Adaptive timber laminated PV shingles; humidity controlled timber structures	1: Adaptive timber BIPV flakes (Milan), 2: Hygroscope (Stuttgart, Paris).
Type C: Modulation of material properties	Case 12	active thermal storage material (PCM)	Façade components/materials with PCM storage	1: PCM Plasterboards, Solar XXI (Lisbon), 2: Solar Trombe Wall; Integrated PCM Wallboards.
	Case 13	passive solar/ translucent insulation material	Aerogel translucent insulation in façade system; Honeycomb solar insulation	1: Gap:Skin (Gap solutions), 2: DFAB house (ETHZ).

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TABLE 3.1 List of reviewed case studies clustered according to their functional type.
Main source is the COST TU1403 case studies report (Aelenei et al., 2018) and individual publications. A detailed list is provided in Appendix 3-1, provided online.

Type	Case No.	Case name	Description	Examples (max. 2)
Type D. Modulation by multi-layered systems	Case 14	Switchable, smart glazing	Change of photometric glass properties	1: Sage Glass, 2: Merck liquid crystal.
	Case 15	Selective coatings, selective material props.	Glass incorporates an adaptive absorption layer (towards photoactive)	1: Microfluidic glass, 2: Printed coatings of EFTE cushions.
	Case 16	Energy harvesting systems (BIPV, biological harvesting)	Integration of biological systems	1: Bio-reactive façade BIQ (Hamburg)
			Dye-sensitized solar cells as multifunctional element	1: various projects with BIPV; 2: Swisstech convention center (Lausanne) using organic BIPV.
			Regenerable PV: micro-vascular network for dye infusion (self-healing)	1: Photosensitive dye infusion
			Solar cell shields follow sun	1: Adaptive Solar Façade (ETHZ)
	Case 17	Heat modulation by fluids in façade	Fluid flow glazing, IGU with fluid in cavity that modulates heat transfer	2: InDeWaG- fluid flow glazing development.
	Case 18	Heat modulation via air cavity in façade	Air flow system in cavity	1: National Library of France (Paris), 2: Solar XXI (Lissbon)
	Case 19	Systems using multi-layered assembly	Multi-layered façades, thin-layered multi-functionality	1: Selfie façade (Florence)
			Multi-layered photonic structures - radiative cooling	1: Daytime cooler, 2: selective paints and coatings
Type E. Modulation by structures	Case 20	Regulative surface structures	Shading function through surface pattern or structure	1: nZEB office (Helsinki), 2: telefonica headquarters (Madrid)
	Case 21	Geometry optimized via parametric algorithms	Geometry optimized for irradiation, BIPV; adapted façade structure	1: Hanwha headquarters (Seoul); 2: energybase (Vienna)

As a first conclusion, it can be said that examples for adaptive façades can be found on various technology readiness levels, from design concepts to established products, embedded in materials or as added functionality in assembled systems. The best known examples on product level that influence directly the thermal quality of a building are solar shading and glare protection. These are considered multifunctional systems influencing the visual and thermal comfort in short dynamic time intervals. The opposite of such dynamic behaviour, which is still considered adaptive, are thermally activated components with changing thermal inertia.

In the following section, their characteristics are analysed more in depth.

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3.3.2 Adaptive characteristics

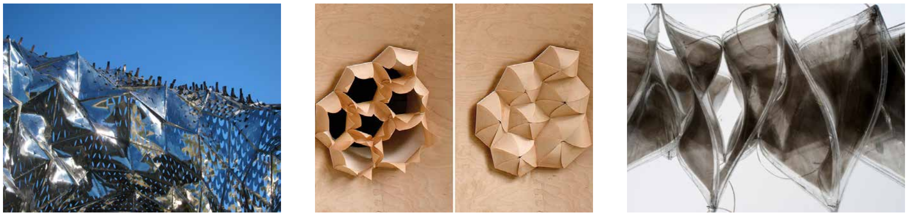
The most commonly used feature for the implementation of adaptivity are responsive components and elements, which are added on specific areas to a structurally fixed façade system. Considering the Technology Readiness Level (TRL) (Wikipedia, 2020), the most common feature found in built projects (TRL 8-9) are automated technical systems (e.g. shading and/or daylight redirecting systems, air exchange units, decentral micro heating/cooling units). Embedded adaptiveness is less common but increases with smart materials, such as smart glazings. In the following, five identified types of adaptative solutions in façades linked to thermal flow adaptations are presented:

Type A: Kinetic motion of elements in façades are represented by the cases 01 to 07 in table 3.1, This type is the most applied one. The cases are well established solutions in the market, reaching a Technology Readiness Level of 8-9 (= 'applied systems, partly assessed'). They are controlled by e.g. integrated daylight and/or temperature sensors and use decentralized motors and extrinsic intelligent automation systems for the operation. The majority often these systems is designed for shading tasks, which is closely linked to architectural expression. Besides the performance duty, the systems are also sometimes used as media performance installations. Thus, the adaptation solution is mainly driven by design aspects adapting the surface geometry and its pattern on various scales, as shown by various examples in Figure 3.3.

A B C

FIG. 3.3 Examples for adaptive kinetic façade systems.
(A) Showroom Kiefertechnic, Bad Gleichenberg (AT) by Giselbrecht + Partner ZT GmbH: Shutters are made of perforated aluminium panels (Image courtesy of Giselbrecht + Partner).
(B) Al Bahr Towers, Abu Dhabi (AE) by Aedas: the complex geometry of the fabric mesh screens is based on a parametric design. (Image courtesy of Andreas Luible).
(C) Gardens by the Bay, Singapore (SG) by Wilkinson Eyre Architects: the form of the shading textiles is following the structure of the glazed roof (Image courtesy of Darren Soh).

Type B: Hybrid systems combining adaptive materials and kinetic motion are represented by the cases 08 to 11 (table 3.1), which contain so-called auto-reactive materials with changeable morphological properties. This type enables an intrinsic, kinetic or morphological adaptation by inherent, self-responsive properties of the material that react autonomously to environmental stimuli, such as temperature, humidity or other ambient triggers. Examples include e.g. shape memory alloys (SMAs) and hygromorphic materials that induce bending through morphological changes within the layers of the material, as shown by the prototypes in Figure 3.4. Type B solutions are not found in built projects (reaching only TRL 8-9), but often in conceptual works (TRL 1-4) and prototypes (TRL 6-7).



A B C

FIG. 3.4 Examples for hybrid solutions in façades using SMAs for kinetic changes.
(A) Installation “Bloom”, Los Angeles (USA) by Doris Kim Sung: laminated metal sheets with a thermo-bimetal behaviour that is activated by temperature differences. (Image courtesy of Doris Sung).
(B) HygroSkin Pavilion, FRAC Centre Orleans (FR) by ICD Universiy of Stuttgart: close-up shows how the 'aperture adapt to weather changes: open at low relative humidity (left) and closed at high relative humidity (right)' (Image courtesy of ICD, University of Stuttgart).
(C) ShapeShift concept, Zurich (CH) by CAAD EH Zurich: electroactive shape-adaptive polymers (EAPs) convert electrical power into kinetic motion (Image courtesy of Manuel Kretzer).

Type C. Embedded adaptivity in materials without kinetic adaptation is explained by the cases 12 to 13 in table 3.1. Like type B, they consist of auto-reactive materials with inherent, changeable properties, but their main focus is the modification of physiological rather than morphological attributes, although both may occur. Thus, the material contains selective, transmitting, redirecting, storing or converting properties. The actuation of the modification is an intrinsic attribute of the material. The result can be invisible, such as PCM (phase change materials) that has no visible change in e.g. colour or surface patterns, or visible, such as smart glazing that changes e.g. the colour. Such solutions are found in built projects reaching TRL 8-9, as well as in conceptual works (TRL 1-4) and prototypes (TRL 6-7). Active thermal insulation materials (cf. Fig. 3.9) and integrated phase change materials for thermal storage control (cf. Fig. 3.10) are the most prominent examples. These two examples are discussed more in detail in Section 3.3.3.

Type B and C are related because they share the property of embedded adaptivity. Smart materials that result in a morphological change (e.g. volume change) without an intended kinetic shading function, such as the Media TIC building in Barcelona (Fig. 3.5) are also counted to type C.

The Media TIC façades, developed by Cloud 9 and constructed in 2010, are an interesting example for the use of smart materials for thermal adaptation: the south-east façade has an inflatable, triangular ETFE cladding, which got known as the "*diaphragm configuration*". The plastic cushions consist of three thin layers, of which only the outer one is completely transparent. The other two have printed dot patterns that are staggered depending on the distance of the layers. Depending on the incident light, which is monitored by light sensors, the pneumatic construction adjusts this distance and thus varies the positions of the dots, resulting in adaptive light selection (Fig.3.5, A and B). Other ETFE cushions on the south-west façade are made of two layers filled with nitrogen gas that is mixed with vegetable oil. This melts when the solar irradiation (and thus temperature) increases and creates a foggy condition within the cushion and thus a shading effect (Aelenei et al., 2018). This solution is called "*lenticular configuration*" (Fig. 3.5, C). During this process its volume adapts slightly, but this is not the targeted function.

A B C

FIG. 3.5 Example for embedded adptive materials.
(A and B) South-east façade of the Media TIC Building in Barcelona (ES) by Cloud 9: the layers of the triangular ETFE membranes are pneumatic and can modify the ligth transmission by changing the spacing of the patterned layers (Image courtesy of Ulrich Knaack).
(C) The south-west façade of the same building is using a different approach to light selection by changing the air density of the gas in the cushions, which creates a solar filter (Image by ACME, 2018).

Type D: Modulation within or due to a multi-layer setting is represented by the cases 14 to 19, which deal with multi-layered solutions, consisting of layers with different functions. They are most commonly static systems, but still cause adaptation on a functional level, such as converting or selecting energy flow. The most established cases of this type are high-tech glazing's, with applied functional coatings or adaptive 'switchable' layers (cf. Cases 14, 15). The most widely applied type herein are electrochromic glazing's, which gain an increasing market share in construction projects with a TRL of 8-9 (Fig. 3.6, A). Further developments for switchable glazing's include the liquid-crystal technology and the older thermochromic attributes, which is mainly applied in interior partition walls. Switchable glazing's are discussed more in detail in Section 3.3.3 (cf. Fig. 3.9). A second huge group within this type are solar energy harvesting technologies, such as photovoltaic or bio-generation systems (cf. Case 16) (Fig. 3.6, B). Other developments regarding this type initiate a dynamic thermal behaviour within the cavity of layered systems by air flow/air pressure modulation, such as modern Double Skin Façades (Fig.3.6, C). These are long established but still constantly improved solutions on TRL 6 – 9. Adaptive behaviour of fluids instead of air in cavities (e.g. the "*liquid glazing*" developed in the project InDeWaG (2020)) are not yet established in the market and reach only TRL 4 – 6. And last but not least, selective paintings and coatings on the outer layer that influence the radiation are also added to this type, because these are often added as functional layers to operate correctly. An example are e.g. the ultra-white paints and coatings. More often applied to roofs, these paints are widely applied in the market reaching TRL 9.

A

B

C

FIG. 3.6 Example for modulation due to layers in a system.
(A) Switchable electrochromic glazing in an office room showing the darker mode on the left window and the transparent mode on the right window (Image by author).
(B) Photovolatic façade of the SOL4 building in Eichkogel (AT): one of the early BIPV façades in Austria aesthetically integrating photovoltaics in the building envelope (Image by author).
(C) Double skin façade of the UNIQA Tower in Vienna (AT) utilizing the thermal behaviour of the cavity to balance the thermal comfort (Image by author).

Type E: Static constructions that influence dynamic adaptation via their particularly designed surface patterns and geometric forms are optimized for a specific performative behaviour depending on the particular local conditions. Examples are individually designed solutions for a performance purpose of the building, such as e.g. the self-shading, folded south façade of the Energybase in Vienna, Austria (Fig. 3.7, A) or the fixed, '*passive adaptive*' shading system of the Pixel house in Melbourne, Australia (Fig.3.7, B). Both solutions are specifically designed for the respective locations. Their geometries are the result of daylight and thermal simulation assessments that make them optimal for the shading and daylight task. Due to the design, they '*react*' passively to the local course of the sun.

A B C

FIG. 3.7 Examples for static constructions providing passive adaptation.
(A) Energybase office building in Vienna (AT) by pos architekten, 2011: the folded south façade prevents in summer direct solar gains and allows at the same time maximum PV electricity production (Image courtesy of Hertha Hurnaus in 'nachhaltig wirtschaften, 2018').
(B and C) Pixel office building in Melbourne (AU) by studio505: the fixed shading system is parametrically designed solution, optimized by dynamic daylight and thermal simulation assessments (Image by author).

3.3.3 Cases targeting thermal adaptation

While there are many market-ready solutions that influence thermal performance by regulating kinetic systems, such as shadings, there are few thermally-adaptive solutions that apply adaptive material or inherent constructive attributes for the same purpose. One possible reason is the steady-state requirements imposed by performance assessments, as discussed in Chapter 2. For example, the development of thermal insulation materials focuses on thickness versus thermal resistance levels as well as ecological qualities; adaptivity is in general not requested (cf. Chapter 2, Section 2.3.4 Conflicting objectives). Thus, adaptive thermal insulation solutions are not in the focus of developments. However, the option of a switching mode for faster or slower heat transmission would be interesting, because the high insulation standards are opposing the requirements for rapid heat dissipation in hot periods.

Inherent adaptive thermal effects are considered e.g. in "*solar-active translucent insulation materials (TIM)*" that make use of solar energy by allowing the solar radiation to penetrate the external, open-structured layer towards the inner, thermally storing or transmission delaying layer (Wong et al., 2007). With higher surface temperatures of the inner layer, daily thermal transmission fluctuations can then be reduced – depending on the solar availability and storage capacity of such systems. Some market-ready products are already applied to new and refurbished buildings, such as GAP:Skin (GAP Solutions GmbH, 2017). The multi-layered construction allows temperature equalisation at lower sun levels (sun penetrates the honeycomb structure and warms the layer behind) and blocks overheating of the heat-storing layers behind the honeycomb layer at higher sun levels (cf. Fig. 3.8, A).

Other market-ready products that address an adaptive U-value behaviour are the *'breathing wall'* systems. The term '*breathing wall*' is used in various contexts that sometimes confuses. While in structural considerations it is associated with structural effects of thermally expanding air in multi-layered systems, in architectural engineering and facade design it is often associated with self-adapting material in the facade. The second meaning also applies to the examples of mimicing a dynamic insulation, such as shown by e.g. Fantucci et al. (2015), Kimber et al. (2014) or Schwarzmayer et al. (2018). Schwarzmayer et al., for example, mounted with the '*thermocollect*' system large louvres in front of opaque, massive walls (Fig. 3.8, B). This adaptive system mimics a ventilated curtain wall, which, through adaptive positions of the louvres, creates an adaptive U-value due to changing convection and surface temperatures of the wall. The automated, lamella-like façade behaves like a shading system. In open position, it lets radiation pass through and stores solar heat in the wall; and in closed position, it avoids overheating of the thermally relevant wall construction behind the louvres.

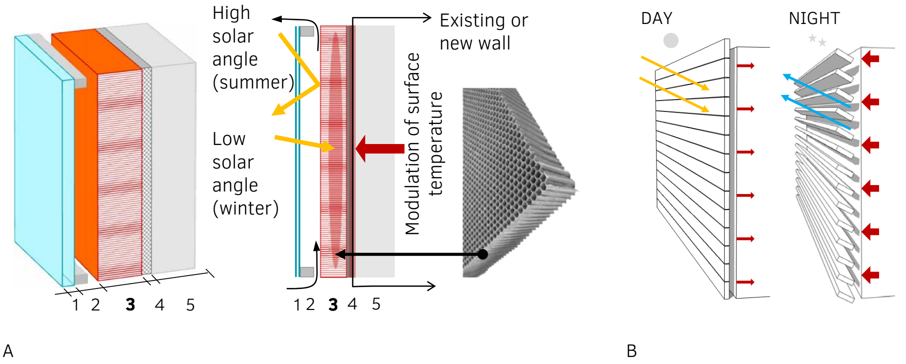
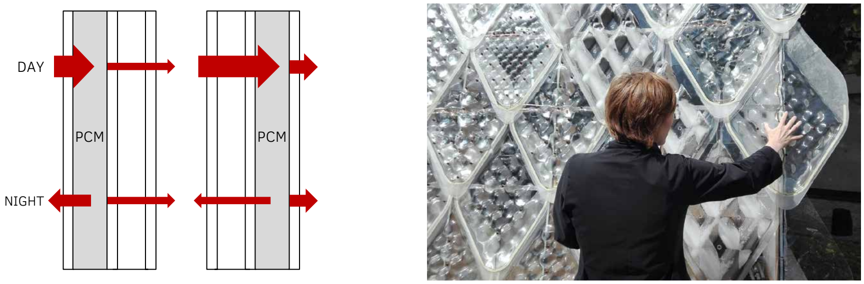


FIG. 3.8 Solar-active walls addressing adaptive U-value.
(A) The system 'Gap skin' of GAP solution (2017) consists of a 6-8mm ESG float glass pane (1), a 29mm air gap for ventilation (2), 30mm honeycomb cardboard that is responsible for the solar-active behaviour (3), and is integrated into a frame with a finishing panel (4). It can be added to a new or existing wall (5) that benefits from the thermal flow modulation (Graphic developed from GAP Solution (2017, p.4 and 7)).
(B) The system 'thermocollect' of Schwarzmayer (2018) consists of an automated slat layer in front of a wall, which regulates the solar impact and thus heat flow. For summer conditions, the slats are closed during daytime to avoid overheating and opened during nightime to dissipate heat (Graphic based on a sketch from Schwarzmayer et al., 2018, p. 17).

The main approach of most of these solutions is the introduction of controllable air cavities in order to adapt the thermal conductivity of air. Still air has a low thermal conductivity value of around 0.022 W/(mK) at 20 °C temperature on sea level. If convection is theoretically reduced to the maximum and air cannot circulate anymore, it would reach even about λ = 0.014 W/(mK) (such as created by Aerogel) or even 0.007 W/(mK) (such as created by Vacuum panels). Established façade solutions of controlled air cavities are glazed double skin façades (DSF). However, these do not aim a still air state. They utilize the thermal flow effects (such as e.g. thermal updrift, stack effect) that happen in the cavity due to temperature and pressure changes to ventilate passively (cf. 'Intelligent glass façades' from Compagno (2002)). Newer, fully glazed DSF systems, such as the 'Closed Cavity' façades (CCF) (architektur Fachmagazin, 2019), target the reduction of air convection towards still air in order to increase the U-value. However, these systems do not aim to create an adaptive U-value.

The modulation of thermal flow is also linked to adaptive thermal storage capabilities of materials, such as phase change materials (PCM) provide. These are implemented in translucent façade elements, such as e.g. once applied in glazing products by GlassX AG (2020). PCM can also be applied in opaque elements, such as e.g. in plasterboards of interior walls offered by Rigips AG (2021). The idea is to store the solar gains in the PCM layer and thus delay the thermal flow into the interior space. For both solutions applies that if the PCM layer is positioned in the outer layer, it prevents solar radiation from overheating the rooms too fast (Fig. 3.9, A).

There are many concepts and prototypes using PCM panel in façades to store heat or balance thermal flow in combination with a ventilated façade (de Gracia & Cabeza, 2015) or building integrated photovoltaics (Čurpek & Čekon, 2020). An interesting new façade concept applying wax as a PCM function is developed by Kieran Timberlake in collaboration with CITA at the Royal Danish Academy of Fine Arts in Copenhagen, Denmark (Faircloth et al., 2018) (Fig. 3.9, B).

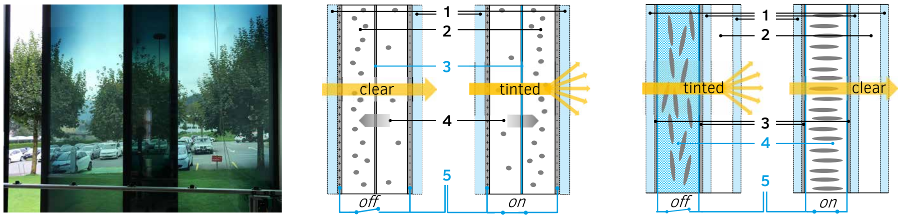


A B

FIG. 3.9 Phase change materials integrated in façade systems are thermally adaptive systems.
(A) The positioning of PCM in the outer layer results in a reduction of heat input to indoors (advantage in summer) and in the inner layer to a compensation of thermal losses (advantage in winter) (own work).
(B) 'Wax façade modeling' is a prototype developed by CITA in 2015-2017 in collaboration with KieranTimberlake: the paraffin wax is encapsulated in a plastic façade shape. The idea is to change the transparency grade rather than thermal flow (Image courtesy of KieranTimberlake).

The use of PCM in a multi-performative 3D-printed façade, such as the CITA prototype, or as multi-layered components (de Gracia & Cabeza, 2015) are prototypes and not yet market ready. Another project by Berge et al. (2015) focuses on the potential of phase change materials that shall adapt the thermal conductivity of the insulation while the thickness stay comparable to traditional solutions. Recent research results on the use of PCM in façades show that the addition of an outer control layer that regulates the thermal uptake on demand are definitely beneficial (Wüest & Luible, 2018) (David et al., 2011) but difficult to control. These projects apply kinetic shading systems in front of the PCM layer to function at any environmental condition and not to overheat the system.

Adaptive or switchable glazing's combine thermal and visual comfort goals with economic efficiency by avoiding additional shading devices. Although electrochromic (ECG), thermotropic (TTG) or thermochromic (TCG) glazing's are market-ready and seem to be established since many years (Compagno, 2002), (Inoue et al., 2008), (Haase et al., 2017), (Cannavale et al., 2018) or (Granqvist, 2019) , their implementation share is still rather small. This is presumably due to the high costs and specific processes for implementation and operation.



A B C

FIG. 3.10 Smart glazing solutions are highly adaptive.
Switchable layers or material properties in glazings are well established but still not standard in built projects. The most often applied glazing technology is the electrochromic glazing. Figure A shows a SageGlass product tested at Lucerne University of Applied Sciences and Arts (HSLU) in Switzerland (Image by author).
The active layer of electrochromic glazing, as shown in Figutre B, is composed of glass layers (1), an ion storage layer (2), an electrolyte layer (= ion conductor) (3) that switches to colour, an electrochromic layer (4) to which the ions flow if the voltage is on and the transparent conductive layers (5) that apply the voltage (own work).
Another option for switchable glazing technology is the liquid crystal technology as shown in Figure C with the glass layers (1) and the gas cavity (2) of an insulated triple glazing, thin films (3) framing the liquid crystal layer (4) and the conductive coatings (5) to initiate the switching modes (own work).

The newer developments regarding switchable glazings apply nanostructures (Haghanifar et al., 2017), adaptive polymers (Hemaida et al., 2020), liquid crystals (Gardiner et al., 2009) or hydrogels (Kim et al., 2015).

Another promising but still experimental approach to modulate the thermal flow is to apply embedded auto-reactive materials in the façade that change the morphology, shape of the surface or openings: shape memory alloys (SMA) are the main studied and tested type for this purpose (Huang et al., 2012). They deform due to temperature, moisture or chemical changes within the material. Basically all examples are applied in experiments to test their potential for use in façades. The range of possible applications spans from self-reactive soft-structures using SMA to change the thickness of the soft structure (An et al., 2020) (Clifford et al., 2017), to fully reactive surfaces made of SMAs, such as the Bloom prototype (DOSU, 2017) (cf. Fig. 3.4 A) or hygro-sensitive material of the institutes ICD/ITKE University of Stuttgart (Reichert et al., 2015) (cf. Fig. 3.4 B), as already presented in 3.3.2.

Most of the current developments try to combine radiative and conductive effects to modulate the thermal transmission property of a material, as demonstrated e.g. by the developed textile-based solar harvesting and transparent insulating heat collector (Engelhardt & Sarsour, 2015).

These examples show that although the idea to adapt the thermal transmission attributes of a building envelope is discussed since many years, but little has been realized. An adaptive capability in thermal insulating materials is a rather new aspect and seems to be a difficult goal. With the employment of adaptive properties of the glazing itself (switchable glazing, selective coatings) or adaptive thermal storage attributes (PCM), attempts are being made towards the adaptive U-value.

3.3.4 Conclusion

The implementation of adaptivity in façades is generally divided into two approaches: constructive integration of adaptive components (e.g. movable shadings), and physiological attributes of adaptive materials (e.g. integration of smart material). Herein, shading systems, or generally speaking kinetic systems, are currently considered established standard for adaptive façades.

Kinetic shading solutions seem also to form the main group when focusing on thermally adaptive façade solutions. Newer developments show further tendencies towards the use of smart materials that regulate either solar impact (switchable glazing's) or thermal transmission (phase change materials). Both are already established in the market, although their benefits for thermal comfort and energy performance are not yet fully assessed.

Developments at the conceptual or prototypical level focus directly on regulating thermal flows without shading tasks, such as solar-active insulation or self-adapting, kinetic systems. Their effectiveness and usability as a market-ready solution are currently unclear, as the technological challenges must first be solved. However, overall it seems that the developments move towards the use of smart, self-adaptive systems, whether they are controlled intrinsically or extrinsically via ICT. The combination of different materials, embedded controls and constructions seems to form another development direction. While both directions aim to lower extrinsic controls and more dynamic, their complexity in the deisgn and operation, as well as maintenance is unclear. In the following section, some of these aspects will be evaluated in order to get more clarity about this.

3.4 Effectivity of adaptive façades

Evidence on the benefits of '*adaptive façades*' still is very reluctant, which could be due to the very different interpretations of its role. Various approaches currently exist that describe concepts, processes and applications differently depending on the perspective. It is important to understand the purpose behind the developments of modern adaptive façades in order to identify possible needs for improvements.

Therefore, to get a rough overview of what stakeholders in the building sector understand by effective 'adaptive' façades, following questions are examined: *What are the advantages and disadvantages of 'adaptive façades'?, What are the current opinions in the market? What are the challenges and needed benchmark criteria?*

In order to conclude with critical success factors for the design and operation of adaptive façades, relevant criteria are then extracted from this examination and summarized as so-called '*design effectivity*' criteria. This criteria shall serve as evaluation tool for the effectiveness of the actual cases and later developed models.

3.4.1 Methodology

For this examination, conclusions on the role of adaptive façades in practice are derived from the report on the results of expert interviews conducted by Shady Attia within the framework of COST TU1403 by (Attia, 2019). This report is one of the very few publications that address the market perspectives and opinions on the topic. It therefore serves as a guide for this discussion, and is supplemented with findings from the publications on the reviewed case studies.

3.4.2 Technical advantages and disadvantages

The technical advantages of adaptive façades is generally seen in (a) the responsive capability contributing to a certain functional goal and user need, (b) possible space gains (elimination of suspended ceiling systems, reduction of ducts by displacement of building services functionalities into the façade), (c) the feasible realization of complex multi-functionality via customized prefabrication and hence, possible reduction of costs in operation, (d) the high potential for cost-effective refurbishments (replacement of parts), and (e) the higher individual user satisfaction through decentralized control of indoor comfort parameters.

The technical disadvantages of adaptive façades are seen in (a) the risks related to the increased design and construction expenses, including higher risks to guarantee a smooth operation due to the involvement of many stakeholders from various fields, (b) the increased costs and time due to the complexity in manufacturing, installation, and operation, (c) the missing standardization, (d) the missing full assessment procedures of such systems, (e) the higher level of maintenance required by complex systems, (f) the needed access to decentralized components, and thus, economic and logistical challenge for the facility management, and (g) the potentially higher energy consumption due to individual (inefficient) user behaviour or overloaded system settings.

3.4.3 Market perspectives

The perceptions about '*adaptive façades*' vary depending on the perspective from which those involved in the construction process view them: the perspective of architectural and design position, represented by architects, defends the design flexibility, a sensitive interaction design between users and the architectural elements, or visibility of the measures. But also pragmatic criteria such as maintenance and economic framework are considered when assessing successful adaptiveness of a façade. Since maintenance has a direct effect on the economic aspects of a building, it is a valid criterion for all stakeholders. For example, cleaning and replacement of parts must be easily accessible and cost-effective. This aspect often takes precedence over design requirements. Sensitive interaction with users and the building is a motivator in the initial phase of the design process, but loses its driving force in the realisation phase, where economic issues often leads to pragmatic solutions. Energetic performance targets are least frequently mentioned by this perspective. What architects share with the next stakeholder group, the so-called technical specialists, is the desire to 'keep it simple'.

The perspective of technical specialists is represented by engineers, planners or manufacturers of adaptive components and systems. The specialist view associates adaptivity with the task to realize changeable properties in order to achieve certain goals in the indoor comfort or energy performance. Furthermore, the realization of architectural intentions must be considered and challenge the visual and functional levels. The view on the effective adaptiveness perceived by this group largely depends on the products, systems, materials or analyses, tests and realization processes with which the interviewed are familiar. Kinetic systems are being mentioned most frequently as established adaptive products, followed by smart functions of glazing‘s. Security issues for smooth operation are the key target to follow. Interestingly enough, adaptivity is also repeatedly interpreted as the ability to replace individual components: the degree of effective adaptivity is measured by the quick and easy exchangeability of parts and components in the façade. Thus, optimized prefabrication and mass customization, like in the automotive industry, are the main interest of this group.

However, for most of the interviewed from both groups, modern adaptability is linked to intelligence of controls and sensors that enable a dynamic, on-demand behaviour. A core focus in recent developments is therefore laid on control hardware (sensors, actuators, operation) and control software for steering the system. The potential of artificial intelligence is mentioned several times in this context with highly adaptive solutions, since systems become more complex by combining user, building and environment parameters and can no longer be sufficiently optimized by 'manual' control profiles.

Building-related boundary conditions, such as physical constraints (wind loads, snow or ice, pressure differences, etc.), safety aspects or material durability and reversibility are critical target criteria that must be checked, just like stability and robustness of the system. These are seen decisive criteria.

In the operating phase, operability and usability becomes important, i.e. overriding control by users or automated building technology profiles. Usability is often linked to user satisfaction and comfort issues. However, since post-occupancy evaluations (POE) or, more generally, monitoring to verify these target criteria are rarely carried out, or only on a fragmental basis, their achieved effectiveness is unclear. An assessment routine for adaptive façades is not yet established. So far, assessments on the adaptive system level have focused on the effects on indoor comfort, energy performance or user interaction. The effectiveness of the system itself, its components, control settings, etc. remains a kind of 'black box' - at least according to the interviews and responses from the market. Assessments are carried out at product level only.

Overall, the economic framework appears to be the most important factor and also barrier in the realization processes, whereat the investment costs are most often mentioned, followed by the maintenance costs and the return cost factor. New economic models, such as leasing models or concepts of the circular economy field are mainly discussed on academic level or within research projects.

3.4.4 Implementation barriers

Per definition, adaptive façades are classified by the level of its operation system, intelligent automatization and physical embedment of the adaptive function. Almost all interviewed experts in the market review see the main advantage of modern adaptive façades in the ability to adapt automatically to changing climatic conditions. Running a building more energy-efficient seems to be less important than meeting higher comfort quality and user satisfaction – although these criteria are finally linked to energy efficiency. The most important decision criterion for most seems to be the time-effective balance between development and available solutions. The intentions for adaptiveness are not necessarily linked to sustainable concepts. Most of the experts also agree that adaptive solutions appear to become more sophisticated and complex in the planning, construction, operation and maintenance, while the wish for 'simple solutions' in terms of maintenance but also design development increases likewise.

Challenges are also seen in the inclusion of other, unfamiliar fields, such as mechanical engineering, software engineering, computational design, etc. A good cooperation is considered the main success factor. Another success factor for increasing the number of adaptive façades is the standardization; this is not yet as far advanced as in other industries, such as in the automotive sector. Size, amount and customization of components determine costs. Therefore prefabricated processes are critical to optimize the costs and increase the implementation of adaptive solutions likewise.

The lack of standardization together with the higher costs of customized solutions are considered huge barrier for the implementation of adaptive façades in the market. The higher costs compared to standard façade solutions with few functional parts are crucial. With fully adaptive façades, the costs per m² can easily be doubled (cf. Attia, 2019, p. 24). An insufficient or unsatisfied usability and control of adaptive façade also affect the costs and thus seen as the main 'operation' barrier of adaptive façades. The implementation share of adaptive high-tech façade is estimated by most of the interviewed experts between about 3-10% (cf. Attia, 2019, pp. 35, 46, 51). Depending on how adaptivity is understood, this share is also set at about 90%, because basically any movable or functional façade part, such as windows or shading systems, can be considered adaptive (cf. Attia, 2019, p. 54).

Interestingly the various experts are not consistent with the ranking of the most critical success factors for adaptive façades in practice: costs, user satisfaction or energetic performance. Depending on the role and background of the experts, these factors are set in different orders, although costs appear to be the biggest issue for most of the experts, while user satisfaction is seen as a first priority.

3.4.5 Assessment constraints

Realized adaptive façade solutions are currently system assemblies of additive, mono-functional high-tech components and controls that are provided by different industry branches. Each part in this system fulfils a single, exclusively certified function, without considered interaction behaviour with the whole system. Technical compatibility issues (particularly if parts must be exchanged), maintenance contracts or guarantee issues coming with this are yet poorly solved. The complexity within the system and the lack of knowledge about the interrelations, and finally the missing performance monitoring to understand the operation and needs for improvements, pose high risks for the involved stakeholders.

Particularly the missing performance assessment standards for adaptive features and behaviour makes it nearly impossible to identify the benefits of adaptive façades. Standard building calculation and testing to assess the energy performance abstract adaptive functions into simplified static features or neglect their dynamic characteristics in order to calculate the performance. Thus, there is only little quantitative evidence of the real performance and contribution of adaptive façades to the energy efficiency. This concerns have been discussed in publications of COST TU1403 'Adaptive façades network' (Favoino, 2018).

Although comprehensive information is provided on the level of the products and on the description of adaptive system features, no comparable indication about the performance or comfort improvement in relation to traditional solutions can be found in the investigated case studies.

Kuhn et al. (2011) mentioned this problematic in the context of transparent components with complex functions and proposed a new method for the assessment for transparent components allowing to keep the real performance capability by bypassing its complexity. The idea is to apply a '*black box*' approach to the investigated system and concentrate on the energy input/output features.

3.4.6 Conclusion

The main implemented group of adaptive façades are kinetic shading systems, as already concluded in 3.3.4. Their current challenge lies in the optimization of the automated control strategy, user interaction and durability – and economic optimisation. Design aspects such as complex 3D shapes and motions are tested in various projects and are considered as part of the parametric design challenges

The main challenge of future adaptive systems is to develop robust solutions that enable the needed adaptive function without imposing high maintenance efforts and short life-time expectancy. Complexity of functions is accepted if the production and design is feasible. The economic factor, including not only the planning and realization process but also the needed time and involvement of various contributors, is a decisive factor for the process. And overall, solutions should be flexible and physically adaptive to allow customization and design flexibility.

The level of controllable operation and automation imposes another important technical challenge for adaptive solutions. In practice, controls are seldom applied as an intrinsic, self-reactive function. The control over changes that directly influence the comfort situation should remain with the user. Considering market trends, however, control systems are currently undergoing a huge development towards stand-alone intelligence, as adaptive features will otherwise not reach their full potential due to weaknesses in manual or semi-automatic control. From the few monitoring and post occupancy evaluations available for adaptive façades, it can be concluded that the expected performance targets are nevertheless often missed due to failures in implementing the complexity of the system in the holistic context with the total building and users. Full controllability depending on user interaction and building management system is quite difficult and the more sophisticated a system is, the more susceptible it is to failure.

Functional conflicts, such as those that occur in thermal insulation (keep versus dissipate), are not solved by adaptive systems. There is too little evidence on the energy efficiency increase of highly adaptive solutions compared to standard solutions. However, there are observations on the decrease of the user satisfaction according to the market review. Finally, the performance expectations are often not fulfilled while the system complexity increases.

Following aspects can be considered for the design effectivity of adaptive façades:

- **Operation and automation level**: *What is the optimal balance between automated control and user interaction? How to reach the full potential of adaptive functions?*
  Related criteria are: self-reactive vs. manual, intrinsic vs extrinsic control settings. This must be investigated by technical performance evaluations, which is not focus of this work.

- **Design flexibility and implementation effectivity**: H*ow to standardize parts while keeping the flexibility for customization needs? How to effectively embed adaptive functions in systems without increasing maintenance efforts? How to design adaptive configurations which might be complex but not complicate in design and production?*
  Related criteria are: standardization and customization goals, scalability (small to big), impact on physical system, complexity in design and production. This question is taken further in this work.

- **Robustness in function**: *How to guarantee a performance function without adding too much failure-prone complexity to a system? How to ensure the needed adaptation in the operation? How to develop robust, long-living solutions?*
  Related criteria are: robustness (low maintenance, long life), effective operability, cost-effective 'simple' solutions. This is partly considered in this work by focusing on resilient solutions; the validation of this must be answered by follow-up projects focusing on technical prototyping and in-situ evaluations, which are not part of this work.

These aspects are transformed into following criteria that allow an assessment of concepts in regards to the market needs:

- Flexibility: Design configuration flexibility for reassembly, reuse, modularity,
- Scalability: Scalability of a unit, element or system to be useable in various applications,
- Robustness: Maintenance effort and redundancy,'simple' solutions,
- Complexity: Design and operation complexity.

The criteria are summarized under the group 'design effectivity criteria' and will be used for the evaluation of the actual cases and future biomimetic models in this work.

3.5 Classification of adaptive façades

The aim of this section is to identify those criteria needed to describe and to design adaptive functions of a façade. These criteria shall be used for the evaluation of cases, the identification and selection of biological analogies and the generation of biomimetic solutions. The criteria list is thus intended to support a systematic transfer process between the domains.

3.5.1 Methodology

For this purpose, various classification approaches of the adaptivity of façades are collected and compared (cf. Appendix 3-3). Based on literature reviews and stakeholder interviews about adaptive façades (cf. Fig. 3.11), these criteria are evaluated and structured into categories of similar intentions. Possible missing criteria are included in the final list of 'adaptive façade criteria'. The list will be arranged in a systematic tabluar form following the concept of Chapter 2 with unique IDs for each criterion. This should allow for parametric use in a later stage.

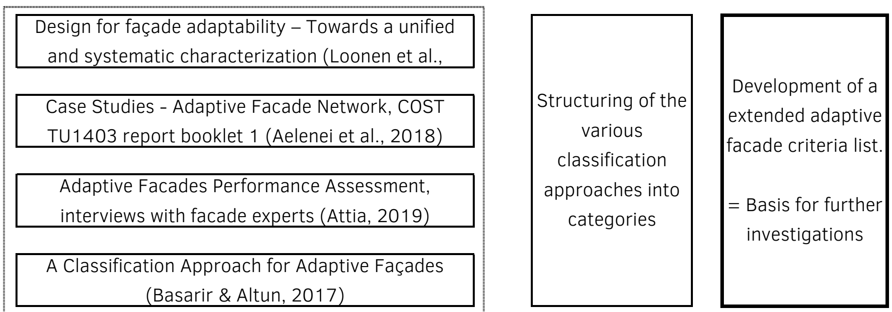


FIG. 3.11 Steps taken to identify classifications and create criteria for thermally adaptive façades (Graphical scheme derived from Fig. 1 in Başarır & Altun, 2018, p.81).

The complete classification comparison can be viewed in the Appendix section as Appendix 3-3.

3.5.2 Various approaches

Kirkegard & Foged (2011) suggest a systematic approach to design tasks for "*adaptive architecture*". As these are interdisciplinary processes, originated in several specific expertise fields, they suggest a systematic and interdisciplinary collaboration of following fields:

- 'material systems' (mechanical engineering, material sciences) that defines "*the physical presence, form, tactility and expression*" (Kirkegaard & Foged, 2011, p. 4),
- 'informational systems' (sensor technologies) deciding the feed-in of dynamic information,
- 'processing systems' (computational sciences) that deals with the handling of the information,
- and 'behavioural systems' (artificial intelligence sciences) that "*transform all this into an architecture that responds to many criteria's simultaneously*" (Kirkegaard & Foged, 2011, p. 4).

Within this context, they also suggested taxonomies for "*responsive and potential adaptable typologies*" based on responsibility capabilities, such as e.g. "*in-direct combined response systems*". These systems combine a multi-level adaptability by the "*primary structural system*" and a two-dimensional surface that form tetrahedral elements, and induce "*double curvature formations*" (Kirkegaard & Foged, 2011, p. 5).

The suggested taxonomy approach seems to be considered in the rather comprehensive classification done by Başarır & Altun (2017), which also includes principles for product development from Hubka & Ernst Eder (1987) and general adaptation criteria suggested by the authors. They subdivided the criteria into following classes (cf. Table 3-2): elements of adaptation, agents of adaptation, response to adaptation agent, type of movement, size of spatial adaptation, limit of motion, structural system for dynamic adaptation, type of actuator, type of control, system response time, system degree of adaptability, level of architectural visibility, effect of adaptation, degree of performance alteration and system complexity. The classes seem to be applied on various levels of detail, as some are related to very detailed specific aspects, such as structural system for dynamic adaptation, while others are rather general (agents of adaptation). It is difficult to extract a systematic from this approach although many aspects are valid criteria to be considered at some point in the design process.

According to Loonen et al. (2013), adaptation measures are either provided by mechanical components on macro scale (e.g. added or integrated subsystems in the building envelope), or by embedded properties of a material on micro scale (e.g. materials with adaptive physical or optical properties). Both are controlled via extrinsic control systems (sensor) or intrinsic, self-controlling behaviour (smart materials).

The classification approach of the case studies booklet in the COST programme TU4103 “Adaptive Façades Network” (Aelenei et al., 2018) proposes the classes: purpose responsive function, operation, components, response time, spatial scale, visibility and degree of adaptability. It is rather similar to the proposal of Loonen et al. (2013) since the autors were involved in the COST programme.

Another classification approach from Attia (2019) establishes a different perspective, as it does not focus on the design criteria for adaptive façades, but on the operation of such façades. Thus, the criteria of this classification follow the needs of occupants and facility management and do not address criteria for the adaptation mechanisms themselves.

In Table 3.2, all approaches are summarized and structured by following five categories of common characteristics:

- Category I deals with the information about the ‘set and actual states’ (ID: I-01 to 02) and the deviation from the required status (I-03). These criteria depict the monitoring, which is essential for any adaptation process to occur. The information gathered in Chapter 2 about the environmental and indoor comfort factors as well as the findings in the classification approaches are used to set up this category.

- Category II describes the control settings required to react to the status deviations and to initiate adjustments. This includes the type of control system, such as e.g. intrinsic or extrinsic types, or the control mode (manual or automatic). Thus, they refer to the '*technical*' setup of the adaptation system.

- Category III deals with the descriptive criteria of the actuation settings, which include adaptation functions and processes to achieve the goal, such as e.g. the type of task (block or admit energy) or response time and degree. It also serves to describe the type of adaptation, such as e.g. the reversibility.

- Category IV is concerned with the design of the physical appearance of an adaptation measure. These include constructive, structural or material-depending properties, on visible or invisible level. Furthermore, the level of embedment is assigned herein, such as 'material', 'component' or 'system'. The spatial needs of the measures or possible flexibility requirements for the design are also part of this category. Finally, design requirements, such as functional scale or visibility, are considered.

— Category V refers to the effects of the adaptation, whether it is comfort or energy-related. Thus, it represents the output type of an adjustment, which is related to thermal effects in the context of this work. This category also relates to category I and thus closes the circle between monitoring and effect.

TABLE 3.2 Investigated approaches to classification sets of criteria for adaptive façades.
The column "Cat." groups similar criteria in the various reviewed approaches. The full comparison of the various approaches can be viewed in Appendix 3-3.

Sources	Cat.	Main classification	Parameters
COSTTU1403 (Aelenei et al., 2018)	V	purpose	energy performance, IAQ, visual, thermal, acoustic comfort, control
	III	responsive function	prevent, reject, modulate, collect
	III	degree of adaptability	on-off / gradual
	III	response time	seconds, minutes, hours, day, seasons, years
	II	operation	intrinsic / extrinsic
	IV	components	shading, insulation, switchable glazing, PCM, solar tubes, integrated solar systems
	IV	visibility	no / low / high
	IV	spatial scale	building material, façade element, wall, window, roof, whole building
CABS (Loonen et al., 2013)	I, V	relevant physical domains	thermal, optical , air-flow, electrical
	III	time-scales	seconds, minutes, hours, day, seasons, years
	III	relevant physical behaviour	blocking, filtering, converting, collecting, storing, passing through
	II	control type	extrinsic / intrinsic
	IV	scales	macro / micro
	IV	robustness	sizing, partitioning, redundancy, scalability
	IV	Flexibility (static to flexible)	adaptability, multi-ability, evolvability
Expert interviews, table 1: criteria of adaptive façades (Attia, 2019)	I, V	energy & environmental performance	energy consumption, embodied energy, embodied carbon, cooling load, heating load
	I, V	functional performance	structural performance, acoustic performance, visual performance, thermal performance, fire resistance
	I, V	user experience and control	thermal comfort, visual comfort, comfort aspiration, feel and look
	IV	Interaction of façade system with building	engagement, command and control, action feedback, reporting technology failure
	IV	maintenance durability and circularity	product take back, material durability, appearance of façade, ease of cleaning, ease of replacing elements, global guarantee

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TABLE 3.2 Investigated approaches to classification sets of criteria for adaptive façades.
The column "Cat." groups similar criteria in the various reviewed approaches. The full comparison of the various approaches can be viewed in Appendix 3-3.

Sources	Cat.	Main classification	Parameters
Classification Adaptive façades (Basarir, Altun, 2017)	IV	elements of adaptation	material, element, component, façade
	I,V	agents of adaptation	inhabitants: individual inhabitants, groups of inhabitants, organisations
	I,V		exterior environment: solar radiation, outdoor temperature, humidity, wind, precipitation, noise
	I,V		interior environment: indoor temperature, humidity, amount/quality of light, air exchange rate, air velocity, sound level
	IV		objects: objects passing through, objects passing by
	III	response to adaptation	static / dynamic
	III	system degree of adaptability	on-off / gradual / hybrid
	III	system response time	seconds, minutes, hours, day, seasons, years
	III	type of movement	folding, sliding, expanding, shrinking, transforming in size/shape, scaling, rolling, twisting, rotating, push-out
	III	effect of adaptation	prevent, reject, admit, modulate (store, distribute) solar gains / prevent, reject, admit, modulate (store, distribute) conductive, convective, long-wave radiant heat flux / controlled porosity for exchange and filtering outside air / prevent, reject, admit, redirect visible light / prevent, reject, admit, redirect sound pressure / collect and convert wind energy / prevent, admit, modulate vision / change colour / change texture / change shape
	II	type of control	internal, direct, indirect, responsive in-direct, ubiquitous responsive in-direct, heuristic responsive in-direct
	II	type of actuator	motor-based, hydraulic, pneumatic, material-based, chemical, magnetic
	IV	size of spatial adaptation	nm, mm, cm, m
	IV	limit of motion	limited (small units), partial, inclusive, variable
	IV	structural system for dynamic adaptation	spatial bar structure consisting of hinged plates, foldable plate, structures consisting of hinged plates, strut-cable (tensegrity) structures, membrane structures
	IV	level of architectural visibility	not visible, no change; visible, no change; visible, surface change; visible, with size or shape change; visible, with location or orientation change
	IV	degree of perf. alteration	minor, medium, significant, variable
	IV	system complexity	system level 1 – 4 according to Hubka and Eder (1988)

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As a concluding remark, it can be said that the functional purpose or output appears in all classifications as the objective for the adaptation. The effect of the adaptation (or responsive function) is considered in the more technical classifications, as well as the type of control, response time, spatial scale and product related implementation criteria. The control type in the classification of Başarır & Altun (2017) is pointing to the tendency of evaluating adaptiveness in façades with ICT measures.
The degree of adaptability (on-off, gradual), the implementation level (material, component, system) and the visibility of the adaptation are only considered in two of the classifications. The functional process itself is described rather general in most of the classification approaches, such as the function 'prevent', 'reject' or 'collect', etc. The mechanisms by which these functions are achieved is not considered.

3.5.3 Adaptive façade criteria list

The categories from above suggest a systematic approach for the description of adaptive features that comprises basically three fields of actions: the materialization of the system (design of the adaptive function), the setting of the adaptation system that conducts the adjustments, and the perception of the adaptation by the environment.

In order to develop an 'adaptive façade criteria list', the defined categories and identified criteria from the review receive a unique ID, such as e.g. criterion "*III-04 Response type*" in category "*III-Actuation settings*". This is to make the list usable for parametric approaches.

Furthermore, the criteria in the categories are complemented by following aspects identified in the review about effectivity of adaptive façades: a) detailed input/output information about the status and signals to initiate adaptation, b) missing operational functions describing the process, and c) missing information describing the magnitude and order of measures that describe the impact and the constructive design and choice of material.

- As for a), adaptive façades allow a morphological and/or physical alteration that instantaneously influences e.g. transmission, exchange, conversion of energy and/or spatial or visual appearance. Alteration processes are initiated either by environmental stimuli (e.g. temperature changes) or given commands (automated controls) that induce a reversible change within a certain time period. The input/output signals and monitoring type that is responsible to monitor these processes need to be added.

- As for b), the operation of adaptive façades is not only based on energetic performance controls, but also on local factors, self-learning abilities or time-related dependencies. Missing information in this regards must be added.

- As for c), the magnitude and order of the measures describe the constructive tasks of the design and the final impact. Information about the type of component, its applicability, perceived response or constructive requirements must be provided. Adaptation measures request different constructive and formal considerations in the design, also including effective repetitive units, maintenance or robustness of the design. These factors are to be elaborated already in the early design phase. Thus, this aspect provides the design information for façade designers und must be comprehensive. Furthermore, information about type and perception of the impact on the environment and particularly users is important to design a robust solution.

Following criteria are added to the categories:

- **Category 'I. Monitoring'**: criteria about the '*signal recording/processing/transport*' (ID: I-04, 05 and 06) are added, because they present the physical settings to allow a monitoring. They also contribute to the robustness of the adaptation system.

- **Category 'II. Control settings'**: a new criterion '*evolvability*' (ID: II-04) is added that describes time-depending, self-learning characteristics. This criterion appears to be important for the controlability of the system.

- **Category 'III. Actuation settings'** receives the new criteria '*adaptation reliability*' (ID: III-06) and '*adaptation dependency*' (ID: III-07), which refer to a reliable functionality over the lifetime of the measure, including the dependencies on local framework conditions for proper functioning (e.g. orientation, solar impact) and reversibility of the function. This responds to the market's wish to keep the solution 'effective and reliable'.

- **Category 'IV. Physical appearance'** receives criteria critical from the market perspective, including the design effectivity criteria as defined in Section 3.4.6:

    - '*type of physical impact*' (ID: IV-02) refers to the impact on architectural elements and requirements that may be of concern, such as positioning of elements or ratio unit to area,

    - '*flexibility*' (ID: IV-06) deals with the design attributes of the adaptive measure as a multi-functional element, including multiple configurations and the flexibility for re-assemble the elements,

    - '*robustness*' (ID: IV-08) summarizes market-relevant criteria related to the reliability of the adaptive function, including its maintenance, service needs and resiliance,

    - '*complexity*' (ID: IV-09) addresses the design, implementation and operation complexity and refers to the market wish to '*keep it simple*',

    - and '*applicability*' (ID: IV-10) addresses the multiplication potential, plug-in or replacement characteristics of an adaptive measure once installed.

- **Category 'V. Effects'** receives a whole set of criteria, because it is least elaborated in the identified classifications:

    - '*physical principle*' (ID: V-02) sets the link to the thermodynamic principles that are applied and supports the description of the thermal adaptation mechanism. It shall also help to structure the findings in the translation process from biology to technology,

    - '*perceived response*' (ID: V-03) points to the user perceptibility of the adaptation and the associated acceptance by the user. Some adjustments are expected to induce an immediate response by users, while for others the adaptation is not perceived,

    - '*controllability*' (ID: V-04) is linked to user interaction. The communication and interoperability of adaptation measures with users, the system response and usability for users are considered by this criterion. Likewise, user acceptance of adaptive systems are part of this,

    - and the '*market implementation*' status (ID: V-06) displays the "*technology readiness levels* (TRL)" to define the solutions' maturity (Wikipedia, 2020).

TABLE 3.3 Adaptive façade criteria list, clustered into four categories that represent the functional settings. The identfied criteria from table 3.1 are summarized into a systematic list with IDs. The added criteria are marked bold. The design effectivity criteria are marked blue.

Type	Cat.	ID	Class	Sub-Class
INPUT / OUTPUT	I. MONITORING	I-01	Set values (ID: E, T)	defined data or condition to be achieved/maintained
		I-02	Actual values (ID: E,T)	observed data or condition in the actual state
		I-03	Input/Output deviation	description of thermal balance deviation
		I-04	**Signal recording**	**photometric (illumination), calorimetric (temperature), hygrometric (humidity), flow (gas, fluids), pressure (gas, fluid)**
		I-05	**Signal processing**	**thermal, chemical, mechanical, electric, acoustic, magnetic, hydraulic, pneumatic**
		I-06	**Signal transport**	
OPERATIONAL FUNCTIONS	II. CONTROL SETTINGS	II-01	Control task	prevent (block), dissipate, reject, reduce, modulate, distribute, filter, convert, collect (store), pass through, admit, etc.
		II-02	Control system	feedback system / actuation system
		II-03	Control type	intrinsic / extrinsic
		II-04	**Evolvability**	**time-depending characteristics considering the actuator/ sensor behaviour and their self-learning ability**
		II-05	Operation type	manual (User) / automatic (BMS) / auto-reactive (inherent property)
		II-06	Operation carrier	gas, fluid, currents, magnets, radiation, mechanical force, chemical reaction, thermal reaction
	III. ACTUATION SETTINGS	III-01	Task to perform	fold, shift, extend, expand, stretch, contract, shrink, roll up, wrap up, bend, colour change, phase change, density change, etc.
		III-02	Actuator type	thermal, chemical, mechanical, electric, acoustic, magnetic, hydraulic, pneumatic, etc.
		III-03	Response time	inherent reaction time depending on system or material properties: sec, min, hour, day, seasons, years (or none if passive)
		III-04	Response type	dynamic / static / hybrid
		III-05	Response degree	on/off / gradual / hybrid
		III-06	**Adaptation reliability**	**reversible / non-reversible; reliable functional operation**
		III-07	**Adaptation dependency**	**independent on location/dependent on location (e.g. sun path); hybrid dependency**
		III-08	Adaptation impact	morphological change (form, volume) / physiological change (patterns, colour) / hybrid change (both)

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TABLE 3.3 Adaptive façade criteria list, clustered into four categories that represent the functional settings.
The identfied criteria from table 3.1 are summarized into a systematic list with IDs. The added criteria are marked bold. The design effectivity criteria are marked blue.

Type	Cat.	ID	Class	Sub-Class
MAGNITUDE AND ORDER OF MEASURE	IV. PHYSICAL APPEARANCE	IV-01	Level of embedment	material / component or element / system; added before surface / on surface / in matter
		IV-02	**Type of physical impact**	**design criteria: impact on positions, size information (e.g. change in volume); adaptation ratio of unit to full element**
		IV-03	Physical characteristics	physical effects of structure or material characteristic
		IV-04	Functional scale	nanometer, micrometer, milimeter, centimeter, meter
		IV-05	Visibility	not visible, no change / not visible, change on other level / visible, no spatial change (on surface, etc.) / visible, spatial change
		IV-06	**Flexibility**	**design configuration flexibility**
		IV-07	Scalability	scalability of unit, element or function
		IV-08	**Robustness**	**redundancy, maintenance and service circles, lifetime resilience of system**
		IV-09	**Complexity**	**design complexity; implementation complexity (installation), operation complexity**
		IV-10	**Applicability**	**capability to act as multi-functional façade element; replacement and plug-in option; multiplication factor building sector, recycling potential**
INPUT / OUTPUT	V. EFFECTS	V-01	Goal	thermal, visual, hygienic and acoustic comfort, energy consumption, aesthetic/media communications
		V-02	**Physical principle**	**radiation, convection, conduction, evaporation, combined**
		V-03	**Perceived response**	**user perception of adaptation**
		V-04	**Controllability**	**user interaction (interoperability of measures with users)**
		V-05	Automation level	responsive (needs a command) / self-reactive (no command needed)
		V-06	**Market implementation**	**TRL levels according to EU classification**

The full version of the 'adaptive façade criteria list' can be viewed online as Appendix 3-2 due to its large data set.

3.5.4 Conclusion

To describe the design characteristics of adaptive façade solutions, a list of categories and subordinate criteria has been compiled that resulted from the literature review on classification approaches of adaptive façades. This list is systematically ordered by IDs in order to be able to use it for a continuous analysis and evaluation in the course of the work without losing the overview.

Gaps identified in the review of design effectiveness (cf. Section 3.4.6) were filled by supplementary criteria. Following structure is set:

- **Monitoring** (I) targeting at criteria for environmental data and signal processing,
- **Control settings** (II) describing the control and operation information,
- **Actuation settings** (III) providing information about the adaptation process, such as e.g. time, degree or type of the response,
- **Physical appearance** (IV) of the system representing the magnitude and order of the design-oriented measures and all design parameters, such as impact level, visibility, size information, robustness, etc. This category is the most important for designers to develop and optimize the design,
- and implementation **effects** (V) that describe of the impact and effectiveness of the adaptation.

3.6 Evaluation of cases

The final task in this chapter is to evaluate the collected cases from Section 3.3 against the developed criteria list (Table 3.3). The intention is to identify the functional goals of the cases, their effectiveness, strengths and weaknesses. Finally, the current situation of design effectiveness is presented by a visualization of the evaluation results based on use cases. This should provide a comparable framework for the development of biomimetic models.

3.6.1 Methodology

The evaluation of the adaptive façade cases and the visualization of use cases is carried out on two levels:

1. on the first level, a qualitative assessment of the functional purpose and design effectivity of the cases is made. Analogous to Chapter 2 (cf. Section 2.3.3) the cases are weighted against specific criteria chosen from the Table 3.3 to understand how important these criteria are assumed. The weighting method is the same as applied for Table 2.4: 1: no/low impact; 3: medium impact; and 5: high impact. Unrated criteria are marked with 'x' when e.g. information, own experiences and reports are not available.
   The estimated impact level is a weighting factor intended to illustrate the median importance that is given to each criterion in actual adaptive façades. Thus, it provides a rough insight into the current desires for their functionality.

   a. chosen criteria for functional purpose: the functional purpose (ID: F08.x) is defined in Chapter 2 (cf. Table 2.5) and represents the types of thermal adaptation goals, such as e.g. heat loss prevention, solar gain control or overheating protection.

   b. chosen criteria for design effectivity: as the review in Section 3.4 showed, the market perspective emphasizes robust and reliable solutions that are low in maintenance and cost-effective, and whose design does not induce any failure during operation. Also, standardizations should support these goals, while the same should not limit the flexibility and scalability in design. To describe this systematically, following criteria from Table 3.3 are defined: ‘flexibility’ (IV-06), ‘scalability’ (IV-07), ‘robustness / maintenance efforts’ (IV-08.2), and ‘complexity / design and control’ (IV-09).

   c. Aditionally, the cooling effect is roughly estimated for all cases applying the same rating scheme.

2. On the second level, the implementation frequency of selected criteria from all categories is shown. Based on the information in the case descriptions, the criteria that appear are counted. This is to make visible how often certain criteria are actually taken into account in the cases.

The chosen criteria that will be counted are combined in groups, of which group 1 and 4 have been already evaluated in level 1:

a group 1 shows the ‘functional purpose’ (F08.x) and ‘functional goal’ (V-01),

b group 2 assesses the ‘monitoring' and 'actuation' system by the criteria ‘signal recording’ (I-04), ‘control type’ (II-03), ‘actuator type’ (III-02) and one criteria from the ‘design effectivity’ list: ‘adaptation reliability’ (III-06),

c group 3 focuses on the ‘effects’ with the criteria ‘adaptation impact’ (III-08), ‘level of embedment’ (IV-01) and ‘visibility’ (IV-05),

d group 4 evaluates once again the ‘design effectivity’ criteria with ‘flexibility’ (IV-06) and ‘scalability’ (IV-07) to count the importance of flexible configurations and sizing options, ‘robustness/maintenance’ (IV-08.2) to count the importance of expected maintenance, and ‘complexity/design complexity’ (IV-09.1) to count how the efforts in the design process are seen,

e and group 5 represents the ‘market maturity’ by the ‘market implementation’ (V-06) showing the TRL level.

Finally, based on the results of the evaluation, use cases of the different types are visualised in a map showing their actual design effectiveness. For this visualisation the design effecitivy criteria are used, which enable then a comparison basis for the developed functional models.

3.6.2 Functional purposes and design effectivity

Table 3.4 shows the qualitative evaluation result of level one. The rating is derived from the findings in the literature about case studies. The evaluation is therefore an assumption and does not claim to be an actual assessment, as interviews with the developers would then have to be conducted. This approach rather demonstrates the method of evaluation.

The energy harvesting target is not evaluated: façade-integrated photovoltaics are included as adaptive solutions in the case studies list. The adaptiveness is designed to increase the efficiency of photovoltaics and do not influence the passive strategies in regards to thermal quality. Thus this type is neglected.

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TABLE 3.4 Estimated relevance or influence of the cases on the 'functional purpose' and 'design effectivity'.
The functional purpose (parameter F08.x), as defined in Chapter 2, represent the various goals for the thermal performance of façades. These are complemented by the 'design effectivity' criteria, as set in Section 3.4. The rating is as following: 1: no/low impact; 3: medium impact; 5: high impact. 'x' means that the impact is unknown/ not applicable.
Remark: case 14: 'energy harvesting' is not evaluated, as it is assigned to photovoltaics and not considered a passive adaptation measure for thermal quality.

			Functional purpose						Design effectivity			
			F08.1	F08.2	F08.3	F08.4	F08.5		IV-06	IV-07	IV-08.2	IV-09.1
Case	Type	Group name	Heat loss prevention	Thermal energy control	Solar gain control	Heat dissipation	Overheating prevention	Cooling effect	Flexibility	Scalability	Robustness/ maintenance effort	Complexity*
01	A: Kinetic systems	moveable shades, 1-dim	1	3	5		5	5	5	5	3	3
02		moveable shades, 2-dim	1	3	5		5	5	5	5	3	3
03		moveable shades, 3-dim	1	3	5		5	5	5	5	5	5
04		adaptive thermal façade (adaptive U)	5	5	3	1	1	3	5	5	3	3
05		kinetic components self-activated by wind							3	3	1	3
06	B: Hybrids combining kinetic motion and smart materials	pneumatic modulation of system	1	3	3		3	3	1	1	5	5
07		shape memory effect as adaptive structure			1		3	1		1		5
08		actuators with EAP, SMA, piezo-electric, etc.			1		1	1		1		5
09		hygromorphic shape changing materials		1		1		1		1		5
10	C: Smart materials	active thermal storage material	3	5	1		3	3	3	3	1	3
11		passive solar/ translucent insulation material	3	3	3		3	3	3	3	1	3

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TABLE 3.4 Estimated relevance or influence of the cases on the ‘functional purpose’ and 'design effectivity'.
The functional purpose (parameter F08.x), as defined in Chapter 2, represent the various goals for the thermal performance of façades. These are complemented by the 'design effectivity' criteria, as set in Section 3.4. The rating is as following: 1: no/low impact; 3: medium impact; 5: high impact. ‘x’ means that the impact is unknown/ not applicable.
Remark: case 14: 'energy harvesting' is not evaluated, as it is assigned to photovoltaics and not considered a passive adaptation measure for thermal quality.

Case	Type	Group name	Functional purpose					Cooling effect	Design effectivity			
			F08.1	F08.2	F08.3	F08.4	F08.5		IV-06	IV-07	IV-08.2	IV-09.1
			Heat loss prevention	Thermal energy control	Solar gain control	Heat dissipation	Overheating prevention		Flexibility	Scalability	Robustness/ maintenance effort	Complexity*
12	D: Multi-layered systems	switchable, smart glazing	1	1	5		5	5	1	3	3	3
13	D: Multi-layered systems	Selective adaptive coatings	1	3	5		3	3		5	1	1
15	D: Multi-layered systems	Heat modulation by fluids in façades	3	3	1		3	5	1	1	5	5
16	D: Multi-layered systems	Heat modulation via air cavity in façades	3	3	1		1	5	1	3	3	5
17	D: Multi-layered systems	System - multi-layered, thin-layers	1	3	1		3	3	1	3		
18	E: Structures and forms	Regulating surface structure design	1	1	3		3	3		1	1	5
19	E: Structures and forms	Geometry, form optimization	1	1	3		3	3		1	1	5
estimated impact level (weighting factor):			1	2	5	0	4	-	4	5	3	9

** The rating for the criteria 'complexity/design and control' differs from the others: 5: high complexity in design and control. 3: complexity either in design or control, 1: no complexity in design and control*

The results in Table 3.4 show that most investigated cases target at the avoidance of overheating and solar gain controls. Established examples are the kinetic systems (type A) and switchable glazing’s (type D). Static forms and surface structures target as well at solar gain control and overheating prevention, while only few types (such as e.g. type C: active thermal storage materials) focus more on heat loss prevention

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or thermal energy control. Multi-layered structures, particularly double skin systems (type D), do also have some strengths in regulating the thermal energy and heat losses but do not particulary focus on these. The newer developments using embedded actuators (e.g. SMA, type B) appear not to be designed for a specific functional purpose yet – at least no information could be found in this respect. None of the case studies show a dedicated impact on heat dissipation.

Most kinetic systems, except of 3D systems, and multi-layered systems are considered medium to low in the maintenance efforts, with exception of 3D shading systems, pneumatic systems and mulit-layered systems with fluids. This is because these systems contain critical elements with high maintenance requirements (such as fluids or air tightness). Smart materials and static forms possess a low maintenance effort.

In contrast, the complexity in design seems to be high for almost all types. This is because most systems, even if seemingly static, are high-tech designs that require special effort in development and installation. Some types deliver lower complexity in the control phase such as intrinsically adapting, smart materials that are complex in the design but need less attentionin operation.

The design flexibility (particularly the reassembly of its elements) varies depending on the type: it seems to be higher for kinetic systems, since the geometric parts of the system are modular and exchangeable. Design flexibility also seems to be sufficient for smart materials with kinetic adaptability, as long as they can be re-assembled or combined with other elements. It becomes less flexible for multi-layered systems and static structures, since they are designed in such way that a reassembly of parts would not be possible. This conclusion about the design flexibility applies almost similar to scalability.

Controllability seems to be high at kinetic systems and switchable glazing's. Unsurprisingly embedded adaptation that reacts autonomous on changes have a low rating in this regard, as well as optimized forms as they are not changeable once built.

Adaptation reliability is difficult to evaluate for smart materials as many solutions are on prototype level and not tested in buildings. But it is high for the established kinetic systems and switchable glazing's as well as coatings if they are market-ready. The reliability of adaptation is very much depending on local conditions for the static structures and surface designs and thus rated low.

3.6.3 Implementation frequency

The second evaluation level presents a higher detail degree by counting the implementation frequency of the selected adaptation criteria as listed in Section 3.6.1. For this evaluation, only those criteria are considered for which information is provided.

Although other criteria from the adaptation criteria list are also essential for the whole system to work, they only indirectly influence the early stage design decisions. For example, signal transport characteristics (Category I. Monitoring) may be electrical or chemical impulses embedded in the material or be part of a sensor system added to the façade system. In both cases, the design parameters of the overall system will look the same, but the technical details vary because the positioning of the sensor and cabling would have to be considered for the extrinsic solution. Thus, intrinsic and extrinsic solutions need to be considered separately.

Group 1: 'functional purpose' and 'functional goal'

As already assumed in the first evaluation, controlling the solar radiation in order to avoid overheating is the most applied functional purpose. Solar gain control is sometimes also referred to as overheating prevention, which means it is counted less frequently. Energy harvesting systems (which are earlier neglected, cf. Section 3.6.2) and thermal energy control are the second most frequently applied targets (Fig. 3.12, left), although there is no sole focus on thermal energy control, without solar gain or overheating control. Of all cases, thermal comfort is the goal that is most often mentioned (Fig. 3.12, right).

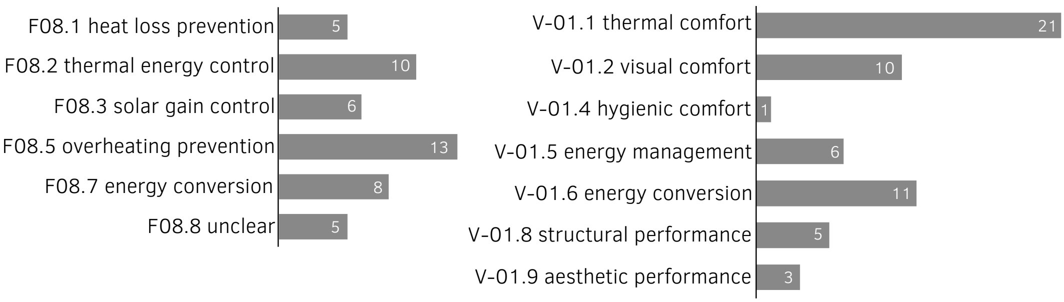

FIG. 3.12 Implementation frequency of criteria group 1 'functional purpose' (left) and 'functional goal' (right).

Group 2: applied 'monitoring/control' and ‘actuation' systems

In regards to the applied monitoring (Fig. 3.13, top left), most often temperature (calorimetric signal) has been measured, followed by radiation intensity (photometric signals) to achieve the functional goals. The control (Fig. 3.13, bottom left) of the systems occurs mainly by embedded solutions (intrinsic), but since many of the case studies are prototypes with embedded functionality (SMA), this conclusion may have to be put into perspective: intrinsic controls are the minority at market-ready solutions, because of the 15 cases at TRL level 8 and 9 only 5 use solely intrinsic approaches (cf. cases in Appendix 3-1).

Most of the cases use mechanical actuators, followed by chemical (Fig. 3.13, right). The dependence on local conditions for proper functioning seems to be present in most cases, but almost as many are independent. This can be traced back to the control options, as e.g. static systems depend fully on local conditions, while kinetic systems depend on orientation and solar path to function correctly, but can be controlled independently.

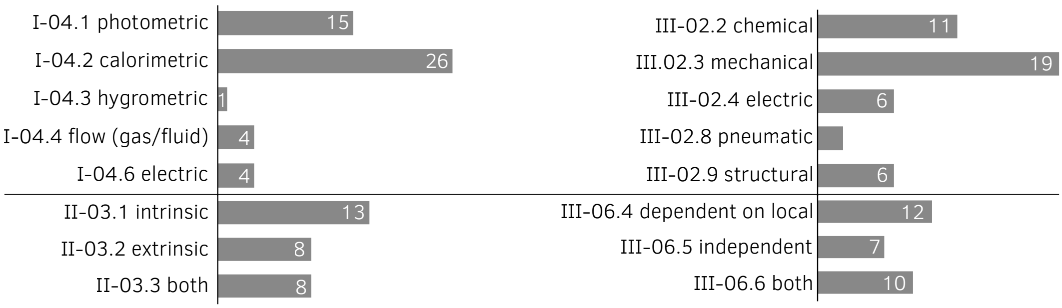

FIG. 3.13 Implementation frequency of criteria group 2 applied 'monitoring and control' (left) and 'actuation systems' (right).

Group 3: 'effects' and 'market maturity' of measures

The impact of the adaptation is equally divided between morphological and physiological effects (Fig. 3.14, top left). Most of the adaptation processes are applied on the component level (Fig. 3.14, middle left) and create visible and spatial changes to the facade; some change only their properties without changing their visible characteristics (Fig. 3.14, bottom left).

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Most of the studies cases are market-ready products applied in buildings, followed by tested prototypes (Fig. 3.14, right).

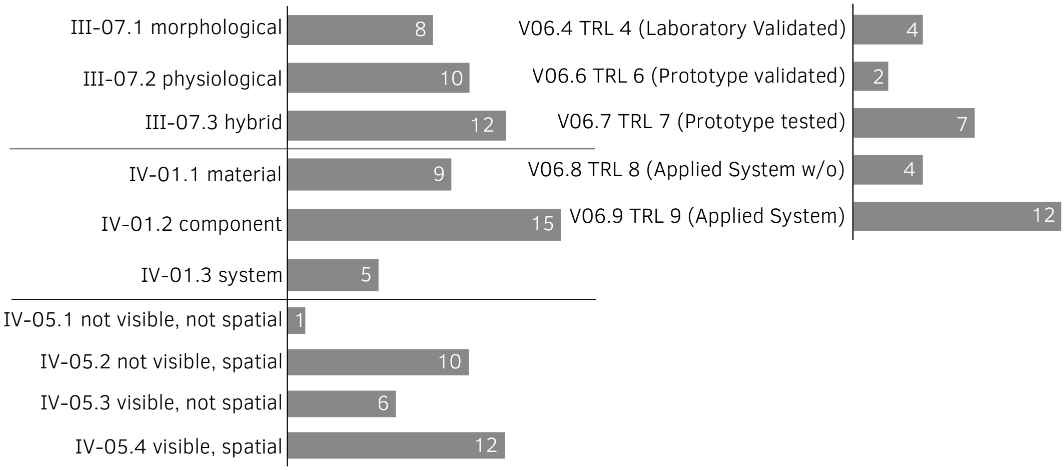

FIG. 3.14 Implementation frequency of criteria group 3 'effects' (left) and group 5 'market maturity' (right).

Group 4: 'design effectivity' comparison

Figure 3-15 shows the quantitative distribution of the design effectivity criteria applied in evaluation level 1: it shows the tendencies of medium to low flexibility and robustness in maintenance, medium scalability and high design complexity applied to most of the studies cases.

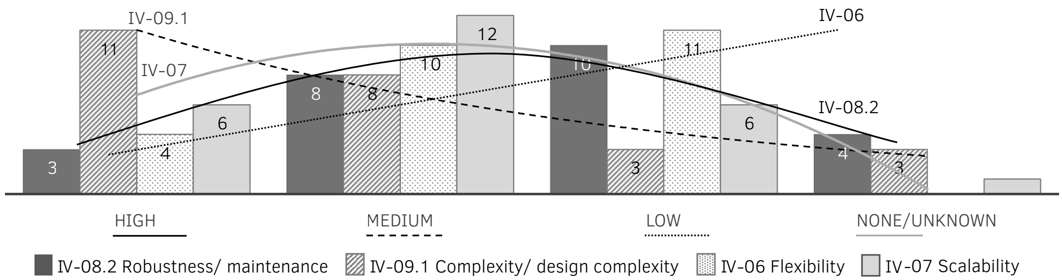

FIG. 3.15 Implementation frequency of criteria group 4 'design effectivity'.

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3.6.4 Weaknesses and strengths

The studied types of cases display certain strengthens and weaknesses regarding the selected criteria for ‘design effectivity’. These are mapped as use cases: mechanically driven, kinetic systems (type A) are mostly applied in the market but show some weaknesses particularly in the maintenance and partly design complexity. Smart materials with kinetic behaviour (type B), such as elements made of bi-metals, are well developed on prototype or laboratory level but not identified as market-ready products for façades. It is currently assumed that they have challenges to solve in almost all design relevant aspects. Smart materials with embedded adaptive properties and without mechanical adaptation (type C), such as switchable glazing’s or PCM, reached market maturity and wide acceptance and show good design solutions, except of some scaling and flexibility issues. Multi-layered systems (type D) with adaptive properties, such as regulative properties in the cavity of a glazed system, can be found on all technology development stages. They display possible weaknesses in all design criteria depending on the individual solution; it may be less critical for more developed double skin systems and more critical for less developed multi-layered systems with fluids. And finally, form-optimization approaches (type E) of building shapes and façade surfaces are found as built solutions as well as concepts. They are expected to have weaknesses when it comes to the design complexity, flexibility and scalability.

A visualization of this evaluation is provided in Figure 3.16. The figure shows a proposed ideal curve (*white line*) and the actual placement of each type as identified in the evaluation of the cases. This assignment is subjective, reflecting the studied literature and evaluation results.

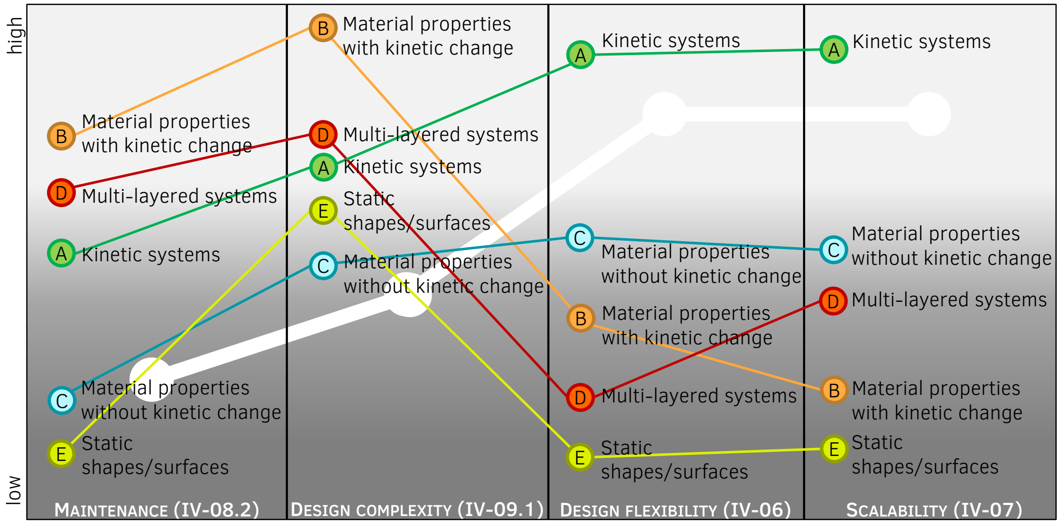

FIG. 3.16 Assignment of the adaptive façade types A to E to the design effectivity criteria. The white line presents the target.

According to Figure 3.16, smart material properties without kinetic change (type C) follows the ideal curve at closest, while smart material with kinetic adaptation (type B) show the greatest deviation from the curve. All others show a strong deviation for some criteria and an approximation for others. Almost all types possess a rather high level of complexity in the façade design phase, and lower scalability and design flexibility.

The most established type according to the cases studies, kinetic systems (type A), seems to reach a high degree in scalability of the units. Their design flexibility and complexity depends on the individual system type and thus is placed in the upper middle. The robustness and reliability in operation of auto-reactive smart materials with kinetic adaptation (type B) is unclear due to the limited experience in use. This applies to e.g. shape memory alloys and polymers, hygro-morphic or other self-reactive materials. It has been set rather high but this cannot be validated. Established smart materials in the building sector, such as switchable glazing, PCM and solar-active insulation materials achieve a higher degree of reliability, but have less user interaction than kinetic systems – with exception of smart glazing's, which are not autoreactive.

This mapping is also applied on the identified functional models to compare them with the respective functional group.

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3.6.5 Conclusion

It can be concluded that heat dissipation is the least considered functional purpose in the studied cases, while overheating prevention is the most often considered one. Heat loss prevention and thermal energy control are targeted by use of smart materials and few multi-layered solutions, overheating prevention and solar gains are addressed more by kinetic solutions of any kind or geometric optimizations.

Smart materials without kinetic actuators, some multi-layered systems and building form optimizations can be considered as robust, as they need little maintenance in operation. Kinetic systems (including those with smart materials) and some multi-layered systems, particularly with fluids, are considered less robust in this context. The fewer moveable parts, the fewer joined elements, and the less contact with the environment, the more robust. Some cases could not be evaluated for this criteria.

Design complexity increases with kinetic systems (both type A and B) and shape-optimized geometries, since many boundary conditions and dependencies must be known in the design process. Scalability and design flexibility appears more difficult for smart materials with morphological changes, multi-layered systems and geometric form optimization. Controllability is only seen well-solved in kinetic systems (without smart material behaviour) and for switchable glazings.

3.7 Refinement of search fields

Comparing the potential adaptability, as it was assumed for the selected design measures in Chapter 2, to the available solutions, following conclusion can be drawn (cf. Table 3.5):

- **Adaptive solutions addressing thermal insulation (P01)** seem to be primarily at concept or prototype stage, except for very few systems on the market that vary solar irradiation rather than thermal conductivity. Most of the developments are solar-active thermal insulation materials allowing angle-depending solar irradiation on the back side while being static. Products are made of glass or cardboard, such as e.g. the solar honeycomb façade element by GAP Solutions (GAP Solutions, 2017). Only few solutions allow a dynamic adaptation of the solar irradiation, such as e.g. the lamella system Thermocollect (2017).

- **Adaptive approaches for thermal mass (P02)** are addressed by the use of phase change materials (PCM). Their market suitability is proved for many years. Their effectiveness in façades is however still under investigation, particularly in regards to the implementation options for façades. Current research projects try to identify their benefit to balance the heat transfer and use the solar potential with a time delay (Wüest et al., 2020) or its potential for refurbishments (Vigna et al., 2018) (Liu et al., 2019) (Sarihi et al., 2020). It seems that PCM effectiveness in façade systems are limited due to the boundary and system conditions but contains a certain potential to contribute to the balance of thermal transmission peaks.

- No approaches utilizing ***t*****hermal boundary layer effects (P07)** have been found in the identified cases. Thermal boundary effects occur in all systems, but are considered a calculation factor for thermal transmission assessments.

- Intentional applications for **passive cooling strategies using radiative attributes (P08.1-2)** have not been found - except of the vernacular examples using bright colours to increase the reflectance. For evaporative cooling strategies (P08.3-4) applied in façades, vernacular measures in hot arid climate zone can be mentioned, such as the well-known clay jar filled with water and placed in a window mashrabya (ElSoudani, 2016) and modern deviations of this principles, as discussed e.g. by Bagasi & Calautit (2020). There are also modern prototypes that incorporate passive evaporative cooling principles in masonry components, such as e.g. the "*Cool Brick*" by Emerging Objects (2019) or the project "*Mashrabiya 2.0*" (3D printed ceramic evaporative façade) published by Leslie Forehand (2018). These solutions may be applicable in certain climatic regions. In the Central European climate, which forms the framework in this work, their use is probably not effective. Due to the high technical standards of façades, which do not allow moisture transport through a wall system, a direct contribution of an evaporation effect is neglectable.

- Parametrically developed **building forms that target at efficient energy performance, by e.g. optimising solar irradiation areas (P09)**, are not uncommon in architectural practices. Many architectural concepts and projects even go beyond the form-optimised building shape and design specific façade morphologies that are ideally adapted to changing sun courses; the possibilities of such parametric façade optimisations are being explored by renowned architectural firms as well as by young research groups, such as rat[LAB] (2021). In their mulit-objective design approach, specific local conditions (e.g. solar path) define the design outcome. This approach is not entirely new (cf. vernacular architecture), but has reached a higher degree of precision and complexity by the use of digital tools.

TABLE 3.5 Search scope based the results of current adaptive façades solutions.
The table is a refinement of the thermal design measures selected in Chapter 2 (table 2.5) by the evaluation of available adaptive solutions done in Chapter 3. The table shows the potential adaptability as assumed in Chapter 2 and the available adaptability as identified in the case studies in Chapter 3. (ample: n = no, m = maybe, y = yes).

ID	Class	ID	Sub-Class	Performance intention	Potential adaptability (Chapter 2)	Available adaptive solutions
P01	Thermal insulation	P01.1	System design	F08.1 Heat loss prevention F08.2 Thermal energy control	y	n
		P01.2	Material properties			
P02	Thermal mass	P02.1	System design	F08.2 Thermal energy control F08.5 Overheating prevention	m	y
		P02.2	Material properties			
P07	Thermal boundary layer	P07.1	System design	F08.2 Thermal energy control F08.4 Heat dissipation	m	n
		P07.2	Surface properties			
P08	Passive cooling at surface	P08.1-2	Radiative cooling - system design and material properties	F08.4 Heat dissipation F08.5 Overheating prevention F08.6 Energy exchange	m	n
P09	Shape and form	P09.1	Solar exposure - system design	F08.3 Solar gain F08.5 Overheating prevention	m	y
		P09.2	Transparency share / design		m	y

Table 3.5 marks those selected search fields in dark blue for which adaptive solutions are not available: thermal insulation (P01) and passive cooling (P08). For thermal boundary layer (P07), no adaptive solutions are identified, but its potential is assumed unclear. For thermal mass (P02) and shape optimizations (P09). adaptive solutions have been identified.

3.8 Summary

Five main types of adaptive façade solutions have been identfied: kinetic systems, smart material solutions without or without kinetic behaviour, multi-layered structures and static construction with a certain passive adaptability. From these types, the first group seems to be most advanced and makret-ready, followed by some smart material solutions (PCM) and multi-layered systems (switchable glazing's). Many of the other groups are still on conceptual or prototyping level.

The major goal of most of the implemented adaptive façades is to enable a responsive behaviour in order to control solar gains or prevent overheating. Only few solutions are targeting exclusively thermal flow modulations. There are some critical factors seen by the market, such as design flexibility, maintenance efforts, customization and prefabrication to lower the costs, reliability, robustness and exchangeability (which can be called applicability). And finally, an optimized design ('keep it simple') is seen important to increase adaptive measures in façades.

From this findings, so-called 'design effectiviy criteria' are developed in order to asses the actual façade types and the later developed biomimetic models.

The design criteria of adaptive functions of façades have been derived from a literature study on various classification approaches and then transferred into a systematic list of criteria. Following aspects are considered in the list:

- **Monitoring** = a constant screening of the environmental conditions and effects of adaptation measures: environmental data (indoor, outdoor), signal recording, processing and transport. Devation of actual and target conditions. The criteria for the monitoring are collected in the group of 'I. Monitoring'.

- **Operation settings** = the setup to control any adaptation: type of action, control system settings, operation carrier, etc. The operation tasks are summarized in the criteria group 'II. Control settings'.

- **Actuation settings** = type of actuation: task to perform, reliability settings, response behaviour (static - dynamic, manual - self-reactive, reversibility, reaction time, etc.), system intelligence, etc. This group is described by criteria of 'III. Actuation settings'.

- **Physical system** = type of physical design that allows the adaptive function: level of embedment, scales, complexity of design, visibility, robustness, etc. This group is described by criteria summarized in ‘IV. Physical appearance’.

- **Effects of action** = type of effect: user perception, response to users (override option), automation level, thermophysical effects, etc. The impatc is described by the criteria group of ‘V. Effects’.

Each criterion of the five groups is given a unique ID (Fig. 3.17), by which it can be clearly distincted and assigned in each phase of the transfer and design process. The total adaptive façade criteria list serves as evaluation, selection and development tool in this work. It can be found online as Appendix 3-2 and as a checklist in Chapter 4 (Appendix 4-1).

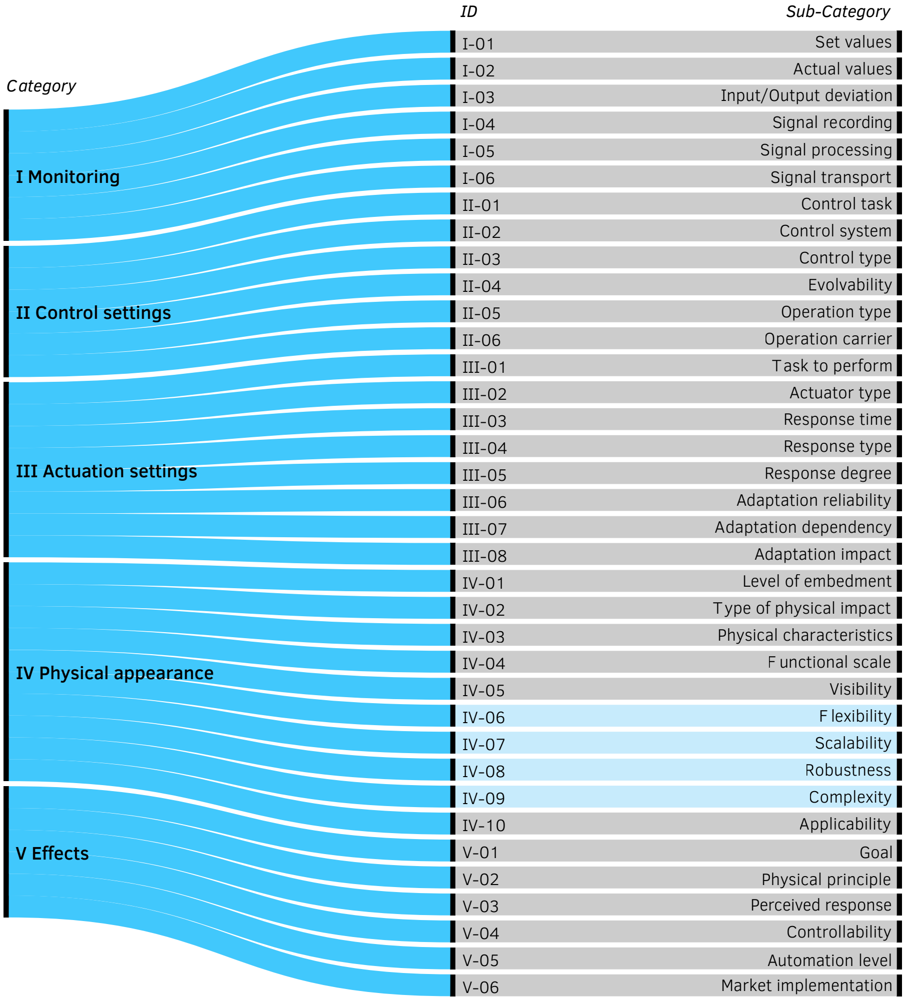

FIG. 3.17 Adaptive façade criteria list.
Those sub-categories that are marked blue are relevant for the 'design effectivity' evaluation. The whole list and detailed description for each sub-category can be viewed in Appendix 3-2.

The results of the design effectivity evaluation, which serves as an reality check of the measures, were transferred into use cases and visualized as a map in Fig. 3.16. The figure shows the actual expected effectiveness for the five main types of adaptive façades (= use cases).

Furthermore, the evaluation helped to narrow down the search fields defned in Chapter 2 to those fields that might possess a potential contribution to cooling energy reduction and could be solved by design approaches. Following search scope is considered referring to the functional principles of Chapter 2 (cf. Fig. 2.16):

- **Thermal transmission adaptations (F01)** addressing '*thermal insulation*' (P01): thermal transmission adaptations may contribute to many functional purposes, such as the heat loss prevention (F08.1), thermal energy control (F08.2), heat dissipation (F08.4) and overheating prevention (F08.5). The reason for the selection is the identified conflict of thermal insulation in CHapter 2, which has not yet been solved by the existing adaptive solutions. Some examples relate to the modulation of the thermal storage capacities by regulating solar radiation. However, solutions that support an active control of the thermal conductivity have not been found in the case studies search. An adaptive controllable thermal conductivity (either by material or structural characteristics) might contribute to lower the cooling energy need in the warmer seasons where night cooling could be more effectively used.

The search question is whether adaptive thermal conductivity can be found in nature? And if so, how do biological role models adapt thermal conductivity and transmission?

- **Radiative energy modulation (F06)** addressing '*passive cooling strategies*' (P08): radiative energy modulations may contribute to the functional purposes heat dissipation (F08.4) and overheating prevention (F08.5). Such radiative processes are related to surface properties and geometric settings that could possibly improve or even establish an active cooling function. The hypothesis is that, regardless of ambient conditions, heat dissipation could be increased by utilizing radiative attributes of the material. Since this contribution to cooling can be added on existing design concepts (surfaces of adaptive elements), a rapid development of solutions might be possible.

The search question is whether and how biological role models use radiative principles to initiate heat dissipation? And if so, which design features are important to consider?

The search field '*thermal boundary layers*' (P07), thus micro air flow effects on the outer surface, is based on the assumption that this measure may support heat dissipation – which is comprehensible as many examples show positive effects (cf. cooling of skin). Most examples in vernacluar architectue and biology likewise have a common basis: a direct connection, or thermally speaking, a good thermal conductivity to the surface to be able to dissipate heat quickly. However, the utlilzation of such air flow effects to increase heat transmission is not intended for façades, as they are designed to protect from such uncontrollable environmental conditions. In addition, the influence of thermal boundary effects is expected to be greatly mitigated by thermal insulation. Thermal boundary effects may influence the urban heat island effect, which in turn indirectly affects the thermal comfort and energy efficiency of buildings. However, its role and possible contribution to cooling would need detailed investigation by the use of aerodynamic simulation tools in order to better understand its magnitude. This topic is reserved for further work but will not be pursued in this work.

For the supportive search fields, '*thermal mass*' (P02) and '*form and shape*' (P09) established adaptive solutions are found. Thus these search fields will not be taken further in the analogy search.

In general, design relevant aspects that support adaptation processes will be further considered, even if they do not associated directly with the scope questions.

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Appendices

Appendix 3-1 Case studies list, full version

Online: https://data.4tu.nl/account/collections/5811071

Appendix 3-2 Adaptive facade criteria list, full list of parameters

Online: https://data.4tu.nl/account/collections/5811071

Appendix 3-3 Comparison of adaptation classifications

PHASE 1: CLARIFY THE PROBLEM (III: Formulate the criteria for search field)

Main classification		1. sub-class		parameters								
COSTTU1403 (Aelenei et al., 2018)	purpose			thermal comfort	energy performanc		IAQ		visual perfor-mance		acoustic performance	
	responsive function			prevent	reject		modulate		collect			
	operation			intrinsic	extrinsic							
	components			shading	insulation		switchable glazing		PCM		solar tubes	
	response time			seconds	minutes		hours		day		seasons	
	spatial scale			building material	facade element		wall		window		roof	
	visibility			no	low		high					
	degree of adaptability			on-off	gradual							
CABS (Loonen et al., 2013)	time-scales			seconds	minutes		hours		diurnal		seasons	
	scales			macro	micro							
	control type			extrinsic	intrinsic							
	robustness			sizing	partitioning		redundancy		scalability			
	flexibility			(fixed, static)	(flexibel)		adaptability		multi-ability		evolvability	
	relevant physical behaviour			blocking	filtering		converting		collecting		storing	
	relevant phys-ical domains			thermal	optical		air-flow		electrical			
Classification Adaptive facades (Basarir, Altun, 2017)	elements of adaptation			material	element		component		facade			
	agents of adaptation	*inhabitants*		individual inhabitants	groups of inhabitants		organisations					
		environment	*exterior*	solar radi-ation	outdoor temperature		humidity		wind		precipitation	
			interior	indoor tem-perature	humidity		amount/qual-ity of light		air exchange rate		air velocity	
		objects		objects pass-ing through	objects passing by							
	respond to adaptation agent			static	dynamic							
	type of movement			folding	sliding		expanding		shrinking		transforming in size/shape	
	size of spatial adaptation			nm	mm		cm		m			
	limit of motion			limited (small units)	partial		inclusive		variable			
	structural system for dynamic adaptation			spatial bar structure consisting of hinged plates	foldable plate structures consisting of hinged plates		strut-cable (tensegrity) structures		membrane structures			
	type of actuator			motor-based	hydraulic		pneumatic		masteri-la-based		chemical	
	type of control			internal		direct		indirect		responsive in-direct		

TOC

		control									
		integrated so-lar systems									
		years									
		whole building									
		passing through									
		noise									
		sound level									
		scaling		rolling		twisting		rotating		push-out	
		magnetic									
	ubiquitous responsive in-direct		heuristic responsive in-direct								

>>>

PHASE 1: CLARIFY THE PROBLEM (III: Formulate the criteria for search field)

Main classification		1. sub-class		parameters								
Classification Adaptive facades (Basarir, Altun, 2017)	system response time			seconds		minutes		hours		day		
	system degree of adaptability			on-off		gradual		hybrid				
	level of architectural visibility			not visible, no change		visible, no change		visible, surface change		visible, with size or shape change		
	effect of adaptation			prevent, reject, admit, modulate (store, distribute) solar gains		prevent, reject, admit, modulate (store, distribute) conductive, convective, long-wave radiant heat flux		controlled porosity for exchange and filtering outside air		prevent, reject, admit, redirect visible light		
	degree of performance alteration			minor		medium		significant		variable		
	system complexity (accord. Hubka and Eder, 1988)			level 1		level 2		level 3		level 4		
Expert interviews, table 1: Criteria of adaptive facades (Shady, 2019)	energy and environmental performance			energy consumption		embodied energy		embodied carbon		cooling load		
	functional performance			structural performance		acoustic performance		visual performance		thermal perfotrmance		
	Interaction of facade system with building			engagement		command and control		Action feedback		reporting technology failure		
	user experience and control			thermal comfort		visual comfort		comfort aspiration		feel and look		
	maintenance durability and circularity			product take back		material durability		appearance of facade		ease of cleaning		

Legend		
	4	functional purpose or output
	3	functional effect of adaptation
	1	functional action
	3	type of control
	3	response time
	2	degree of adaptability
	2	implementation level
	3	spatial scale
	3	product related
	2	visibility

	seasons		years								
	visible, with location or orientation change										
	prevent, reject, admit, redirect sound pressure		collect and convert wind energy		prevent, admit, modulate vision		change colour		change texture		change shape
	heating load										
	fire resistance		ventilation		water tightness abd air permeability						
	ease of replacing elements		global guarantee								

4 [Systematics] Translation rules

This chapter moves away from the applied field of '*thermally adaptive façades*' and concentrates on the translation task in order to define a guideline for the whole process. The goal is to understand the differences and bridges between biology and engineering and the needed rules and methods that are needed. For this, literature on suitable methods for such transdisciplinary transfer work is studied and basics on thermodynamic processes and on '*geometric rules*' are compiled. Knowledge about these topics facilitates the creation of a suitable translation process.

Thermophysical processes based on structural settings are the common denominator in this work. In this chapter, questions such as: *Which strategies apply thermal change processes for cooling?* are therefore discussed. The scratches made here in the depths of physics and especially thermodynamics are only on the surface with the intention of get a common baseline for a '*translation language*' (= guideline) between the target domain and the search domain.

The mission of this chapter is explained at the beginning in Section 4.1. Sections 4.2 to 4.4 provide basics on the common topics in both domains, biology, and façade design: thermodynamic principles with strategies to keep cool or warm, geometric principles that apply in both domains when creating physical solutions, and the adaptation mechanisms focusing on the peculiarities in biology and technology. The examination of geometric strategies is essential to the work in order to illuminate the options of constructive approaches for thermal adaptation of façades. The overview of the basics is also intended to build a methodological bridge between engineering and biology.

The chapter moves further on to transfer methodologies by introducing the biomimetic approach in Section 4.5 and translation methods for dynamic processes in Section 4.6. The intention is to identify a feasible transfer method for the design process in façade engineering. To this point, literature reviews are conducted to identify and prepare the basis for an own systematics.

Finally, based on the findings, an own transfer systematics is developed in Section 4.7. The systematics provides a method for each process step, from the search to the evaluation. In particular, it shows how the domains of biology and engineering can be linked without losing the function-oriented approach. A set of tools for the transfer task in Chapter 5 and 6, and the modelling and evaluation tasks in Chapter 7 is created. In addition, an 'selection and *evaluation checklist'* (Appendix 4-1) that refers to the corresponding criteria of the '*adaptive façade criteria list*' for each transfer step from Chapter 5 onwards is created.

4.1 Introduction

In order to identify and transfer biological principles, an understandable translation language is required. This should be prepared in such a way that various experts from the different disciplines can work with it. To accomplish this, a common basis must be found and rules created. Energy or heat flows follow certain physical processes whose strategies, mechanisms and basic rules regarding structural and physical factors are equally valid for biology and engineering. Thus, a guiding aspect that links both domains, engineering and biology, are geometric and physical laws, as these are the same in both disciplines.

Additionally, investigations about the adaptation process must be made, because it can be assumed that this is described differently in the two domains. Adaptation is a term that is defined individually in each discipline. In façade engineering, it is even a young and not yet completed definition process, as already discussed in Chapter 3.

The search for biological analogies uses a filter based, among other goals, on the definition of search key words. Thus, it becomes clear that the biomimetic analogy process is strongly driven by the involved knowledge background and intentions of the involved experts. Additionally, biomimetic transfer methods provide a certain degree of freedom in interpretation and creative translation, which also applies here. The process of identification, selection and interpretation of the selected organisms takes place in the framework of a (self-defined) transfer ethic that follows a subject-specific and professional interpretation of biological principles under the premise of a scientifically sound basic. In the case of this work, the transfer towards functional models intends to provide ideas for thermal adaptability within the context of façade construction. For this intention, the following approaches are considered:

- Physiomimetic approach: According to Rupert C. Soar (2013), one option about how to look at biological systems is to look at the '*transition processes*', not at the form or function. He suggests that nature is driven by processes – transient changes of energy, matter and information that generate form and function. For example, the gas exchange in termite moulds generate the way the ventilation tubes and branches and the form of the mould is set up. This approach is considered in the analyses and translation of selected biological role models by looking at the system-related adaptation processes, including the physical settings but also the non-physical information and relation between environment and matter, all summarized in the adaptation criteria list (also called parameter list). The suggestion of Rupert Soar appears very plausible and therefore the term "physiomimetic" has also been adopted for the title of this work in order to clarify the character of the translation.

- 'Constructal theory' concept: Another viewpoint that is considered is the "*constructal theory*" by Adrian Bejan and Sylvie Lorente (2008) respectively initiated by A. Bejan (2012), who points to the importance of *structural patterns* in nature that are designed to facilitate flow. This approach fits well to the tools of design engineering and also to the demand to focus on transition processes. Since the motivation of the work is to provide information useable for façade designers, the physical settings and the '*why*' something looks the way it does are crucial.

In the following sections, all aspects are discussed: the common basis in regards to physical and geometric laws, the particularities of adaptation processes and the complexity of translation processes. From these examinations, a specific systematics is developed that is applied for the search and analyses of biological principles, the transfer from biology to the engineering and generation of functional models.

4.2 Thermodynamic principles

The intention of this section is not to provide a comprehensive essay about heat transfer and thermodynamics – literature on this subject is extensive. Rather, the aim is to set the framework within which the analogy search and development of functional models takes place. Since the work deals with thermally adaptive functions, the following section explains what is meant by this respectively on what the functional search targets.

4.2.1 Heat flow types

Heat flow occurs whenever thermal equilibrium between two environments is not balanced. The underlying physical process is described by the thermodynamic laws, which use physical quantities such as temperature, energy or entropy to explain it.

Thermal modifications occur either via sensible heat flow (temperature differences) or latent heat flow (phase changes). Heat flow thereby takes places in three forms: conduction, convection, and radiation (Fig. 4.1). The temperature difference $\Delta T = T_1 - T_2$ is in all three forms a physical variable for the magnitude of the heat flow, while the surface geometry plays a critical role for the flow rate. Heat flow is thus closely linked to the attributes and geometry of a matter.

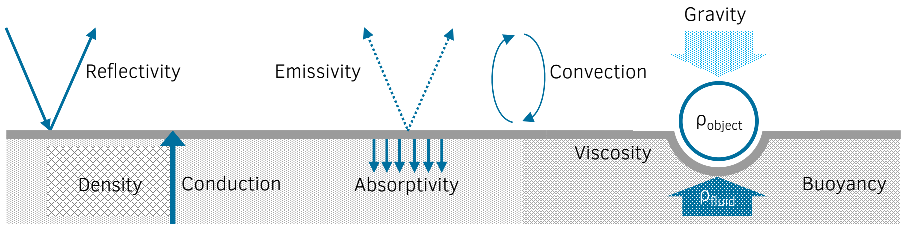

FIG. 4.1 Physical principles for thermal modification processes.

In the following, the three forms of heat flow are briefly explained in context to the geometric attributes.

Conduction

Conduction describes the heat flow in matter. It depends on the thermal conductivity, density, and specific heat capacity of the material, as well as a temperature difference (cf. Davies, 2004, p. 21ff):

- Thermal conductivity

$$\lambda = \frac{Q \cdot l}{A \cdot \Delta T} \quad [W/(m \cdot K)] \qquad [4\text{-}01]$$

where Q is the amount of heat transfer through the material,
l is the length, A is the body area, ΔT is the temperature difference.

- Density

$$\rho = \frac{m}{V} \quad [kg/m^3] \qquad [4\text{-}02]$$

where m is mass, V is Volume.

- Specific heat capacity

$$c_p = \frac{Q}{m \cdot \Delta T} \quad [J/(kg \cdot K)] \qquad [4\text{-}03]$$

where Q is the amount of transferred heat energy, m is mass, and ΔT is the temperature difference.

The values that are mainly used to determine the thermal quality of a building envelope component with the dimension-related R-value and its coefficient (U-value) (cf. Chapter 2, Section 2.2.2).

The thermal conductivity of materials is the key attribute to define the quality of thermal insulation. Bad heat conductors are good insulating materials. In general, materials with a low density are poor heat conductors. Material with low conductivity, such as porous and fibrous materials, are considered good insulators. It shall be noted that these materials are sensitive to moisture content and would increase their conductivity with the increase of moisture content.

Conduction, respectively the heat flux under stationary conditions through a matter, can be generally described as:

$$\dot{Q} = \frac{A \cdot \lambda \cdot \Delta T}{d} \quad [W] \qquad [4\text{-}04]$$

where Q is the heat flux [W], A is the area, λ the thermal conductivity of the material, d the thickness of the material, and ΔT the temperature differences of ($T_{1higher}$ -T_{2lower}). The heat flux is assumed perpendicular to the surface. (cf. 2nd law in thermodynamics).

Convection

Convection describes the heat flow transfer between a body and fluid or gas, depending on the temperature difference, the fluid properties, and surface properties (such as e.g. the roughness or size). The heat flux can be described in a simplified way as the product of the surface area, the heat transfer coefficient h_c [4-06], and the temperature difference:

$$\dot{Q}_v = A \cdot h_c \cdot \Delta T \quad [W] \qquad [4\text{-}05]$$

where Q_v is the heat flux in [W], A the surface area, h_c the convection coefficient and ΔT the temperature differences of ($T_{1higher}$ -T_{2lower}). This equation can be applied at a vertical surface.

The calculation of the heat transfer coefficient h_c [W/(m²·K)] considers also the thermal boundary layer thickness δ, viscosity μ, buoyancy F_B, as well as velocity and volume flow of the fluid. Its magnitude depends "*on the position of the surface, the direction of the heat flow and the velocity of the fluid*" (Szokolay, 2004, p. 11).

The natural convection at a vertical surface correlates with the average heat flux as following:

$$h_c = \frac{q}{\Delta T} \quad [W/(m^2 \cdot K)] \tag{4-06}$$

where q is the heat flux [W/m²] and ΔT the temperature difference between the solid surface and e.g. the gas (air) [K] (q = Q/A).

Radiation

Radiation can be described either as irradiation to a matter or radiation from a matter. With radiation, non-dimensional material parameters, such as emittance, absorptance and reflectance are considered. The temperature of the surface T_{sur} and the surface geometry determine the impact of wavelengths:

- reflectance ρ indicates how much radiation is reflected by a surface (wavelengths that bounce off the material surface),

- absorptance α is expressed as a relation to the "*perfect absorber*", the theoretical black body with α = 1. The darker the surface, the more is absorbed. It varies between α = 0.9 and 0.2. For opaque surfaces ρ + α = 1 is applied. (Szokolay, 2004, p. 11),

- emittance ε is related to the "*perfect emitter*", again a black body, and presents how much heat is emitted to the surroundings. For homogenous surfaces, α = ε applies for the same wavelength of radiation. If the surface is selective, the values differ from each other (e.g. high absorptance but low emittance occur in solar collectors, or white paints possess the opposite attributes). The emissivity of materials ranges from 0 < ε < 1, depending on the material properties and surface temperature. Radiation is emitted continuously by any material.

Radiation from a matter is a complicate analysis since several surfaces define the effect (Davies, 2004, p. 115ff). The heat flux rate of radiation emitted by bodies (other than the ideal black body) can be described by following equation:

$$\frac{\dot{Q}}{t} = \varepsilon \cdot \sigma \cdot A \cdot T^4 \quad [W]$$ [4-07]

where Q is the heat transfer per unit time [W], ε the emissivity coefficient of the body [-] (1 = ideal black body), σ is the Stefan-Boltzmann constant [-] (= radiation constant of an ideal black body with = 5.67 e^{-8} [W/m²K⁴]), A is the area of the emitting body [m²] and T^4 is the absolute temperature [K].

A particular characteristic of radiation is the wavelength dependency: while the visible solar radiation is a short-wave radiation range of high energy intensity, the long-wave radiation emits at relatively low temperatures in all directions. Long wave radiation cannot pass through materials and therefore is trapped within a closed system – the greenhouse effect is a well know example of this.

Although evaporation is not directly linked to the heat flow types, it is part of the sensitive heat energy processes: the ratio of the moisture content in the air, the relative humidity, depends on the air temperature, as only a certain amount of water vapour can be taken up until saturation by a given temperature. This effect is well demonstrated by the psychrometric chart, which shows the absolute moisture content in air in [g/kg], the dry bulb (=air) and wet bulb temperatures in [°C], and thus, the relative humidity (RH) and saturation line at any given temperature. This dependency is the underlying principle for evaporation: simply said, the lower the humidity in the air, the stronger is the evaporation effect. Cooling and heating processes can be traced on the psychrometric chart by showing the effects of increasing or reducing moisture content and temperature (cf. Chapter 2, Fig. 2.13).

4.2.2 Heat regulation strategies

Heat regulation strategies in biology and engineering apply whenever a system is defined by a rigid limit of the thermal conditions. Is this limit surpassed, various adaptation mechanisms are activated to equalize the unwanted change of state. While nature employs also biochemical and behavioural strategies for such adaptation, building envelopes are limited to the physical material attributes and system design. The ‘tasks’ to achieve the equilibrium can be summarized as following: '*keep warm*' pursues all strategies to store heat or respectively lower the heat losses while '*keep cool*' pursues the opposite, to dissipate heat or not allow to enter heat into the system. '*keep balanced*' is the most moderate strategy that aims for a regulating heat flow, i.e. neither blocking from gain nor holding back from loss.

Keep warm

The strategies to passively keep warm, or generally said, to reduce the heat flow from inside to outside in order to minimize thermal losses are as following:

A Thermal insulation (Fig. 4.2, A): *reduce the thermal transmission through a material/ wall/skin.* This can be done by materials with a low thermal conductivity and/or by the increase of the heat flow path (thickness d_1) through the matter. The process is time-dependent.

B Thermal zoning or thermal boundary (Fig 4.2, B): *lower thermal transition from air to matter*. By geometric measures in front of the surface or by the surface geometry itself, the thermal flow speed can be reduced in the thermal boundary zone (d_2). Hairs or feathers, for example, work as such thermal buffer.

C Absorption of heat (Fig 4.2, C): a*bsorb (solar) radiant heat and store it*. This is linked to the thermal storage capacity of a material (specific heat capacity c_p), density and conductivity, but also to the surface attributes, such as the reflectivity of it. The intention is to allow heat to transfer and store it in the matter (d_3).

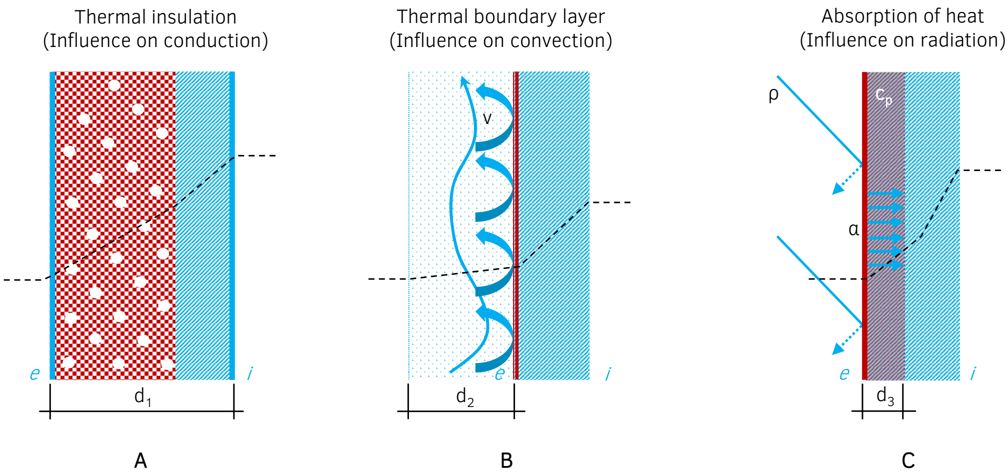

FIG. 4.2 Strategies to keep warm.
A: reduce the thermal transmission by low density, light-weight materials (low conduction). B: lower the air flow speed at the surface by a rougher surface geometry (low convection) and C: absorb solar energy by higher material absorptance and reduced reflection (higher irradiation). The dotted line indicates the heat flow.

Keep cool

The strategies to passively keep cool, to block heat impact or increase the heat flow from inside to outside are divided into 'preventive' and 'active' strategies:

A Preventive strategies

a Heat gain control (Fig. 4.3, A_a): *reflect solar radiation to the maximum.* To prevent solar radiation from increasing the heat flow into the interior, it is either blocked before it hits a surface (shading) or the surface is treated with highly reflective material. The orientation to the sun and shading by other or own geometries also contribute to this.

b Thermal optimization (Fig 4.3, A_b): *apply thermal protection measures to reduce heat flow.*

- Thermal zoning or thermal boundary: as with the 'keep warm' strategies, a thermal buffer zone also prevents the loss of 'cooler' heat to the outside by taking appropriate measures to reduce the convection flow speed.
- Thermal insulation is also advantageous for the cooling strategy; for the same reason as in the warming strategy, lowering the thermal conductivity of the material and/or increasing the thickness slows down the heat flow.
- Thermal inertia: the use of thermal mass is another effective strategy to keep 'cooler' heat from inside. It is more efficient when combined with ventilation (cf. B_a).

B Active strategies

a Ventilation/air flow (Fig. 4.3, B_a): *cool down by ventilation*. Natural ventilation can be considered on two levels: a) Increased air exchange on macro-level (ventilation) or b) increased convection at the surfaces on micro level (surface attributes that support a higher air flow speed). The effect only works at temperature differences. To achieve a cooling effect, the external temperature (outside the system that shall be conditioned) must therefore be lower. This strategy is not an active cooling process, but a 'cool feeling' through the initiated convection processes.

b Evaporation/adiabatic cooling (Fig. 4.3, B_b): *increase the air humidity for cooling.* Adiabatic cooling processes work at ambient conditions and are 'automated' as soon as there is a source of water, pressure and temperature difference between air and water. The liquid evaporates on the surface when the pressure/temperature differs. This process is only possible until the water saturation of the air is reached.

c Stack effect within structure (Fig. 4.3, B_c): *cool the structure by earth-coupled cool air.* The cooler soil temperature cools air flowing through, in earth ducts, for example. These are connected to a system that cools through the supply air. Is the duct vertical, the air movement is driven naturally by the stack effect.

d Radiant cooling (Fig. 4.3, B_d): *emit radiant heat.* The emission of radiant heat is possible when the emitting surface faces a cooler environment, e.g. the clear sky/atmosphere. To support this effect, the material properties of the surface (emission, absorption and reflection) must be matched to the atmospheric conditions, i.e. there must be sufficient differences in the long-wave radiation range.

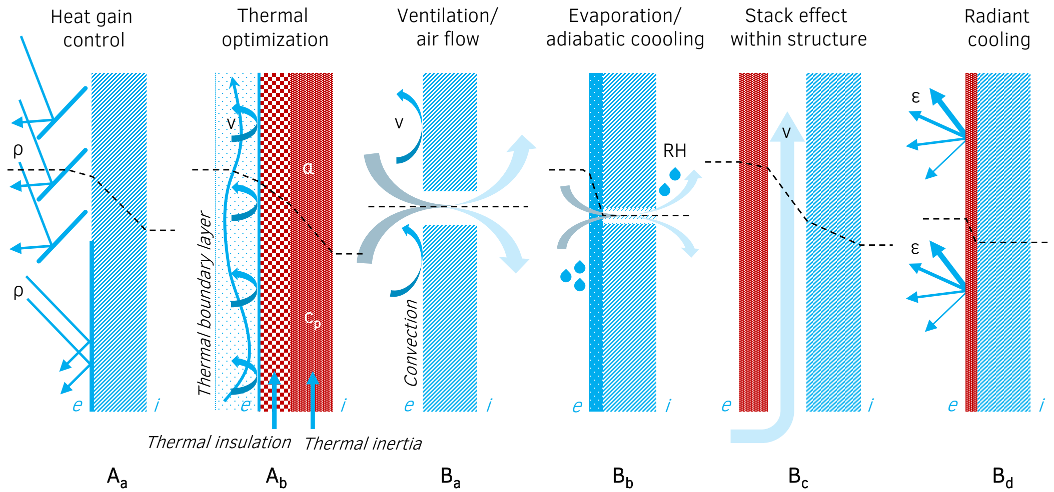

FIG. 4.3 Passive (A) and active (B) strategies to keep cool.
A_a: reflect and block solar radiation to its maximum; A_b: use thermal boundary layer, thermal inertia and thermal insulation to reduce heat flow from outside to inside, B_a: ventilate when external conditions are cooler; B_b: evaporate water at surface and profit from cooled air; B_c: use cool earth-coupled air to cool down a multi-layered system by the stack effect, and B_d: dissipate heat to the outside by surface properties with high emissivity.

Keep balanced

The heat transfer rate depends on the temperature difference; the smaller the temperature difference between two media, the slower is the heat exchange and opposite. A counter-current heat exchange system uses this thermodynamic principle to enable a bi-directional heat flow. The media used for temperature exchange can be gas, liquids, or sometimes even solid powder. An essential factor for heat exchange systems is the (exchange) surface. The larger the surface area, the more contact is possible between the two different environments and the more heat can be transferred (Fig. 4.4, A). The formation of 3-dimensional patterns enables the realization of extensive surfaces, since there is usually not enough space for flat formations. This leads, for example, to ribs in engineered solutions with - as provided in nature - fractal structures to create a large area within confined bodies (Fig. 4.4, B).

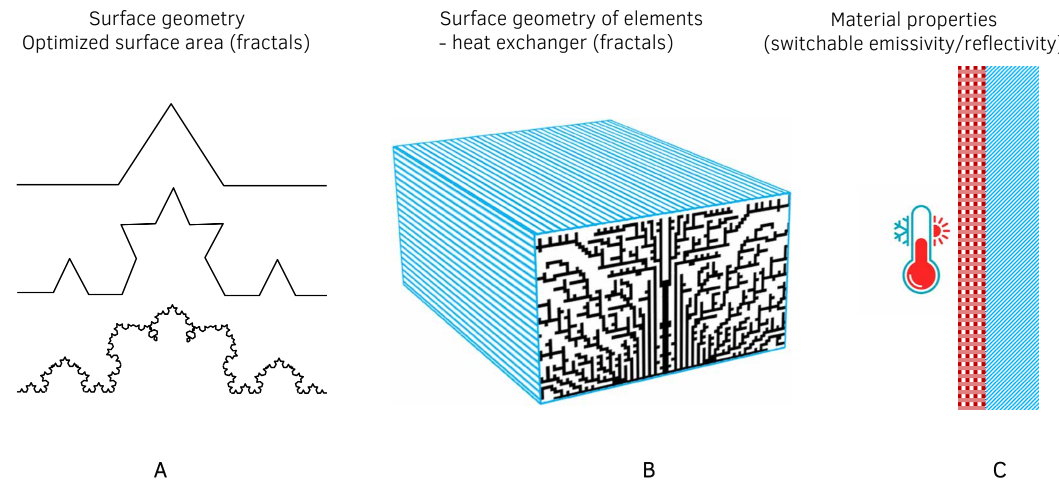

FIG. 4.4 Strategies to balance warm and cool.
A: Fractals allow the growth of the surface area within confined spaces. B: when fractal patterns are applie in 3D bodies with high conductivity (such as e.g. a metal block), an extensive surface is created to exchange heat. C: Switchable surface attributes, respectively thermal effects caused by these attributes, may allow a bi-directional behaviour.

Another strategy to create a bi-directional flow for cooling or heating is to apply selective radiation control through switchable surface properties or through morphological changes to adapt the influencing factors (Fig. 4.4, C). This causes a reversal of the temperature direction (e.g. the change of the sun's position).

4.2.3 Conclusion

The most important parameters in thermodynamic processes are identified. By this, the parameters and their assignments in the 'adaptive façade criteria list' (Appendix 3-2) as well as in the 'selection and evaluation checklist' (Appendix 4-1) are reviewed. Following processes are particularly interesting for the scope:

- Gas migration, fluid transport,
- Transmission regulation of heat flux,
- Radiative processes.

The dependencies between the structural factors (length, width, area, volume) and the physical parameters of a material (density, conductivity, viscosity, etc.) became visible. The characteristic of geometric parameters is discussed in the next section.

4.3 Geometric principles

An interesting theory that discusses thermodynamics in relation to geometry, and in a broader sense to construction, is the "*constructal theory*" first published in 1996 by Adrian Bejan and further developed by Bejan and Lorente in "*The constructal law of design and evolution in nature*" (Bejan & Lorente, 2010). The constructal theory deals with the evolutionary forms of natural geometric patterns and shapes that use flow configurations to modulate/optimize thermodynamic processes. It claims that a natural flow of finite size "*must evolve freely such that it provides greater access to its currents' in order to persist in time*" (Bejan @ TEDxTalks, 2012).

A

B

FIG. 4.5 Growth patterns in nature applying fractals and fibonacci series.
A: Frozen tree branches where both, branches and ice, are based on the same fractal pattern. B: Growth patterns of petals of flowers (seeds) are based on the combination of the golden ratio and Fibonacci series.

It is long known that growth and form-developing processes in nature use basic laws in geometry, whether inanimate or animate bodies (Thompson, 1992) (Ball, 2009). Certain geometrical patterns in nature allow growth at any type and any direction, such as fractal patterns (Fig. 4.5, A) or patterns that apply the golden ratio in combination with Fibonacci series (Fig. 4.5, B).

Such geometric principles are found in many appearances. They also allow analytical access to the thermodynamic principles of biological role models: "*Thus, applying mathematical analysis to understand growth patterns in nature (cf. Turing RD model) (Kondo & Miura, 2010) might also support the understanding of adaptation mechanisms*." (Gosztonyi, 2018).

4.3.1 Forms and size matters

Although geometric forms and patterns are not immediately recognized in an active role for a dynamic change process, it can be assumed that they support or even enable dynamic adjustments. This assumption can be validated by looking into nature: geometric forms and patterns, together with hierarchy and non-uniformity, are crucial for the evolution of organisms. Organisms rely on limited resources to interact with changing climatic conditions. Thus, form becomes part of function. As already learned in this chapter, geometric factors always play a role in thermodynamic processes, such as extensive surfaces, thicknesses, lengths, etc. The optimal use of these factors is particularly important when the organism is bound to an environment. This applies, for example, to plants that cannot move and thus use geometric (morphological) and chemical (physiological) principles for adaptation targets.

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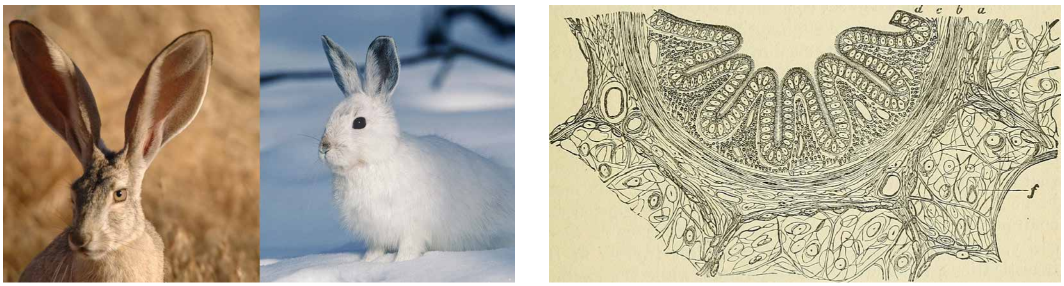
The surface-area-to-volume ratio, the SA:V ratio, is one of these factors that is employed. The SA:V ratio determines the energy exchange area with the environment (Eq. 4-07). It can be found in biology and engineering to optimize the energetic efficiency of a form in relation to the environment. In the scope of this work, the parameter is considered to indicate possible increase or decrease of heat exchange with the environment. For building physics, this means that a larger surface area in relation to the volume of a body increases the probability of heat losses.

$$SA:V = \frac{A \quad [cm^2\ ,m^2\ ]}{V \quad [cm^2\ ,m^2\ ]} \quad [L^{-1}] \qquad [4\text{-}07]$$

In nature, the SA:V ratio has an enormous impact on the survival chances of mammals, and thus is well considered in their morphological evolution. For example, mammals in hot climate regions regulate their body temperature by dissipating heat as fast as possible: the SA:V ratio of the ears of the rabbit 'Desert Cottontail' is much larger than the SA:V ratio of their relatives in colder areas ('Arctic hare'). The desert cottontail uses the large surface area to dissipate heat (through vasodilation) fast and effectively; the arctic hare has short ears and a little exposure surface to avoid heat losses (Fig. 4.6, A). This relation is expressed by the *Allen’s rule*, which deals with the size relation of mammal´s appendages in various climate regions.

This relation also applies to folded surfaces: the larger the SA:V ratio becomes, the more energy or information can be exchanged with the adjacent environment. This is the case, for example, with internal organs such as lungs or intestinal organs (Fig. 4.6, B) or with plants such as cacti.

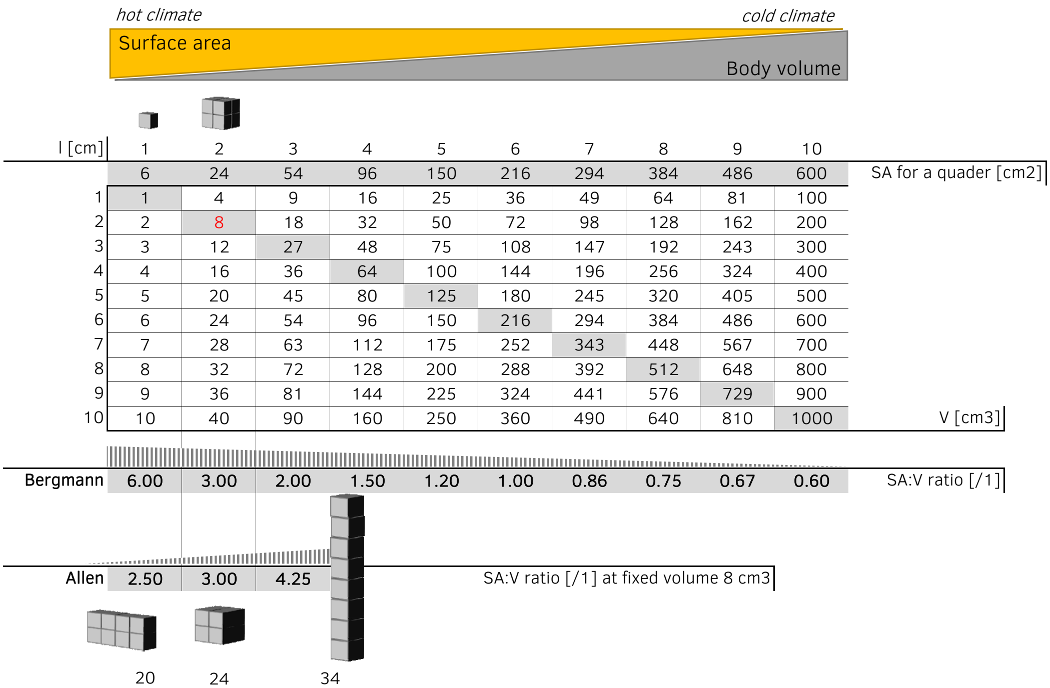


A B

FIG. 4.6 Evolutionary adaptation to climatic regions applying the *Allen's rule*.
A. Rabbits evolved different sizes of ears to increase (left, Desert Cottontail) or decrease (right, Arctic hare) the heat dissipation and maintain homeostasis of the body. B: Organs apply the same rule depending on their function - bronchial mucous membrane must exchange much 'energy' - air and thus possess a large surface (Image by Triplett, 1885)

Furthermore, the body masses of mammals in hot climate regions are smaller for the same reason as for the SA:V ratio; and it is bigger at mammals in cold climate regions. This is described by the *Bergmann's rule* that describes the proportional relation of body volume to the surface area directly related with the temperature of the region. In cold climates the body mass of mammals increases proportionally to the surface area to reduce heat losses. The smaller the SA:V ratio, i.e. the larger the body volume, the more heat can be produced and stored, and less gets lost.

Figure 4.7 shows how both rules of Allen and Bergmann are linked to each other.



l [cm]	1	2	3	4	5	6	7	8	9	10	
	6	24	54	96	150	216	294	384	486	600	SA for a quader [cm2]
1	1	4	9	16	25	36	49	64	81	100	
2	2	8	18	32	50	72	98	128	162	200	
3	3	12	27	48	75	108	147	192	243	300	
4	4	16	36	64	100	144	196	256	324	400	
5	5	20	45	80	125	180	245	320	405	500	
6	6	24	54	96	150	216	294	384	486	600	
7	7	28	63	112	175	252	343	448	567	700	
8	8	32	72	128	200	288	392	512	648	800	
9	9	36	81	144	225	324	441	576	729	900	
10	10	40	90	160	250	360	490	640	810	1000	V [cm3]
Bergmann	6.00	3.00	2.00	1.50	1.20	1.00	0.86	0.75	0.67	0.60	SA:V ratio [/1]

FIG. 4.7 Graphical representation of the surface area-to-volume ratio.
The graphic shows that on the one hand the SA:V ratio decreases with a bigger volume proportional to the surface area (a) (Bergmann's rule), but on the other hand increases if the volume stay the same (b) (Allen's rule).

The rules of Allen and Bergmann belong to the '*eco-geographic rules*', which describe morphological variations of organisms that are evolutionary adapted to the respective geographical latitude.

The sizing of the surfaces/form is also closely linked to the energetic goals for either dissipate or keep heat, respectively increase or decrease the heat flow.

4.3.2 Surface structures and patterns

Patterns and surface structures in façade construction are more a question of architectural aesthetics than of functionality. At least, in the case study collection of Chapter 3, no example was discovered in which the patterns and surface geometries (apart from the proportion of transparent surfaces and shading element designs) would have a significant influence on performance or adaptability. In the broader sense however, moveable shading systems that are rolled up, folded or tilted are part of these considerations. The way in which shading systems adapt morphologicallyd depends on the geometry of their elements. These determine the type of motion and the surface pattern. Analogies can be surely found in biology, where such adaptive patterns play an important role in the dynamic functionality of an organism. The variability in the use of these patterns is much more versatile than with technical solutions. Elementary geometries are brought to functional perfection in the most diverse combinations.

Hereby, geometric arrangements for optimal packaging, space utilization or growth are the most commonly used types in biological organisms. These are well studied, as illustrated by many examples in online databases such as 'asknature' (asknature.org, 2018) or in publications such as by Ball (2017) or by Pawlyn (2011). In some publications, a more in-depth analysis has been applied to understand the dependence of geometries and functionality and derive design methods from it, such as the analysis of numbers in nature of Stewart (2017), the examination of structural principles by Mattheck (1998) or by Gordon (1978) or the mentioned studies on flow patterns by Bejan & Zane (2012).

Arranged patterns on surfaces following the Fibonacci sequences allow e.g. the enlargement of the surface in limited space (ie. sunflower), the packaging or protecting of abiotic factors or predators (ie. Mimosa pudica). But the same principle is also applied to adaptive systems: the foldable wings of insects allow the necessary buoyancy area when flying while they are virtually wrapped up and 'vanish' when moving on legs on the ground. The folding itself is a functional work of art - designed for the specific mechanical loads, aerodynamic needs and structural tasks of the species. Many publications that deal with folding patterns and their principles, such as Schieber et al. (2017) or Houette et al. (2019), investigate mathematical principles that allow such adaptation mechanism.

Tessellation, polygonal geometries or Archimedean solids are geometries that allow growth in all directions. The mathematics behind the growth rules is documented well and also used for biomimetic investigations and developments of expanding adaptive geometries, such as found in origami-like structures (Chandra et al., 2015) (Fratzl et al., 2016) (Graves, 2009).

TABLE 4.1 Collected basic geometries using growth characteristics.

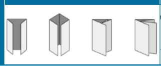
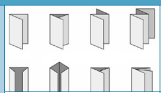
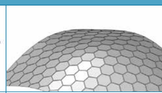
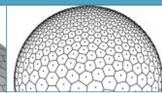
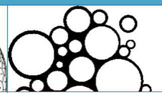
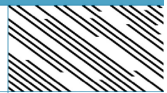
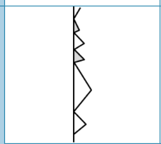
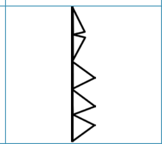
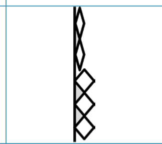
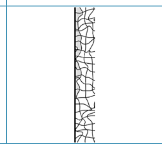
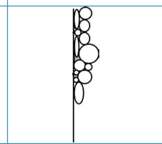
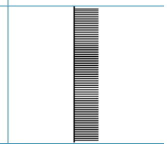
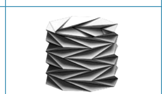
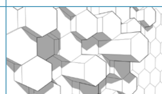
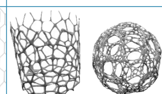
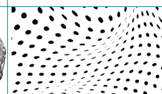
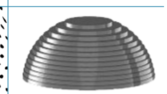
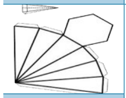
Basic geometries	rectangular	triangular	hexagonal	polygonal	cricular	linear
						
Growth questions						
3-dimens-ionality of shape possible?	 folded, flat	 prismatic, spherical	 cylindric, flat	 spherical, flat	 uneven surface, flat	 *uneven surface, flat*
fillings and gaps: Do cavities remain when fitting to flat surface? (Section)	 cavities remain	 no cavities	 many cavities remain	 few cavities remain	 many cavities remain	 no cavities
mono-dimensional growth possible? (spatial coordinate system)	 yes, linear in either x-, y- or z-axis	 yes, in z-axis as 3D form or linear	 yes, in z-axis (body growth, no shape deformation)	 yes, in all axes as deformation, change in all directions	 yes, in all axes as deformation, change in all directions	 yes, linear in z-axis
multi-dimensional growth? (spatial coordinate system)	unidirectional growth, expansion at the edges	multidirectional growth, expansion by adding elements	unidirectional growth, expansion at the edges	multidirectional growth, expansion by adding elements	multidirectional growth but with fillings only, expansion by adding elements	unidirectional growth, expansion on layers
gradients in pattern possible?	only if trianglular elements vary (surface areas)	only if trianglular elements vary / surface area)	only in z-axis as body length	yes	yes, depends on filling	only in thicknesses of layers
tesselation variation?	n/a	yes	yes	yes	n/a	n/a
 *wrapping on which form?*	cylindric, flat	flat, cubic, cylindrical, conical, pyramidical, spherical	flat, cubic, cylindrical, conical, spherical	flat, cubic, cylindrical, conical, pyramidical, spherical	flat, cubic, cylindrical, conical, pyramidical, spherical	flat (no wrapping)
deformation possible?	no, but shifts	no, but shifts	yes, 2-dim	yes, 3-dim	yes, 3-dim	no, but shifts
bending possible?	yes, 1-dim	partly in 2-dim, generally stiff	no, stiff	yes, soft form	yes, soft form, filling-depend.	no, stiff
Patterns in nature						

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Table 4.1 shows an attempt to examine basic patterns for growth-specific characteristics. The most common planar geometries with linear, polygonal to circular units are evaluated using some growth questions found in the literature.

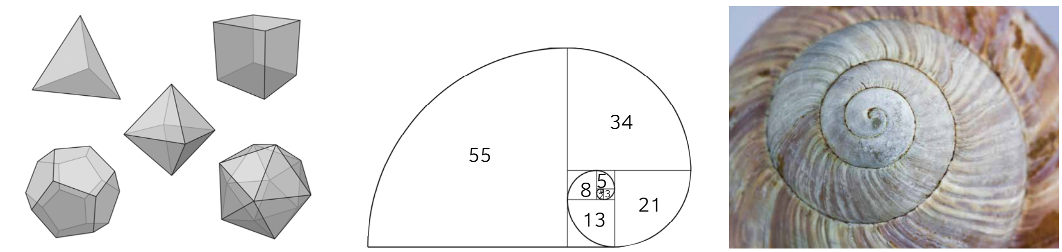
In the search and analysis of the biological role models in Chapter 5 and 6, these patterns and the growth characteristics are considered.

4.3.3 Elementary geometry

Kinetic systems rely on geometric patterns to enable the mechanism. To allow geometric patterns to adapt, scale or repeat as a function, fundamental design criteria are applied. These criteria are based on elementary mathematical principles, such as the *golden ratio* and *golden angle*, *platonic bodies* and sequential growth principles, such as *fractals* and *Fibonacci sequence*.

The basic geometric form (starting already at the molecular level) in biological morphologies is often a grid-based shape, with circular or polygonal units. Together with certain repetitive growth rules, such as spiral and sequential growth, biological systems develop and adapt to any form.

Due to the need to change scale and size of a body when growing, pentagonal figures are the most '*suitable*' basic forms (Fig. 4.8, A). Particularly, figures of pentagonal symmetry are closely connected to growth. The golden ratio defines these figures' change ability by e.g. a proportional growth of the golden ratio (phi or ϕ) (Fig. 4.8, B) in a rectangular pentagon (and sequential growth patterns, such as seen in the Fibonacci numbers of a snail shell (Fig. 4.8, C).



A B C

FIG. 4.8 Geometric basics: platonic bodies (A) - golden spiral (B) - biological role model applying the Fibonacci sequence (C).

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The *golden ratio (phi, ϕ)* is a division ratio of a dimension, in which the total to its larger part corresponds to the ratio as the larger to the smaller part. The golden ratio is a basic mathematical element and defined as following:

$$\Phi = \frac{A+B}{A} = \frac{A}{B} \quad \rightarrow \quad \Phi = \frac{1+\sqrt{5}}{2} = 1.6180339... \qquad [4\text{-}08]$$

For circular equivalences of the golden ratio, the *golden angle* (GA) can be applied with approx. 137.508° degree, which derives from:

$$GA = 2\pi \cdot (1 - \frac{1}{\varphi}) \qquad [4\text{-}09]$$

The golden ratio and golden angle can be observed in many structures and patterns in nature, making them a successful principle for growth.

The golden ratio is also linked with sequential growth patterns, such as the already mentioned *Fibonacci sequence,* which is defined by the *recurrence equation* (Livio, 2008, p. 101). Equation 4-10 refers to the Fibonacci sequence $F_{n\ (n>1)}$ where each result is the sum of the preceding two numbers.

$$F_n = F_{n-1} + F_{n-2} \qquad [4\text{-}10]$$

The sequence starts with 0 for F_0. For example, if F_1 = 1, then F_2 = 0 + 1 = 1; F_3 = 1 +1 = 2; F_4 = 1 + 2 = 3; F_5 = 2 + 3 = 5, and so on.

4.3.4 Conclusion

Growth patterns are applied in biology almost in any species and matter, since they follow a '*simple*' rule: repetition and sequential behaviour. The idea is also found in architecture, particularly of ancient times where such geometric repetitions were a symbol of the worship of gods, which was associated with natural phenomena. Nowadays these principles are taken further to develop complex solutions due to the possibilities digital parametric design provide (Khaira, 2009) (Zhai &

Previtali, 2010). Attempts can now be made to imitate highly complex geometries of biological role models (Overvelde et al., 2016) (Callens & Zadpoor, 2018).

For example, the artist John Edmark (2017) demonstrates the idea of sequential growth by his kinetic sculptures and transformable object growth effects through the use of mathematical principles. The artwork is animated by progressive rotations to visually generate a growth appearance. The function is intrinsic to the specific formation of the geometry and depends on the rotation that serves as the kinetic mechanism. For the impression of growth he applies the golden angle.

4.4 Adaptation mechanisms

In general, thermoregulation is a process that requires a change of states to achieve a desired goal. Thermal regulation processes are temporal, dynamic and (in nature) self-organizing, and resond actively to changing conditions. Thermoregulation systems have a sensor and control system that constantly detect current conditions that may force an action to perserve a needed condition. The actuators and physical factors that enable a change are of many types.

4.4.1 Adaptation in biology

Adaptability is one of the most fundamental evolutionary strategies in nature. Based on the optimal use of available resources and conditions, adaptability is driven by the evolutionary processes of propagation and selection. Some organisms have the ability to exist in the most diverse - even extreme - habitats. They can withstand strong heat and winds, freeze, drought or flooding. These so-called '*extremophiles*' survive apparently undamaged in such extreme conditions over a longer period of time, which would be lethal for most other organisms (Fig. 4.9); they were able to adapt evolutionarily to these challenges, which is a long-term process over generations.

A

B

FIG. 4.9 Extremophiles - animals that survive under extreme climatic conditions.
A: The wood frog (Rana sylvatica) in Alaska is able to freeze solid in the harsh winters and thaws when it gets warmer due to a chemical that prevents ice crystal formations in the body. (Image by Huth, 2011, CC BY 2.0).
B: The Saharn silver ant (Cataglyphis bombycina) tolerate heat up to 70-80 °C on the surface due to its specifically designed hairs. The ant is densely covered by triangular shaped hair structures that regulate heat by high reflection and emission abilities. (Image by The Biomimicry Institute, 2018).

These examples require a deeper look into the definition of the term '*adaptation*' or '*adaptability*' in biology, as it is applied with other time intervals and actions than in engineering. '*Adaptation*' in biology is seen as a long-term alignment to the environment rather than an immediate reaction of a quick change which is then called '*acclimatisation'* or '*adjustment*'. Adaptation strategies of an organism evolve over generations in relation to a particular climate region and is manifested in genetic attributes of an organism ('*aptitudes'* of a species). Acclimatisation or adjustment allows an individual organism to adapt to fluctuations within a life cycle. The metabolism of a mammal has, for example, the purpose of maintaining the balance between internal and external conditions in a dynamic process within certain limits (=homeostasis) (Spektrum, 2016a).

Animal adaptation levels as responses to climatic stress:

- Aptitudes: adaptation on population level → '*specific'* body size, shape, structural composition that does not change in a life time (cf. Bergmann's and Allen's rules),

- Acclimatization: individual responses by increased physiological efficiency or altered morphological appearance → metabolism, circulation, sweating, shivering, volume change,

- Adjustments: fast responses to the surrounding by action (behaviour) → changing the position, surface structure, exposure to environment (folding of leaves).

Thermal adjustment mechanisms in nature

The biological mechanisms of thermal adjustments can be of various types: they can be of morphological nature by i.e. change of structure and form of an organism (and thus change of volume/surface), of physiological nature by i.e. physical and biochemical processes (and thus change material attributes), or of behavioural nature, which induces change of positions in the environment.

The activation strategies that enable these mechanisms are based on different principles: one is called *conformity*, the ability of organisms not to compensate actively for, but to deal passively with changes in the environment. *Poikilothermic* and *poikilohydric* organisms need to obtain heat from the sun because they do not produce endogenous heat or can regulate water content (sweat, evaporate), i.e. is the case for reptiles. Thus these organisms adapt to the environmental conditions. The opposite principle is called *homoiothermic* (= constant, independent from surrounding environment), which makes organisms less dependent on the influence of external factors through inner regulatory processes such as thermoregulation (metabolism) or osmoregulation (Spektrum, 2016b), i.e. is the case for mammals. The biological process to maintain a constant body core temperature, the metabolism, is temperature-bounded: heat is generated by biochemical processes to regulate the body temperature, where the balance between heat production and output, as well as the heat flow speed is crucial. The thermal threshold for the adjustments is not strictly defined, but functionally displaceable. It depends on the activity level of the organism and the ambient temperature, when and how the body temperature adapts: high temperatures extend, for example, the area of the core temperature in the body while the surface temperature reduces, and vice versa.

Thermal adjustments can be divided into three types:

- Morphological adjustments: The main characteristic of morphological adaptations of organisms is a functional optimiziation of body shapes or certain body parts. The effect is initiated by environmental conditions over time. Repetive variations of certain forms occuring in different environments prove the effectiveness of this strategy. In *functional morphology*, one of the main disciplines in biological morphology, this diversity is investigated with focus on the relationship between the appearance and the functional goals, and their interaction and dependencies. The identification of features of function-oriented appearances also determine the search and selection of role models: What influence do size, shape, pattern and structure of organisms have on thermal adaptability? Which conditions and prerequisites have to be considered? What role do time-dependent relations play, such as 'scaling', 'reversibility' or 'initiation', and what are their interactions?

 - Typical morphological adjustments are: folded shapes of cacti, large surfaces of leaves or mammal parts (ears), and generally geometric sizes, such as e.g. diameter, height, length, etc. of organisms.

- Physiological adjustments: Physiological processes are predominantly of biochemical or physical nature and can be implemented at all levels of the organism, i.e. in cells, tissues or organs. A well known example is the *metabolism*, which causes absorption, transport, transformation and release of substances at the biochemical level. Sweating is another example, which creates a short-term physiological adaptation effect by evaporating water. One of the most important characteristics of physiological adjustments is the concentration of the effects mainly on nanoscale or microscale. This must also be considered in the analogy search. Many physiological processes are resulting from nanoscaled mechanisms, which cannot be easily mimicked without specific material attributes. Since morphological processes interact often with physiological processes or are induced by them, a sharp differentiation of both is not possible. Therefore, both adjustment processes must be considered in the search, but weighted in the transfer process.

  - Typical physiological adjustments are: colour change by refraction or chemical reaction, density change by phase changes, radiant control by chemical reaction, etc.

- Behavioural adjustments: Behavioural adaptation refers to perceptible and/or active change of position, which is temporary and reversible. This includes movements (move to a shaded position) or tracing the sun path (sun flower). Behavioural changes are generally linked to mammals, but plants are also able to adjust by motion. Behavioural processes are defined by genes, but also by learning processes in order to optimise the performance. They also interrelate with physiological and morphological processes. The search for internal and external influencing factors raises central questions in the behavioural research, which addresses ecology or evolutionary biology.

  - Typical behavioural adjustments are: motion of mammals, adaptations of leaves caused by the actions: move, swell/shrink, bend, stretch/contract, expand (all dimensions), extend (one dimension), etc.

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In this work, the focus is laid on adjustments without applying biochemical processes. If existing material properties mimic such biochemical adjustments and are known products in the building sector, they are considered.

Although biology uses the term '*adjustment*' for the responsive, short-term actuation, the term '*adaptation*' will be further used in this work, sinceee it is common in the façade engineering field.

4.4.2 Technical approach to adaptation

The general idea behind adaptation systems is that a certain change of a state A (= condition, i.e. environmental factors such as fast temperature drop) requires an action of a '*system*' to reach a certain state B (= target, i.e. thermal equilibrium). This action (= change process, i.e. putting on a jacket) is only just as successful as its system settings, dependencies and framework conditions (= i.e. energy for dressing, insulation quality of jacket, temperature difference, etc.).

The adaptation mechanism consists of following '*components*': the *trigger* or *monitoring* that observes and sends information, the *controller* that initiates the process, and the *actuators* that perform the adjustment. The *monitoring* in engineering is usually an electro-sensory system, while nature uses a wider range of information sensing and transmission, such as biochemical or physical processes. In engineering, *controllers* are equally mechanical or electrical pulse generators, while nature has again a larger spectrum available due to the combination of biochemical, physiological and morphological processes. The *actuators* that conducts the task are particularly interesting for design, as sensor and controller are less often applied within the façade system, but actuation must be part of it. It is mastered usually by kinetic or hydraulic mechanisms. In nature, again the difversity of actuators reaches from chemical to kinetic processes.

Monitoring, controller and actuator components are usually embedded in biological organisms and even form one and the same system. In technology, the individual parts of the system are put together additively. In both cases the communication or the exchange of information between the individual tasks is complex.

Some biological mechanics can partly be compared to engineering solutions, such as kinetic solutions (insect wings unfold through muscle motion) or pressure-adaptive solutions: the plant *Mimosa pudica* folds its leaves due to the so-called Turgor pressure. The turgor pressure is an osmotic process for which fluids are separated by a membrane (e.g. a cell wall) and diffuse through this membrane at unequal pressure (= concentration of solutes). According to the cell pressure level, the cell will become either rigid or flaccid in this change (Burgert & Fratzl, 2009) (Volkov et al., 2010). Pneumatic technical systems also use pressure differences to actuate a morphological change but on a different scale and without applying osmotic processes.

Monitoring of states

The parameters linked to the state monitoring of a function are e.g. temperature, humidity or radiation. Its context has been discussed already in Chapter 2 in Section 2.4 'Boundary conditions'. The parameters representing the monitoring are the SET and ACTUAL values of category I and the parameter group E 'environment' and group T 'Thermal comfort' in the parameter list of Appendix 3-2.

Signal recording and processing

Sensors collect signals that are linked to time and/or measurable physical quantities and are considered as functions, because they physically capture and translate information. The physical quantity of the input signal (recording signal) is not necessarily identical to that of the output signal (processing signal). This means, for example, that a sensor thermally measures temperature and processes this information as an electric signature. Their task is to send the information about the environmental factors to which they are assigned (e.g. moisture sensor measures relative humidity). Technical signals record the following parameters: '*state', 'rate', 'level', 'shape'*, or *'frequency content*', and are classified as either digital (on/off, binary) or analogue (gradient information depending on time) (Webster, 1998, p. 96–100). Signal are usually based on low levels of electric, pneumatic, hydraulic or manual (human-powered) energy. The signal recording, processing and transport information is also added as criteria (I-04 to I-06) to the parameter list of Appendix 3-2 in category I.

Controller

The control centre contains the processor (which can be software-based but also human-based behaviour) that compares the provided information of the signals based on a specific scheme to identify deviations from the SET values. In general, deviations trigger the actuator. This requires a detailed specification of values to be compared and checked. For this, the criteria of category II in the parameter list are screened and completed by system-relevant information.

Actuators

The control system can fulfil its task only by actuators; functions that convert information into action. Their purpose is to start the desired action for a change of state. Actuators types are e.g. hydraulic, pneumatic, electric, thermal or acoustic, or mechanical. Actuators responding time-depending and show either a gradual or on/off actuation. Programmable materials are herein a large potential field, since they change shape or property of a material, reconfigure characteristics, become more breathable, more rigid or transform themselves into other phases. The criteria that describe the actuation type and other details are refined in category III in the parameter list of Appendix 3-2.

The factor time

In physics, time plays a crucial role in almost all thermodynamic processes and thus is also considered in various assessment procedures as a factor. For example, the fluctuations of temperature and heat flow are described via a long-term average value using a sinusoidal function as a function of time. The parameter list of Appendix 3-2 contains time-related criteria in the categories II (control settings) and III (actuation settings).

4.4.3 Conclusion

It can be concluded that '*adaptation*' in engineering means '*adjustments*' in biology. The focus of this work is laid on all types of adjustments, but without applying complex biochemical processes or behavioural adjustments involving local change (dislocation), as the framework conditions are then similar to building requirements and transfer potential are more likely to be found. Chemical processes are only considered in this work when no new material developments are necessary.

The adaptation mechanisms in biology can be summarized by these aspects:

e Monitoring, necessary to verify the current and desired states and deviations.

f Thermodynamic process that initiates a change. The process is defined by the criterion F08. functional principles to which a few criteria in regards to the physical performance are linked.

g Adaptation mechanism that controls and performs a change of states. It consists of the ccontrol settings that check the states and deviations in order to initiate a change and of the actuation system that has the task to perform the change.

h Physical design that provides information about the type and material of the system.

They are equal to the technical classification (for adaptive facades) made in Chapter 3 and thus are used as the common baseline for the translation process. These aspects are called '*rules for adaptation*' in the translation process.

4.5 Biomimetics in architectural engineering

Biomimetics enables the exploration of biological principles and allows linking technical innovations with natural sciences knowledge in favour to generate novel solutions that answer a problem or offer a better alternative to a problem. The discipline provides scientific methodologies to explore biological principles and transfer possible principles for technical solutions. In the case of this work, the exploration in Biomimetics focuses on the identification of functional principles for a ‘*design-driven*’ thermal adaptability in façade solutions. Nature achieves a high level of functional intelligence and thermal regulation by sophisticated morphological (Atwell et al., 1999), physiological or behavioural ‘operation modes’ and by embedding the required multifunctionality in the raw material itself. Hence, nature does not assemble monofunctional units to a system. Thermoregulation strategies found in nature are based on very effective principles of costs (effort) and benefits (achievements), with organisms utilizing local conditions and generating remarkable functional solutions that lessen energy and materials losses in order to meet a desired thermal state. Known principles shall be identified in this work.

4.5.1 Biomimetics and architecture

Biomimetics is a recognized discipline for product development in the architectural and engineering, as shown by several publications over the last two decades. The viewed publications range from early biomimetic case studies on technical devices, as presented by Lindemann and Gramann (2004), to computer-aided biomimetic approaches, as presented by Kruiper et al. (2016); from general discussions on the differentiation of biomimetics and biotechnology or other fields, as discussed by Rawlings et al. (2012) to discussions on the role of biomimetics in architecture, as provided by Gruber and Jeronimidis (2012). And computational methods applicable for the biomimetic process in architecture have been developed and discussed in many projects, such as e.g. by Knippers et al. (2016) or Tan et al. (2019).

Particularly in structural engineering, biomimetic computational methods have proven to be effective tools that, for example, allow stress optimizations. Applied methods to simulate the biological growth rules in order to reduce stress are for example the SKO (Soft-Kill-Option) or CAO (Computer-Aided-Optimization) methods, which are both developed at the Karlsruhe Research Center KIT (Inzenhofer et al., 2018). Researchers use furthermore parametric CAO methods for the development and construction of biomimetic prototypes, such as the University of Applied Sciences in Saarbrücken (Pohl, 2011). The transfer of process-related phenomena in nature, such as energy conversion and regulation, is more complex and less developed biomimetic solutions are found. Energy efficiency strategies in nature often use a well-orchestrated combination of physical, geometric, chemical and behavioural processes, which are difficult to imitate in a technical solution (Helfman Cohen et al., 2014). The dynamic interaction and control of the various processes is the decisive success factor of the biological model and the most difficult challenge to imitate in technology. Digital parametric tools and additive manufacturing as well as the development of smart materials play an important role in this challenge. Although it still seems difficult to imitate such complex processes, these tools promise a potential solution approach for successful biomimetic translations.

4.5.2 Approaches and methods

Biomimetics focuses on the functional principles of biological role models that have well adapted to their environment in the course of evolution. In order to develop biomimetic solutions from these role models, the biological principles must first be well understood. With increasingly improved analytical tools and methods, it has become easier to understand biological systems at all levels of their functional and structural hierarchy and also to decipher process-relevant functions at the various scales from nano to macro. However, the debate on how to apply this analysis systematically in various fields is still ongoing (Vincent, 2017) (Yaraghi & Kisailus, 2018) (Drack et al., 2017) and options for architecture are many (Kuru et al., 2020) (Badarnah, 2017) (Deldin & Schuknecht, 2014).

This understanding process is the basis for a biomimetic transfer into products, systems and procedures – and differentiates biomimetics from other related disciplines such as biotechnology or bio-inspired solutions (seen as imitating the obvious appearance). The present analytical approaches link well with methodological product developments that deal with interdisciplinary research, such as the TRIZ method ("*Teoriya Resheniya Izobretatelskikh Zadatch*") developed by the Russian researcher G. Altshuller (1999) or the product development strategy proposed by Ehrlenspiel (2009). Kuru et al. (2020, Table 1) collected various methodological approaches particularly for the biomimetic design framework, also pointing out to the importance of functional performance and not only to adaptation mimicry per se.

A biomimetic transfer process requires a high degree of interdisciplinary participation of various experts from the origin and target domain and a well-coordinated communication language between the domains in order to successfully transfer information between the fields. It further needs a systematic processing of data about system, material and process characteristics in order to derive the principles for possible technical applications. Thus, the Association of German Engineers VDI started to publish a series of guidelines on biomimetics to facilitate the transfer process for designers and engineers (VDI, 2020). The series includes the following guidelines: '*Biomimetics, concepts and strategies*' (VDI-6220-1, 2012), '*Biomimetic surfaces*' (VDI 6221-1, 2013), '*Biomimetic robots*' (VDI 6222-1, 2013), '*Biomimetic materials, structures and components*' (VDI 6223-1), '*Biomimetic optimization – application of evolutionary algorithms*' (VDI 6224-1, 2012), '*Integrated product development process for biomimetic optimisation*' (VDI 6224-3, 2017), and '*Biomimetic information processing*' (VDI 6225-1, 2012). The guideline '*Biomimetics – architecture, civil engineering , industrial design – basic principles*' (VDI-6226-1, 2015) finally deals with approaches applicable in façade engineering discipline. Herein, the bottom-up approach, or Biology-Push, and the top-down approach, or Technology-Pull, are the defined methods to start investigations. The top-down approach is a multi-stage method and focuses on solving a technical problem by searching and abstracting functional analogies in biology. The goal is to improve the existing technical functionality or to identify new solutions that replace the original technical function. This process was chosen for this work. The choice is justified by its advantages in using this approach in applied sciences with shorter development times and effective problem solving of existing systems.

4.5.3 Biomimetic activities and examples

Biomimetic projects in architecture and related fields have become increasingly popular in recent years. The approaches to biomimetic or bio-inspired solutions for architectural questions are extremely diverse, ranging from morphological developments of free forms using evolutionary algorithms to highly specialized product developments of components and material. Particularly in the field of architecture, '*bio-inspiration*' has been applied since ancient times, because architecture has always imitated natural shapes and functions.

Nowadays, it's the structural engineering discipline that transfers biological phenomena to human-made solutions in the most accurate manner. Hereby, load curves and stress optimisation of biological structures are being investigated in order to transfer this to technically engineered structures. Well-known in this field are the biomimetic research pavilions developed by the institutes ICD/ITKE at the University of Stuttgart (ICD/ITKE University of Stuttgart, 2020) (Menges & Knippers, 2015) and (Knippers et al., 2016). These biomimetic solutions are named "*materialstructures*" (Hensel & Menges, 2008). Materialstructures can be briefly described as hierarchical composed structures, made of few raw materials, which embed many functions through the structural composition on various scales. The desired solution can be achieved with minimal material use. Furthermore, many studies and prototypes have been developed in a sub-area of structural engineering, form-adaptive materials, in which again the University of Stuttgart is active with self-adaptive wood composites (Menges & Reichert, 2015).

Research in the field of façade engineering also starts to use biomimetic methods, particularly for the combination of façade design and energy efficiency, as shown in studies on multifunctional façades using biomimetics for better energy efficiency (Kuru et al., 2019) (Badarnah, 2017) (Gosztonyi et al., 2013) or developments of adaptive building envelope components (Körner et al., 2017) (DOSU, 2017).

Biomimetic products and solutions in the building sector are showing an increasing share in research but are less often seen as market ready products. Most of the screened examples are prototypes (Kuru et al., 2018). The few built projects that show a systematic convergence between nature and technology are e.g. focusing on natural ventilation (Turner & Soar, 2008) or on kinetic components (Flectofin, Lienhard et al., 2011). Realized biomimetic solutions are generally more common in material developments. An example that has been known for a long time and is applied in the market is, for example, the self-cleaning Lotus effect, applied as Lotussan colour® by Sto AG (2020) or as a film on glazing's. Various selective films and foils, such as anti-fouling surfaces, also claim to be biomimetic products

(Sullivan & O'Callaghan, 2020). Research on smart surface technologies currently has the most applied biomimetic solutions for energy efficiency of façades. Most of the current bioinspired architectural solutions are not using the strict biomimetic approach but rather inspirations imitating biological forms.

4.5.4 Conclusion

Although biomimetics is the basis of this work, its defined and tested approaches and methods are critically questioned in order to understand why, despite many innovative ideas and concepts, relatively few implementations have happened in the past decades in the building sector . The potential to learn from biological role models is the underlying motivation for many of the innovations at prototype level. However, it appears that at a certain point, many architectural solutions transform this motivation into a more (and only) design-driven interpretation.

The definition of a robust transfer system that keeps the learning process at the functional level until the design is developed does not yet seem to be within reach. The methods identified in the various biomimetic projects do not consequently follow a systematic approach. However, as this is an important pillar in this work, further transdisciplinary fields and their approaches are explored in the following section in order to identify a suitable firm systematics.

4.6 Transfer methods for dynamic processes

Preparing a systematics in order to track and evaluate dynamic processes and understanding their relationships is the basis of every effective product development process (Gaag, 2010) or construction process (Ehrlenspiel et al., 2007). Especially in processes that are transdisciplinary and use information from other domains to identify innovation, as is the case for architectural engineering in biomimetics (VDI-6226-1, 2015), a function-oriented understanding of connections, goals and a structured processing of data is essential in order not to get lost in superficial observation of phenomena.

To be able to employ this approach to thermo-adaptive processes in a time-efficient and successful way, the definition as well as the transfer and analysis of the role models require an explicit guidance. There is currently too little applicable information available in the façade design field to support such process accurately. The increasing complexity poses major challenges for the involved persons: the way information about dynamic processes is gathered and interpreted is often not comprehensible and verifiable, particularly in the architecture field where systematic data analysis and creative innovation are often considered as contradictions. A biomimetic project in the architecture field can thus quickly become extremely fragmented and fuzzy in regards to function-oriented transfer - and runs the risk of unintentionally generating laminations of the process or imitations of looks instead of innovative transfer solutions. This phenomenon can be particularly observed in the development of biomimetic adaptive façade solutions: "*Bio-inspired*" adaptive façades often show more artistically free interpretations than functional comprehensible translations of biological analogies. The originally sought functional solution is subordinated to the desire to imitate morphological or phenomenological observations.

Architectural drafts and product designs share many similarities. Both are intended to incorporate function(s) into a well-designed solution. Appearance, needs, requirements and functions must interact, which leads to complex design processes. Thus, next to the biomimetic research field, suitable methods for functional models are also sought in product design field – focusing on dynamic processes.

4.6.1 Literature review on various methods

To identify suitable methods and approaches for the transfer, the objective must be clear: the aim is the generation of '*biomimetic*' functional models that help to make the adaptiveness of a biological principle useable for the design development of thermally adaptive façade functions. These functional models must be such that they can be applied already in the early design stage.

Thus, the information must be interpreted, structured and set in relation in such way that an '*easy and clear*' idea of the function is given and an evaluation of its feasibility is possible. One approach for the representation of abstracted dynamic processes is the use of semantic structures displaying parameters together with their relationships and dependencies. Another approach is to apply classifications.

The literature search starts with semantic approaches and then lets the publications guide through to identify further key words. Thus, the key words applied to identify approaches are refined on the go in order to identify e.g. semantic ontologies, functional-oriented design, performative product development, as well as biomimetic designs. Table 4.2 displays the results.

TABLE 4.2 Literature review list for transfer methods
The list shows the key words, application domains and the identified publications about transfer and functional modelling methods linked to biomimetics, architecture and product design. It is listed in alphabetic order of the author(s).

Progressive key words	Application domain	Title of publication	Description	Year	Author(s)
Biomimetic database, Bio-inspiration, building skins	Biomimetics, façade design	Biomimetic building skins: An adaptive approach	Systematic study on mechanisms, functions and materials of adaptive biomimetic building skins	2017	(Al-Obaidi et al., 2017)
Biomimetic database, Bio-inspiration, building skins, thermal performance	Biomimetics, façade design	A methodology for the generation of biomimetic design concepts A Biophysical Framework of Heat Regulation Strategies for the Design of Biomimetic Building Envelopes	Biomimetic role model database, structured into various levels of function, process, factors	2014, 2015	(Badarnah & Kadri, 2014) (Badarnah, 2015)
Functional-oriented design, product development, effective design modelling	Mechanical engineering, product development	„Entwicklung einer Ontologie zur funktionsorientier-ten Lösungssuche in der Produk-tentwicklung“ (in German)	Semantic knowledge database for product development	2010	(Gaag, 2010)
Biomimetic data, Bio-inspiration, building skins, energy efficiency	Biomimetics, façade design	BioSkin - Research potentials for biologically inspired energy efficient façade components and systems (in German)	Analogy search and concept design evelopments for energy efficient biomimetic façades	2013	(Gosztonyi et al., 2013)

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Progressive key words	Application domain	Title of publication	Description	Year	Author(s)
Biomimetic data, Bio-inspiration, architecture	Biomimetics, architectural design	Biomimetics in Architecture: Architecture of Life and Buildings	Potential of biomimetics in architecture, classification approach	2011	(Gruber, 2011)
Semantic structures, data structure, biomimetics	Ontologies	An Ontology Explorer for Biomimetics Database	Development of an biomimetic design database	2014, 2015	(Kozaki & Mizoguchi, 2014)
Industrial research, ontology engineering	Ontology engineering	Towards Ontology Engineering	Definition of ontologies	1996	(Mizoguchi & Ikeda, 1996)
Semantic, ontology	Ontologies	Ontology learning for the Semantic Web	Ontologies, WWW	2001	(Maedche & Staab, 2001)
Biomimetic transfer methods, Bio-inspiration, design	Biomimetics, design, methodology development	Exploring the Use of Functional Models in Biomimetic Conceptual Design; A Thesaurus for Bioinspired Engineering Design; Function-Based Biologically Inspired Design	methodology examination of bio-inspired products, systematic design methodology for bio- inspired design	2008, 2014	(R. L. Nagel et al., 2008) (J. K. S. Nagel, 2014) (J. K. S. Nagel et al., 2014)
Biomimetic data, Bio-inspiration, architecture	Biomimetics, architectural design	Biomimetics for Architecture & Design: Nature - Analogies - Technology	Biomimetic concepts, prototypes, projects, built examples in architecture field	2015	(Pohl & Nachtigall, 2015)
Biomimetic transfer methods, Bio-inspiration, design, physiomimetic approach	Biomimetics, design, methodology development	Part 2: Pushing the envelope. A process perspective for architecture, engineering and construction	understanding on how nature 'works' at process level without distinguishing between function and form	2013, 2016	(R. C. Soar, 2013), (R. Soar, 2016)
Functional-oriented data bases, biomimetic ontology	Biomimetics, engineering	An Ontology of Biomimetics	Biologically Inspired Design, Methods and Tools		(Vincent, 2014)

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Progressive key words	Application domain	Title of publication	Description	Year	Author(s)
Product design, design theory	Engineering, product development	“Integrierte Produktentwicklung: Denkabläufe, Methodeneinsatz, Zusammenarbeit“, Cost-Efficient Design	Methods and processes for systematic product development	2007, 2009	(Ehrlenspiel, 2009), (Ehrlenspiel et al., 2007)
Methodical construction	Mechanical engineering, design-product development	“Vorgehensmodelle, Grundprinzipien und Methoden” (Process models, basic principles and methods)	Use of systematic methods for construction design	2005	(Lindemann, 2005)
Design methods, biomimetics	Design methods and processes for biomimetics	VDI 6226-1:2015 - Biomimetics - Architecture, civil engineering, industrial design - Basic principles	Methods for biomimetics and design	2015	(VDI-6226-1, 2015)

4.6.2 Discussion about transfer methods

In biomimetics, the utilization of semantic models to represent dynamic processes of biological principles is gaining a lot of attention, as these allow to consider mechanisms, processes, their relationships and dependencies before proceeding further to the development of engineered concepts. As a representative example, the work of Julian Vincent (2014) can be mentioned. He stated that focusing exclusively on key words in the search and even more in the transfer of functional processes in biology is unlikely to lead to new effective solutions. Biomimetic databases based on key words are designed to point out a few distinctive physical or chemical features of role models. The processes and factors that are responsible for the adaptation are not described. Thus, Vincent suggests choosing a descriptive approach that includes the dynamic process by applying the logic of semantic phrases (namely ontologies). For this, Vincent proposed an open-access ontology database for biomimetics many years ago. The goal is to identify universal design rules behind the processes of biological phenomena, provided that the database has sufficient entries and a systematic arrangement for statistical analysis.

Ontologies, as defined in the context of information representation, are structured descriptions of knowledge using concepts that can be expressed within a domain. Unlike taxonomies or relational database schemas, ontologies express relationships and enable users to link concepts in various ways. They formalize information and, as descriptive systems, make changing circumstances and relationships visible. This means that attention is paid not only to a mere match of words (example: syntactic web browsers that use keywords to suggest results), but also to the relationship of each word to the other and the contextual meaning of the query. One of the main areas of application for this are digital information systems, such as Semantic Web Systems (Maedche & Staab, 2001). These systems perform a linguistic analysis, such as the identification of nouns, verbs, adjectives, or adverbial determinations of a query, and then search for synonyms for each term to conclude how the query should be evaluated. Only then can a search for appropriate answers be conducted to obtain meaningful results. For example, the query "*Dog-friendly campsite with bathing facilities in the Austrian mountains*" would be understood similarly to a direct conversation between persons and would not be converted into separate terms according to which the hits are broken down. A semantic system tries to understand search queries and interpret them logically. Contextual knowledge created in semantic systems can thus more correctly identify processes in an established context. For such, a common vocabulary for the concepts and their relations, a structured scheme for the data, standardized components and rules for the use are needed (Mizoguchi & Ikeda, 1996).

According to Gaag (2010, p. 97), an ontology is set up and also evaluated by three target indicators: *performance, usability* and *completeness*. Based on the technical development of the data structure, the *performance* of an ontology is concerned with the systematic processing of data contents. The development of the basic structure starts with the definition of the requirements to the ontology from the perspective of the solution search, which includes the clarification about functions (main terms, criteria), abstraction of principles (to overcome semantic barriers) and ends with the evaluation through exemplary instantiation of the main concepts. Finally, also a user guidance and operation support of the ontology (context to use) must be generated. The *usefulness* of an ontology is an essential evaluation criterion for practice and is determined by the definition of a clear purpose for the ontology. This includes also the graphic appearance of the ontology. It is of great importance to check the usability iteratively during the development process and to adjust the purpose of the ontology well to the target group. Therefore, the work steps for usability and performance run parallel to each other in order to coordinate both data and preparation. *Completeness* is regarded as an evaluation instrument for ontologies. The requirements for completeness are based on case studies, or respectively use cases. Use cases are created in order to check the structure and data connections. Here, above all, a sufficient amount of data is essential, i.e. the achievement of the necessary critical mass of data for the assessment and validation of the ontology. Therefore, this indicator is often the most time-consuming - the collection of data usually also flows into the period of use. An extension, correction or refinement of the structure is therefore an iterative, longer-term process that extends into the ontology usage phase.

Publications about the application of ontologies in biomimetics suggest that this approach might be the most holistic method to represent the complexity of performance-oriented solutions, but it is also the most complicated one (Vincent, 2014) (Kozaki & Mizoguchi, 2014). Biomimetic activities seek to move away from the sole collection of biological inspirations based on keywords, as is the case with many current biomimetic data bases (Biomimicry Institute, 2016) and process-oriented databases, such as e.g. provided by Al-Obaidi et al. (2017), Badarnah (2015), Pohl and Nachtigall (2015), Gosztonyi et al. (2013) or Gruber (2011). These biomimetic databases are structured with (wished) ‘action verbs’, such as '*transfer*', '*gain*', '*dissipate*', '*prevent*', etc. (cf. Badarnah & Kadri, 2014) (Gosztonyi et al., 2013) or stimulus for change (cf. Al-Obaidi et al., 2017). The action verb is specified as a target function, which is subdivided hierarchically into possible processes and influencing factors, which are ultimately assigned certain role models, such as the example in Figure 4.10 shows.

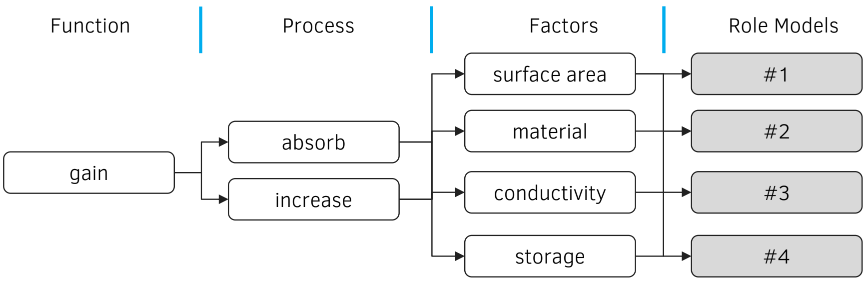

FIG. 4.10 Applied search structure in biomimetic design publications (Graph adapted from Badarnah, 2015).

However, this approach does not provide translatable information about *HOW* the process works, *HOW* the principle is to be translated into a physical system, and *HOW* the functional settings relate or interact with the design factors. Thus, the functional mechanisms and design components remain in a kind of black box logic. This approach is useful for searching inspiring analogies and identifying ideas. However, it does not seem to be usable as a systematic guideline and support for the generation of functional design concepts.

More detailed information on the functional level beyond the black box level is provided by e.g. Nagel et al. (2008), who splits the '*action verbs*', or functional tasks, into steps to be done, such as e.g. '*transfer*', '*convert*' thermal energy into '*kinetic*' energy. This approach guides through change tasks of a system and makes it easier to compare technical and biological system settings.

Another more detailed transfer of dynamic processes can be achieved by the use of computational modelling, such as applied by Soar (2013). Soar studies the relationships and dependencies in process-related functionalities by applying digital agents and processes to represent the dynamic complexity. In this approach, a detailed analysis of the physical process is sought, which allows an accurate transfer of the role model's principle but is also the most limiting in the search for new options, as the transfer process is oriented towards strict mathematical models.

4.6.3 Conclusion

Most of the reviewed publications identified ontologies and digital processes to be suitable methods for the description of adaptive processes. This requires a precise understanding about the settings and preparation of a huge data pool to work properly. Thus, the development of a semantic database would go much beyond the limits of this work and would also require a team of various experts from different disciplines to implement the structure and data. But the idea of systematizing parameters and functions, putting them in context with a semantic description and applying a classification with which data can be ordered and processes can be explained, is considered.

4.7 Applied transfer method

The literature reviews of Chapter 3 and 4 shows very different approaches to describe adaptive processes. Within the framework of the COST TU1403 “*Adaptive Façades Network*”, for example, Loonen et al. (2015) submitted a proposal for the classification of adaptive façades, which essentially structures the system into physical attributes, demand targets and adaptation criteria (cf. Chapter 3). The proposal intends to display adaptive concepts via an engineering approach of designing and constructing adaptive façade (components): it starts with the definition of a goal via performance indicators, and continues with the description of the adaptation system attributes, such as the operation type, response time or scale of measure.

Other publications focus on one adaptation type, such as either kinetic systems (Ramzy & Fayed, 2011) (Fox & Yeh, 1999) that discusses kinetic systems, or smart materials (Addington & Schodek, 2004) presenting various materials that change their properties. The former derives a classification for kinetic systems subdivided into configuration of the system, control characteristics, and the impact of the motion. Particularly Fox and Yeh (1999) address various kinetic systems through the description of the environmental and human factors that induce change and types of motion (= controlled movements). This model approach is rather similar to the models applied in the information sciences dealing with intelligent control systems.

The most abstract model to display adaptive changes can be found in the thermodynamic field: the *state function* is used to represent a certain state of a system with relating state variables. The state functions do not display any change or path of the change, but describe the equilibrium state of a system. To display thermodynamic processes and the paths of a change, certain diagrams are used, such as e.g. T-E (temperature – entropy) or P-T (pressure – temperature) diagrams.

The reviewed approaches offer various information depths and are based either on precise mathematical analyses, such as the thermodynamic process diagrams, or on semantic conclusions, such as the biomimetic design approaches. While the former would be effective for evaluating measures, but requires detailed data that is often not available in the early planning phase, the latter lacks of an sufficient level of detail to be useful for practical design development.

However, no method has been found that is applicable for creating biomimetic façade designs and provides enough detail to make a decision, but still remains at an abstract level that does not require calculations. Therefore, a translation process is defined that combines semantic descriptions and parametric classification.

4.7.1 Procedure and steps

The defined process consists of following steps:

1. **Search process**: The established biomimetic Top-Down method has been chosen for this work in order to define the search in Chapter 5. The above mentioned '*action verbs*' thus serve as search key words for the initial identification of analogies. But, unlike in the related publications, these action verbs are not taken further to describe the transfer of the biological principle to engineered concepts. The search keyword and search process is described in detail in Chapter 5.

2. **Semantic description** will be used for the generation of biological concepts in Chpater 6. A simplified semantic description explains the biological principles following the idea of the semantic ontology without a classification like the reviewed ones. The concepts are assigned to one or more role model and linked to the parametric classification of the adaptive façade criteria list (Appendix 3-3); this connection allows a systematic transfer of the process-related principles into a language, where the function could be analysed. It is further used for the evaluation of the biological rol model and the technical solutions. Both, the semantic phrases and paramteric criteria are added to the selection and evaluation checklist (Appendix 4-1).

3. **Parametric classification**: The parameter collection that has been started in Chapter 2 to describe the thermodynamic process, the physical system and adaptation mechanisms as well as the external influencing factors (via monitoring) is further developed towards a comprehendsive list of criteria. This list shall be useable for the façade description but also for the description of biological principles. By abstracting the criteria according to the basics discussed in this chapter, the list can be used as an assignment tool for the search and selection process and for the development process of the models.

4. **Modelling process**: Following the approach of Nagel et al. (2014) and inspired by the approach of R. C. Soar (2013), the '*HOW*' in the dynamic process is put in focus. The immaterial, functional processes (adaptation mechanism) and physical settings (physical design) of a functional principle are merged together in the design process proposed for Chapter 7:

    - Physical design shows the design solution derived from the biological principles. It shall cover the functional purpose and level of physical embedment including material (properties, surface), structure (e.g. configuration) and conditions (e.g. external conditions).

- Adaptation mechanism describes the factors leading to a change. While the conventional approach of such models follows a black box concept of '*status 1*' is '*processed*' to '*status 2*', the suggested modelling approach divides the status information, process-related information and design information into categories and show how they work together.

Furthermore, the two design tasks are linked to the parameter list of Chapter 3. Figure 4.11 shows the relationship of the five adaptive façade categories, as defined in Chapter 3. By this approach, the factors of the adaptive process and of the physical settings of the system are made visible separately but related to each other by the defined criteria of the parametric list (Appendix 3-2).

A higher degree of usability and evaluability shall be achieved in the early design phase by using this scheme.

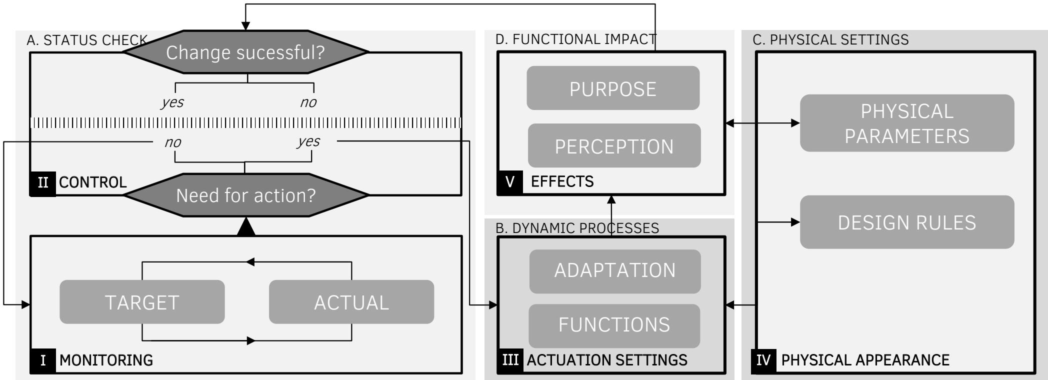

FIG. 4.11 Scheme of the functional modelling approach.
The scheme shows the five categories of the parameter list and how these relate to the adaptation process.

A detailed description of the modelling process is provided in Chapter 7.

5 **Evaluation process targeting at the 'rules for design'**: To evaluate each step in the process, particularly the design relevant aspects, some criteria of the adaptive façade criteria list and the design effectivity criteria of Chapter 3 are used. The evaluation is done qualitatively, supported by quantitative analyses whenever helpful.

6 **Generic constraints and limitations**: Some general constraints are made for the procedure that particularly apply to the modelling process: design developments based on existing material is preferred; 'simple' solutions are preferred to avoid developments of new materials or time-consuming generation of complex forms. Thus, role models that for example use nanoscaled strategies are excluded from further investigations. Furthermore, biochemical adaptation processes occurring in nature are not considered in the translation process, although the author is aware that a connection of biochemical and physical processes is common in nature.

Limitations in certain steps, such as e.g. in the selection process of biological role models are defined separately in the respective step.

4.7.2 [Physiomimetic terms] Function-oriented translation bridge

The rules for adaptation of Section 4.4.3 are related to each other by applying following '**physiomimetic**' terms: 'status check', 'functional principle', 'change process' and 'impact'. These terms bridge the languease of biology and engineering, because they describe a change process in a general understood way. Figure 4.12 shows this connection.

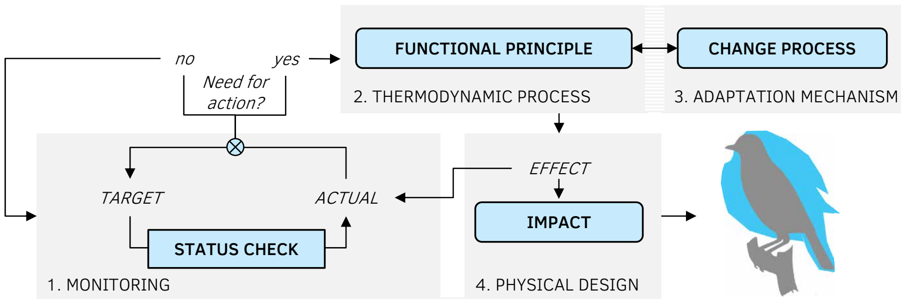

FIG. 4.12 Scheme of the physiomimetic types and their relationship.
The scheme shows a simplified process from checking the states (1. Monitoring), initiating a change by a certain functional principle (2. Thermodynamic process) and conducting that change (3. Adaptation mechanism) to meet the target. The impact (4. Physical design) is the result of the change but also 'new' input status for the monitoring.

In order to complete the bridge between the general descriptions of biological role models and systematic technical descriptions necessary for façade developments, the process-related principles must then be linked to the parameter and criteria identified in Chapters 2 and 3 (summarized in the 'parameter list' of Appendix 3-2).

Connecting these types reveals that e.g. a 'change process' is depending on the type of thermodynamic process and adaptation mechanism, and can be described by control and adaptation criteria. Or a 'status check' is part of the monitoring but also defines the thermodynamic process type, which is described by goal and monitoring criteria. This relation between the general thermodynamic adaptation process and the parameter categories is expressed by physiomimetic terms. These terms form the link between biology and technology and are presented in Figure 4.13 (middle column) as level 1, because they are further detailed for the creation of biological concepts.

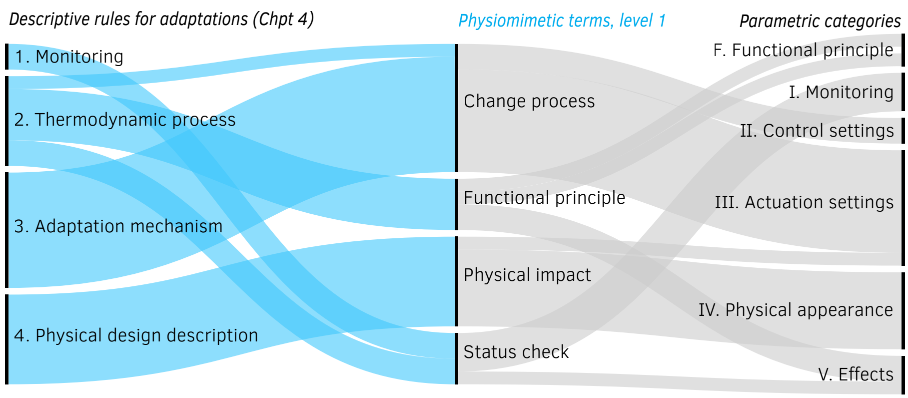

FIG. 4.13 Physiomimetic terms link the rules for adaptation with the parametric categories.
The scheme presents the relation between the rules for the thermodynamic process and technical parametric categories via linking 'physiomimetic terms'.

By this step, the search and target domains are now linked. This level is used for the search and selection of the role models. A detailed refinement of the scheme is then needed to create the biological concepts. The information about this refinement is directly provided in Chapter 6 when creating the concepts.

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4.8 Summary

The insights into the basics of thermodynamic processes, geometric rules and adaptation systems helped to extract terminologies and characteristics that connect the two fields of biology and engineering. Based on this analysis and due to the lack of a suitable transfer method, a systematics has been developed, which is based on the prepared parametric classification (Appendix 3-2) and a simplified ontological method to allow descriptions of organisms in semantic form. The key element of the systematics are the physiomimetic terms that link the semantic language with the technical language of façade engineering.

Furthermore, to serve as a supportive checklist throughout the biomimetic transfer process, the main classes of the adaptive façades criteria list of Chapter 3 have been taken and completed by eight columns that represent the evaluation and selection tasks along the process (Appendix 4-1). For each stage, certain criteria are chosen that are considered important according to the level of information and analysis. The criteria are divided into relevant (marked with '+') and optional (marked with '*').

1. Criteria for the case studies evaluation
('U' for use cases, Chapter 3)
2. Criteria for the identification of role models
('s' for selection, Chapter 5)
3. Criteria for the analyses of the adaptation process and functions
(Analyses , step 1, Chapter 6)
4. Criteria for the analyses of the relation between geometry, material and function
(Analyses, step 2, Chapter 6)
5. Criteria for biological concept generation
(Concepts, Chapter 6)
6. Criteria for the development of design variants
(Model development, step 1, Chapter 7)
7. Criteria for the description of functional models (
Model description, step 2, Chapter 7)
8. Criteria for the evaluation of the functional models with the use cases
(Evaluation, step 3, Chapter 7)

In Chapter 3, certain criteria were selected that evaluate the 'design effectivity'. These are marked as 'D' in the checklist, of which particularly following criteria are chosen: (1) Robustness/maintenance (IV-08.2), (2) Design complexity (IV-09.1), Design flexibility (IV-06), and (3) Scalability (IV-07).

This checklist is used as a navigation tool for the search and selection of biological role model principles and the generation of functional models in the following chapters. It can be viewed in the Appendix (Appendix 4-1).

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Appendices

Appendix 4-1 Selection and evaluation checklist

PHASE 2: SEEK SOLUTION (Systemize and analyse)

Biological concept description (Chpt 6)				ID	Category	ID	Task	
INPUT / OUTPUT		[status check]		I	Monitoring	I-01	Set values (equal to ID: E,T)	
		[status check]		I	Monitoring	I-02	Actual values (equal to ID: E,T)	
		[status check]		I	Monitoring	I-03	Input/Output deviation	
		[status check]		I	Monitoring	I-04	Signal recording	
		[status check]		I	Monitoring	I-05	Signal processing	
		[status check]		I	Monitoring	I-06	Signal transport	
OPERATIONAL FUNCTIONS		[achieve a target]		II	Control settings	II-01	Control task	
				II	Control settings	II-02	Control system	
		[conditions]	[adapting parameters]	II	Control settings	II-03	Control type	
				II	Control settings	II-04	Evolvability	
				II	Control settings	II-05	Operation type	
				II	Control settings	II-06	Operation carrier	
	[a system does]			III	Actuation settings	III-01	Task to perform	
		[conditions]	[adapting parameters]	III	Actuation settings	III-02	Actuator type	
		[adaptation rules]		III	Actuation settings	III-03	Response time	
		[adaptation rules]		III	Actuation settings	III-04	Response type	
		[adaptation rules]		III	Actuation settings	III-05	Response degree	
		[adaptation rules]		III	Actuation settings	III-06	Adaptation reliability	
				III	Actuation settings	III-07	Adaptation dependency	
		[impact]	[results x]	III	Actuation settings	III-08	Adaptation impact	
MAGNITUDE AND ORDER OF MEASURE	[type of effect]	[purpose]	[a system does]	IV	Physical appearance	IV-01	Level of embedment	
	[type of effect]	[purpose]	[a system does]	IV	Physical appearance	IV-02	Type of physical impact	
				IV	Physical appearance	IV-03	Physical characteristics	
	[type of effect]	[purpose]		IV	Physical appearance	IV-04	Functional scale	
	[type of effect]			IV	Physical appearance	IV-05	Visibility	
		[purpose]		IV	Physical appearance	IV-06	Flexibility	
				IV	Physical appearance	IV-07	Scalability	
				IV	Physical appearance	IV-08	Robustness	
				IV	Physical appearance	IV-09	Complexity	
				IV	Physical appearance	IV-10	Applicability	

Description	Search		Selection/ Analyses		Transfer			Evaluation	
	U	S	Aa	Ab	C	M1	M2	E1	E2
defined data or condition to be achieved/maintained					*	o	o		
observed data or condition in the actual state					*	o	o		
data that display the thermal disbalance principle (In vs OUT)			x		*	o		#	#
photometric (illumination), calorimetric (temperature), hygrometric (humidity), flow (gas, fluids), pressure (gas, fluid)	2						o		
thermal, chemical, mechanical, electric, acoustic, magnetic, hydraulic, pneumatic, structural (inherent)							o		
thermal, chemical, mechanical, electric, acoustic, magnetic, hydraulic, pneumatic, structural (inherent)							o		
prevent (block), dissipate, reject, reduce, modulate, distribute, filter, convert, collect (store), pass through, admit, etc.			x		*				
feedback system / actuation system									
intrinsic / extrinsic	2			x			o	#	#
time-depending characteristics considering the actuator/sensor behaviour and their self-learning ability									
Manual (User) / automatic (BMS) / auto-reactive (inherent)							o	#	#
gas, fluid, currents, magnets, chemical reaction, physical reaction				x	*	o	o	#	#
Fold, shift, extend, expand, stretch, shrink, roll up, wrap up, bend, colour change, phase change, density change, etc.					*	o	o	#	#
thermal, chemical, mechanical, electric, acoustic, magnetic, hydraulic, pneumatic, etc.	2			x	*	o	o	#	#
inherent reaction time depending on system or material properties: sec, min, hour, day, seasons, years			x		*	o	o	#	#
dynamic / static				x	*	o	o	#	#
on/off / gradual / hybrid					*	o	o	#	#
reversible / non-reversible; reliable functional operation;	2				*	o	o	#	#
(in)/dependency on local conditions (e.g. sun path)			x		*	o	o	#	#
morphological change (form, volume) / physiological change (patterns, colour) / hybrid change (both)	2		x		*	o		#	#
material/component or element/system / added before surface, on surface, in matter	2			x	*	o	o	#	#
Impact on positions, sizes or geometry/structure; ratio unit to full adaptation element; static considerations					*	o	o	#	#
physical effects of structural and material characteristic			x		*	o	o	#	#
nanometer, micrometer, milimeter, centimeter, meter			x		*	o	o	#	#
not visible, no change / not visible, change on other level / visible, no spatial change (on surface) / visible, spatial change	2			x	*	o	o	#	#
design configuration flexibility	1								
Scalability of unit, element or function	1		x		*	o	o	#	#
Redundancy, maintenance and service circles, lifetime resilience of system	1								
design complexity; implementation complexity (installation), operation complexity	1								
capability as multi-functional element; replacement and plug-in option; multiplication factor building sector, recycling potential									

>>>

PHASE 2: SEEK SOLUTION (Systemize and analyse)

Biological concept description (Chpt 6)				ID	Category	ID	Task	
INPUT / OUTPUT				V	Effects	V-01	Goal	
				V	Effects	V-02	Physical principle	
				V	Effects	V-03	Perceived response	
				V	Effects	V-04	Controllability	
				V	Effects	V-05	Automation level	
				V	Effects	V-06	Market implementation	
THERMAL PERFORMANCE FACTORS		[achieve a target]		F08	Functional purpose	F08.1	Heat loss prevention	
		[achieve a target]		F08	Functional purpose	F08.2	thermal energy control	
		[achieve a target]		F08	Functional purpose	F08.3	solar gain control	
		[achieve a target]		F08	Functional purpose	F08.4	heat dissipation	
		[achieve a target]		F08	Functional purpose	F08.5	overheating prevention	
		[achieve a target]		F08	Functional purpose	F08.6	energy exchange	
		[achieve a target]		F08	Functional purpose	F08.7	energy conversion	
DESIGN PARAMETERS			[purpose]	F	Functional principle	F01	Thermal transmission	
			[purpose]	F	Functional principle	F02	Thermal storage	
			[purpose]	F	Functional principle	F03	Radiative transmission	
			[purpose]	F	Functional principle	F04	Gas exchange	
			[purpose]	F	Functional principle	F05	Thermal convection	
			[purpose]	F	Functional principle	F06	Radiative energy	
			[purpose]	F	Functional principle	F07	Regulation of sensible and latent heat	

U	*Criteria for the case studies evaluation. U/1 = first level eval., U/2 = second level eval. (**U**se cases, Chapter 3)*
S	*Criteria for the identification of role models (**S**election, Chapter 5)*
Aa, Ab	*Criteria for the evaluation of potential role models, Aa = first stage eval, Ab = second stage eval. (**A**nalyses, Chapter 6)*
C	*Criteria for biological concept generation (**C**oncepts, chapter 6)*
M1	*Criteria for the development of design variants (**M**odels, Chapter 7)*
M2	*Criteria for the description of functional models (**M**odels, Chapter 7)*
E1, E2	*Criteria for the evaluation of the two functional models with the use cases (**E**valuation, Chapter 8)*

	Description	Search		Selection/ Analyses		Transfer			Evaluation	
		U	S	Aa	Ab	C	M1	M2	E1	E2
	thermal, *visual, hygienic and acoustic comfort, energy consumption, aesthetic/media communications*	2				*				
	radiative, conductive, convective, evaporative principle		*			*	o			
	user perception of adaptation									
	user interaction (interoperability with users high-low)									
	responsive (needs a command) / self-reactive (no command needed)									
	TRL levels according to ISO 16290:2013	2								
		#	*		x	*				
		#	*		x	*				
		#	*		x	*				
		#	*		x	*				
		#	*		x	*				
		#	*		x	*				
		#	*		x	*				
		*	*			*				
						*				
						*				
						*				
						*				
		*	*			*				
						*				

5 [Analogy search] Biological role models

Nature offers a remarkable diversity for thermal adaptation mechanisms, as organisms' survivability rely on temperature and thus, the capacity to regulate it (Angilletta Jr., 2009). The variables to consider are comparable to the building envelope conditions, such as temporal and spatial criteria, the refinement to location (although some behavioural adaptation allows limited change of position), limitation in materials (limited source of materials) or a certain set of parameters for material changes (physiological and metabolic adaptation). Biomimetic methods can be applied to search the wide range of biological solutions for transmission, exchange, storage, transport control of thermal energy, all seamlessly embedded in apparently robust and simple systems.

The chapter enters into the biomimetic phase 2 of the process: the '*seek of potentials*' phase. It starts the biomimetic search process with a brief introduction (Section 5.1) and the search methodology (Section 5.2), which is created to identify and select suitable role models. The method follows the biomimetic top-down approach, including some new steps on how to handle the identification and selection process. The identification of the role models is divided into the search and selection process. Section 5.3 provides about 72 identified role models clustered in 14 groups of similar adaptation mechanisms. The full list of biological role models is provided in Appendix 5-1, while in the chapter only exemplary representatives are shown. The arrangement of these representatives follows a structured format, which includes some criteria from the adaptation criteria list. Finally, applying the selection process, a final list of suitable role models is extracted in Section 5.4.

5.1 Introduction

The main intention of this chapter is to collect and present biolodgical role models. This means to leave the field of façade design and engineering and enter the natural sciences domain. Search biological role models, and particularly understanding their functional strategies, demands a structured and careful approach. In the following the methodology developed for this step iand the results of the search are presented.

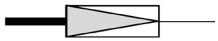
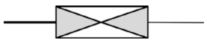
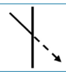
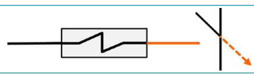
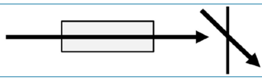
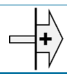
5.2 Identification of biological role models

5.2.1 Methodology

For the search in biological databases, *action verbs*, as discussed in Chapter 4 (cf. Fig. 4.10) are used as search keywords. The action verbs orientate at the functional purposes defined in Chapter 2 and 3 and are summarized also as 'Control tasks' criteria (II-01) in Category II (cf. Appendix 3-2).

The use of such search keywords is also described in the German biomimetic guideline (VDI-6226-1, 2015), a systematic guideline for the biomimetic field, respectively the international standard for Biomimetics (ISO 18458:2015, 2015). Further, it is also applied (with some variations) in many practiced biomimetic processes, as Fayemi et al. (2017) describe in a review about biomimetic tools and practices. Some of the mentioned approaches in that article target at methodical approaches in architectural design, such as by Badarnah & Kadri (2014), (Gosztonyi et al., 2013), Gruber (2011) or Pawlyn (2011).

TABLE 5.1 Search keywords and their relation to functional purpose of the search scope.

Category	Key search words [II-01: Control tasks in Appendix 3-3]		Functional purpose [F08.x]	Aspects related to cooling
II-01.1	FUNCTION: BLOCK ENERGY (matter)		F08.1 Heat los prevention	Block thermal energy flow when it enters matter
	block			
	refuse			
II-01.2	FUNCTION: BLOCK ENERGY (surface)		F08.1 Heat los prevention	Reflect thermal energy flow before it enters matter
	reject			
	reflect			
II-01.3	FUNCTION: CONTROL ENERGY FLOW		F08.2 Thermal energy control	Reduce thermal energy transmission within matter
	confine, limit			
	reduce			
II-01.4	FUNCTION: CONTROL ENERGY FLOW		F08.2 Thermal energy control	Regulate thermal energy transmission in matter
	modulate			
	regulate			
II-01.5	FUNCTION: CONTROL ENERGY FLOW		F08.2 Thermal energy control	Maintain constant thermal energy flow within matter
	maintain			
II-01.6	FUNCTION: CONTROL RADIATIVE ENERGY IN/OUT		F08.3 Solar gain control F08.5 Overheating prevention	Filter thermal radiant energy
	select			
	filter			
II-01.7	FUNCTION: CONTROL RADIATIVE ENERGY IN/OUT		F08.3 Solar gain control F08.5 Overheating prevention	Scatter thermal radiant energy
	distribute			
	scatter, spread			
II-01.8	FUNCTION: KEEP ENERGY		F08.2 thermal energy control F08.7 Energy conversion	Store thermal energy in matter
	store, keep			
	accumulate			
II-01.9	FUNCTION: CONVERT ENERGY		F08.6 Energy exchange F08.7 Energy conversion	Convert thermal energy in order to cool
	exchange			
	convert			
II-01.10	FUNCTION: TRANSFER ENERGY			
	pass (through)		F08.6 Energy exchange	Allow thermal energy transfer to pass
	allow, transfer			
II-01.11	FUNCTION: DISSIPATE ENERGY			
	dissipate		F08.4 Heat dissipation	Emit thermal radiant energy to dissipate heat
	expend, emit			
II-01.12	FUNCTION: GAIN ENERGY			
	gain, collect		energy gain	How to gain energy to cool the interior environment?
	absorb			

Sources

For the search of suitable role models various sources are employed: the role model collection developed in the research project BioSkin (Gosztonyi et al., 2013) serves as the initial source. The collection contains about 250 biological role models targeting energy efficiency with the keywords '*light*', '*heat*', '*cool by ventilation*', '*cool by evaporation*', '*cool by exchange*', and '*energy generation*'. This collection is complemented by following scientific databases:

- 'AskNature' database of the Biomimicry Institute (2021) in the United States (publicly accessible database on strategies in nature with currently more than 1700 entries as of 2021),
- Scientific databases, such as 'Nature' (2021) or 'ScienceDirect' (2021) for in-depth searches,
- 'Google Scholar' for certain key word meta-searches,
- and a personal biological role model archive, which has been continuously maintained since the BioSkin project in 2009.

The data collection of the BioSkin project has been validated by interviews with experts from biology, physics, natural sciences, and biomimetic research and supplemented by on-site research in the project. Thus, this source serves as a good basis. For the further role models found in the other sources, closer studies are only done for those models that are rated promising.

Search process

The search process, as shown in Figure 5.1, starts with a meta-search using the keywords and the Bioskin project database as the initial source (cf. Appendix 5-1, column 'BioSkin source'). After selecting and studying the abstracts of the identified publications, further keywords are added to perform further search rounds, which are then include the other sources mentioned earlier. In total, five search rounds are conducted to generate an unstructured list of role models (cf. Appendix 5-1, search column D to G).

TOC

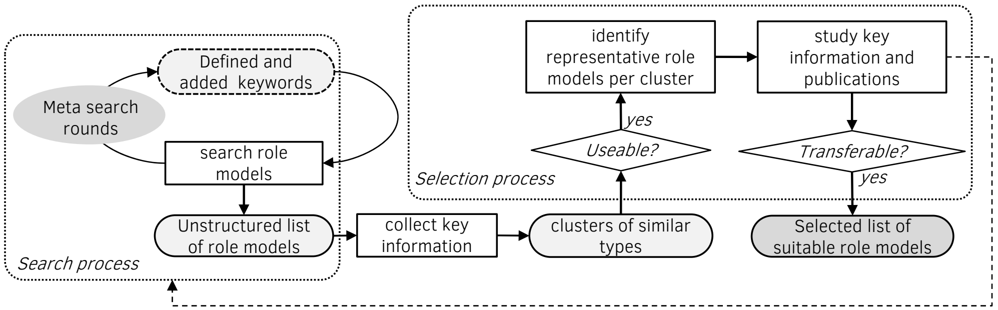


FIG. 5.1 Scheme of the applied process to achieve a selected list of suitable biological role models.

5.2.2 Identified biological role models

About 72 role models are collected by the search and selection process. The whole list of role models can be viewed in Appendix 5-1, due to its comprehensive information. For better readability in this chapter, the role models are presented by clusters of similar characteristics of the adaptation principles. Those clusters marked in *italic* are not presented in detail, because their functional principles are either not estimated crucial for summer efficiency or are outside the scope of this work:

1. Radiant modification by super-thin materials, structural colours
2. Thermal protection and thermal regulation by hairs
3. *Thermal protection by furs*
4. Thermal protection by coatings
5. Surfaces with radiant modifications for cooling purposes
6. Selective heat transmission by pigmental attributes
7. Heat dissipation by convective processes at surfaces
8. *Cooling by evaporation*
9. *Ventilation systems*
10. *Counter-current energy processes within matter*
11. Thermal conductivity modifications
12. Geometries allowing growth
13. Self-shaping and kinetic functions
14. Shape optimizations

In the following, for each cluster exemplary role models are presented with their main features ("*short description*", "*relevance to design level*", "*main principle*", "*strategy*", "*mechanism principle*", "*key search words*", and "*references*") and assignments to criteria of the adaptation criteria list (F08: "*functional purpose*" and V-02: "*physical process*").

The full collection of the biological models is provided in Appendix 5-1. All identified role models, their descriptions and first assessment can be found in this Appendix.

Cluster 1. Radiant modification by super-thin materials, structural colours		7 items (Appendix 5-1)
		**Exemplary role model:**
		01_Lepidoptera wings (butterfly, moths)
		Short description
		Wing structure creates black colour that absorbs light and minimizes reflection and transmission
		Relevance to design levels
		Modulation by system/material design (structural colours)
Blue morpho butterfly (Morpho didius)		
Main principle	**Strategy**	**Mechanism principle**
hierarchical scales of nanostructures with refracting and infereing radiation	black parts: adjacent inverse V-type ridges in structure of wings reduce reflection while keep transmission at a relatively low level. Other parts diffract.	structural colours / nanostructure, hierarchical settings influencing radiation
Key search words	**Functional purpose assignment (F08)**	**Physical process (V-02)**
light modification, structures, 3D material, regulate radiant energy	Visual purposes (not in the evaluation list)	V02.1: radiation
Sources, references		
AskNature (12.05.2020). Wing scales aid thermoregulation. https://asknature.org/strategy/wing-scales-aid-thermoregulation/ Ingram A.L. Parker A.R (2008). A review of the diversity and evolution of photonic structures in butterflies, Phil. Trans. R. Soc. B 2008 363, 2465-2480 Tsai, C.-C., Childers, R. A., Nan Shi, N., Ren, C., Pelaez, J. N., Bernard, G. D., Pierce, N. E., & Yu, N. (2020). Physical and behavioral adaptations to prevent overheating of the living wings of butterflies. Nature Communications, 11(1), 551. https://doi.org/10.1038/s41467-020-14408-8 Zhao, Q., Fan, T., Ding, J., Zhang, D., Guo, Q., & Kamada, M. (2011). Super black and ultrathin amorphous carbon film inspired by anti-reflection architecture in butterfly wing. Carbon, 49(3), 877–883. https://doi.org/10.1016/j.carbon.2010.10.048		

An example using the principle of colour change by structures but another mechanism to adapt this is the Hercules beetle: the colour of the beetle's exoskeleton changes according to the humidity level of its surroundings. The hydro-chromic cuticle contains "*cavities*" that can get filled and diffract light as a consequence (Rassart et al., 2008). The Selaginella ferns, e.g. spikemosses (*Selaginellaceae*) uses the principle of an interference filter to change colours under light. The leaves create iridescent blue colour on certain sunlight impact (depending on the angle and intensity) (Hébant & Lee, 1984).

This cluster does not target at thermal regulation, although its adaptations may indirectly contribute to this purpose. The mechanisms are more comparable to cluster 5, which is obviously aiming at the purpose of thermal regulation. Furthermore, the principle is scale-sensitive and thus needs solutions on nanoscale which asks for material development. Thus, the principles of this cluster are not further studied.

Cluster 2. Thermal protection and thermal regulation by hairs		5 items (Appendix 5-1)
		**Exemplary role model:** 10_Edelweiss trichomes **Short description** Epicuticular wax layer and trichomes (wooly hair) of plant prevent from UV radiation by absorbing UV wavelengths in hairs **Relevance to design levels** Modulation by surface/material design (hairy layer)
Edelweiss (Leontopodium alpinum)		
Main principle	**Strategy**	**Mechanism principle**
Absorption of radiant energy, selective properties	Optical structure and function of the white filamentary hair absorb UV radiation; filaments forming the hair layer have internal photonic-like structure.	photonic structure, surface properties
Key search words	**Functional purpose assignment (F08)**	**Physical process (V-02)**
Modify radiation, absorb, reflect, heat dissipation, change, control reflectance	F08.3: solar gain control F08.5: overheating prevention	V02.1: radiation
Sources, references		
AskNature (12.05.2020). hairs absorb ultraviolet radiation. https://asknature.org/strategy/hairs-absorb-ultraviolet-radiation/ Attenborough, D. (1995). The Private Life of Plants: A Natural History of Plant Behavior. London: BBC Books. 320 p. Vigneron J.P. et al (2005). Optical structure and function of the white filamentary hair covering the edelweiss bracts, PHYSICAL REVIEW E, Volume: 71, Issue: 1 Article Number: 011906, Part 1		

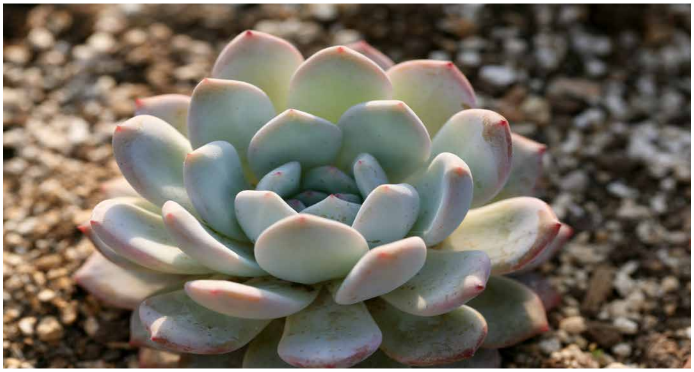
Other examples in this cluster use the principle of radiant modulation through the shape of the hairs, such as e.g. the Saharan silver ant (*Cataglyphis bombycina*): the ants use nano-scaled hair structures to reduce heat absorption by efficiently reflecting sunlight and dissipating heat. This effect occurs due to unique triangular prism shape of the hairs, which reflects the light. Furthermore, the hairs are densely packed to avoid irradiation of body surface and they also reduce heat absorption by reflecting near infrared radiation. The shape further increases the ability to radiate heat (emissivity) in the mid-infrared range (most effectively dissipate heat energy via thermal radiation) (Shi et al., 2015).

Many other examples use hairs to create a microclimate using the principle of thermal boundary layers (e.g. cacti) or thermal insulation (e.g. mammals). The hairs serve then as an air trapping, porous structure that influences the convective process at the surface and reduces the heat transmission, respectively heat loss.

The radiation modulation in the hair structures promise interesting approaches for cooling aspects, but also indicates a need in material development because material with such capability is not known to the author. Thus, this cluster will not further be considered for detailed analysis but recommended for further analyses.

The same applies for **Cluster 3. Thermal protection by furs**, which is not presented in detail since its principles would not contribute directly to the cooling target. Thermal protection by furs is dedicated to cold areas protecting from heat losses and usually combined with a thermal storage layer in order to store solar energy. As an example, the Polar bear can be mentioned, because its fur is not only an insulator but has also the capability to redirect light within the structure of the fur hairs towards the skin where the heat is stored (Vogel, 2007).

Cluster 4. Thermal protection by coatings | **5 items (Appendix 5-1)**



Exemplary role model:

17_Succulent plants (Crassulaceae)

Short description

Surface waxes on plants protects from heat (research suggest that this is done by melting of waxes)

Relevance to design levels

Modulation by surface/material design (waxy coatings)

Succulent plants (e.g. Crassulaceae)

Main principle	**Strategy**	**Mechanism principle**
Absorption, reflection of radiant energy, selective properties	The composition of waxy surface on nano- and microlevel is used to create a thin protection film that adapts. Research suggests that the wax changes its consistency (PCM)	Reflective coatings, surface properties
Key parameters	**Functional purpose assignment (F08)**	**Physical process (V-02)**
Regulate radiation, change modify radiation, thermal heat control, overheating prevention	F08.2: thermal energy control F08.3: solar gain control F08.4: heat dissipation F08.5: overheating prevention F08.7: energy conversion	V02.1: radiation

Sources, references

Karwowska et al, (2015). Anatomical structure of the leaves of Crassula cordata (Crassulaceae). DOI: 10.5281/zenodo.159830
Jetter, Sodhi, (2011). Chemical composition and microstructure of waxy plant surfaces: Triterpenoids and fatty acid derivatives on leaves of Kalanchoe daigremontiana. DOI: 10.1002/sia.3430

The creation of waxes on the surfaces is also used by other examples in this cluster such as spurges. Cockroaches use waxy coatings to control moisture content (Wigglesworth, 1945). Another type of '*coatings*' are barks of trees which provide thermal insulation by reflecting and absorbing light. The bark material is particularly designed and porous for this purpose (Pásztory & Ronyecz, 2014).

To provide heat-related tasks to coatings of a certain thickness is interesting, as this could enhance the role of plaster, which so far has had no heat regulating function. Comparable established functionals coatings are ultra-white paints, which are part of cluster 5.

The reviewed role models in this cluster use phase changing wax coatings to protect against excessive heat or cold, with the ability to adapt at critical thresholds. This approach seems interesting, but also scale-sensitive and thus difficult to apply to typical coatings used in the building sector. The author has found established phase-changing products in plaster for interior use, such as e.g. microencapsulated PCM panels (*Micronal (R) PCM* by microtek laboratories, 2020). However, they require a certain minimum thickness to function and thus do not seem applicable as films.

There are experimental tests on the effects using PCM in the interior to reduce high temperature fluctuations, such as e.g. done by Lachheb et al. (2017), Karkri et al, (2015) or Toppi and Mazzarella (2013). Only few publications have been found that investigate the use of PCM on the external surface of façades, such as done by Wüest et al. (2020), Shahrzad and Umberto (2019) or Heim and Wieprzkowicz (2018).

PCM use for façades is a considered research objective and biomimetic role models might not add much to the current knowledge. An investigation points to material development objectives, which excludes this cluster from further in-depth analysis. However, considerations to use PCM principles in the models is kept open.

Cluster 5. Surfaces with radiant modifications for cooling purposes		6 items (Appendix 5-1)
		**Exemplary role model:**
		24_ Lepidoptera wings (butterfly, moths)
		Short description
		Thermal emissivity is increased by nanostructure of wings: the wings have different regions with different emissivity and absorptivity. Depending on the positioning of the wings to the surface of the surroundings and sky, the thermal exchange effect can be regulated
		Relevance to design levels
		Modulation by system/material design (nanostructure)
Cruiser butterfly on leaf (Vindula erota)		
Main principle	**Strategy**	**Mechanism principle**
hierarchical scales of nanostructures with refracting and infereing radiation	Same like cluster 1 but uses the function of nanostructures in the wings to modulate radiant energy	Nanostructures, hierarchical settings influencing radiation
Key parameters	**Functional purpose assignment (F08)**	**Physical process (V-02)**
radiation modification, nanostructures, 3D material, regulate radiant energy	F08.2: thermal energy control F08.3: solar gain control F08.4: heat dissipation F08.5: overheating prevention	V02.1: radiation V02.5: geometric (position)
Sources, references		
Zhuang, Y. (2014). Thermal properties of leaf traits [MSc Thesis]. University of Twente.		

Other examples using nanostructures to reflect light to its maximum are beetles, such as e.g. the Cyphochilus beetle. Its cuticle structure refracts and reflects light in such way that the translucent tissue appears ultrawhite (Vukusic et al., 2007).

Particularly species in arid extreme climate regions apply more than one function to reach a thermal regulation optimum. Desert snails, for example, possess a highly reflective coating on its shell and an optimized shell form to limit the contact points to the soil in order to reduce thermal conduction. This is called *thermobiosis* – the combination of a highly reflective shell, optimization of form and position change if needed (Schmidt-Nielsen et al., 1971).

An analogy in the building world for such reflective surfaces are the ultra-while paints, which are widely applied. Although these are less sophisticated in the composition to achieve the ultra-white, they probably achieve similar levels of effectivity like the biological analogies. Highly reflective surfaces are also provided in the façade field by mirrored coatings (metallic coatings on glazings, polished metals).

The optimisation of the thermal emissivity of surfaces, as shown in the example of this cluster, is particularly interesting, especially in the context of the relative positioning of the surfaces to each other. This approach will be pursued further.

Cluster 6. Selective heat transmission by pigmental attributes		7 items (Appendix 5-1)
		**Exemplary role model:** 30_Shell attributes of eggs **Short description** The pigments cells of the bird's eggs reflect most of the near infrared radiation; balance of heat transmission through eggshell and overheating protection depending on pigments **Relevance to design levels** Modulation by surface/material design (pigmental colours)
Pigmented shells of bird eggs		
Main principle	**Strategy**	**Mechanism principle**
Reflectance or absorptance of surface directed by pigments	Pigment colour decide whether radiant energy is more absorbed or reflected to maintain the inner of the egg for a good brooding temperature	Pigmental modifcation / colour depending heat transmission/reflection
Key parameters	**Functional purpose assignment (F08)**	**Physical process (V-02)**
Radiation modification, absorption/ reflection on surface, regulate radiant energy	F08.2: thermal energy control F08.3: solar gain control F08.4: heat dissipation F08.5: overheating prevention	V02.1: radiation
Sources, references		
Vogel S. (2005). Living in a physical world IV: Moving heat around. Journal of Biosciences, 30, 449–460. Lahti DC, Ardia DR. (2016). Shedding Light on Bird Egg Color: Pigment as Parasol and the Dark Car Effect. Am Nat. 2016 May;187(5):547-63. doi: 10.1086/685780. Epub 2016 Mar 17. PMID: 27104989.		

Examples for Cluster 6 have various intentions to apply pigments: while the exemplary eggshells intend to regulate the thermal energy (Vogel, 2007) (Lahti & Ardia, 2016), other examples like the chameleons (Green et al., 2019) or the cuttlefish (Duarte et al., 2017) use pigments for colour change of their skins. Their rapid change is intended for camouflage (protection or attack) and initiated by biochemical processes.

Other examples use pigmental adaptation to filter excessive light, such as ice algae or the balloon fish. Again, the pigmental adjustments are done by biochemical processes (Kondrashev & Gnyubkin, 1999).

The examples in this cluster provide solutions to the functional purpose of overheating avoidance but employ bio-chemical processes to change the pigments as the adaptation mechanism. The adaptation mechanism itself is therefore not further studied, but if applicable solutions with such change behaviour are available for the building sector, an application in the models is considered.

Cluster 7. Heat dissipation by convective processes at surfaces	5 items (Appendix 5-1)
	**Exemplary role model:**
	33_Desert plants (e.g. Encelia farinosa, Cactaceae)
	Short description
	Enlarged (folded) surfaces creates thermal boundary layer; regulation of thermal heat flux.
	Relevance to design levels
	Modulation by system/material design (shape and hierarchical surface design)

Cactus ribs with needles

Main principle	Strategy	Mechanism principle
Thermal boundary layer by hierarchical structure (form, spikes, hairs), large exposed surfaces	Heat dissipation at low wind conditions or even still air by free convection; density and temperature differences generate a thermal boundary layer to regulate heat transmission.	Convection system, heat dissipation through geometric typology of plant surface/mammal extremeties
Key parameters	**Functional purpose assignment (F08)**	**Physical process (V-02)**
Regulation of heat, heat exchange, thermal convection, thermal boundary layer, geometric settings	F08.1: heat loss prevention F08.2: thermal energy control F08.3: solar gain control F08.5: overheating prevention	V02.1: radiation, V02.3: convection (V02.4: evaporation) V02.5: geometric

Sources, references

Koch, K., Bhushan, B., & Barthlott, W. (2009). Multifunctional surface structures of plants: An inspiration for biomimetics. Progress in Materials Science, 54(2), 137–178. https://doi.org/10.1016/j.pmatsci.2008.07.003

Althawad A.M.,Grace J. (1986). Water use by the desert cucurbit Citrullus colocynthis (L.) Schrad. Oecologia, 70 (3), 475-480

Roth-Nebelsick A. (2001). Computer-based analysis of steady-state and transient heat transfer of small-sized leaves by free and mixed convection, Plant, Cell and Environment (2001) 24, 631–640

Vogel J. (1970). Convective Cooling at Low Airspeeds and the Shapes of Broad Leaves, Exp. Bot.; 21: 91-101

Schuepp P.H. (1993). Leaf boundary layers, Tansley Review No. 59 New Phytol., 125, 477-507

Other examples that can be added to the principle of thermal convection and heat dissipation deal with inner enlarged surfaces, such as e.g. the trachea of mammals: the commonality of both exemplary groups relates to the surface geometry (Vogel, 2005) (Hill et al., 2008): heat convection with the environment is more efficient when the surface area is large. For example, noses ensure effective heat exchange through their relatively long inner surface. The more the mammal relies on this type of heat dissipation, the larger the surface area (due to e.g. folds and winding internal passages).

Surface size/volume adjustment is an essential design criterion to regulate the thermal convection processes. Folded or protruding geometries create a surface that influences the thermal layer between the surface and the free air by changing air velocity and temperature gradients. This strategy could be implemented in façade constructions, e.g. through shading components. However, there is usually an air gap between the shading and the thermally relevant façade skin and thus the heat dissipation is not as effective as in the biological role models.

Pneumatic building envelope constructions that can change the shape of their outer skin while allowing direct heat transmission through the skin could potentially support the strategy. This idea is very interesting and shall be explored via in-depth studies using fluid dynamic calculations.

For **Cluster 8. Cooling by evaporation**, many role models can be found in plants and mammals alike. The adaptability and variability of the enthalpy is a survival-securing function of most living beings. Plants regulate heat energy by water transpiration through stomata on their leaves. These openings control the transpiration process, which is determined by temperature and the need to avoid overheating, but also by nutrient transport for growth. Stomata are micro-openings on the underside of leaves with a kinetic mechanism initiated by turgor pressure (Volkov et al., 2010). The evaporation efficiency is hereby depending on the opening width and durations (cf. cluster 13).

This evaporation principle works in animals, especially mammals, in a similar way: water is transported to the surface of the skin to evaporate and thus cool the surface. Evaporation is stimulated by physiological processes, whereby the influence of the exposed surface and convection are the decisive factors. The more surface is in contact with the external environment and air movement to dissipate heat, the more evaporation can take place. This is also valid for internal surfaces, such as the nasal conchae of macrosmatic mammals like dogs (Barrios et al., 2014). The inner surface of their noses is folded intensively and, together with tiny hairs, provides a large evaporative surface that also ensures that it does not dry out.

The anatomical structure thus plays a crucial role in the effectiveness of evaporative cooling, but also in maintaining a moisture-healthy surface (Craven et al., 2007).

Evaporation processes require water reservoirs or a water reservoir and they are support mould growth. Therefore, such processes do not appear suitable for application to façades. Nevertheless, there are practicable examples in traditional architecture that use hydrophilic materials in the façade area (mashrabiya in front of the windows) to achieve passive cooling via evaporation (cf. Chapter 2). This effect works best in dry-hot climates where the enthalpic conditions are in such a way that evaporation can take place effectively. Since this work focuses on the Central European region, this effect is neglectable and thus the cluster will not be further considered - even though the cooling potential is obvious.

Cluster 9. Passive ventilation systems primarily require spatial considerations for air-bearing structures. The biological examples found for passive ventilation create a built environment with corridors and ducts to regulate heat and gas exchange. These are arranged in such a way that they cause changes in air pressure and thus acceleration or reduction of the air velocity. This is described by effects such as the Bernoulli effect or stack effect. Bernoulli's law describes the dependence of the flow velocity and the static pressure; if the flow velocity increases, the pressure decreases. This can happen, for example, when the cross-section of a channel is reduced. If the pressure is lower than that of the environment, the air is literally 's*ucked in*' by the environment in order to achieve pressure equalisation. This causes air to flow in the desired direction. The stack effect, in turn, is based on buoyancy forces: the greater the thermal difference and the structural height of a '*duct*', the greater the airflow. Termite structures or subterranean structures, such as that of the prairie dog, make use of these effects to ensure air flow through winding air ducts, as discussed in many publications (King et al., 2015) (Turner & Soar, 2008) (Korb, 2003) and (Pohl & Nachtigall, 2015).

The principle of passive ventilation is already being applied effectively in building design, even in multi-layered double skin façades. Since the effect is based on aerodynamic principles that require investigation using fluid dynamic simulation, a continuation of the analysis in this thesis is excluded. This would go beyond the scope of this work and should be considered in a specifically dedicated task.

The functional principle of **Cluster 10. Counter-current energy processes in matter** behaves similarly to that of cluster 9. The heat exchange principle of the identified role models is based on mechanisms that again require a channel system, i.e. pipes and channels in which a gas or liquid can flow through. The difference to cluster 9, however, is that these are so-called closed systems. The liquid or gas has no direct connection to the environment and can therefore only exchange heat indirectly with the '*external*' environment via conduction (regulated by convection) through the surrounding surfaces. Here, too, the surface plays the decisive role. The size and arrangement of the heat exchanger geometry are the critical features in the design of such systems. Biological examples using this heat exchange principle are manifold, such as the bloodstreams in mammals, but also in birds and insects (cf. Appendix 5-1). This cluster would again require deeper investigations in fluid dynamics and is therefore recommended for a separate PhD topic, like for the previous clusters.

Cluster 11. Thermal conductivity modifications		5 items (Appendix 5-1)
		**Exemplary role model:** 56_ Birds' plumage **Short description** Down feathers insulate: adaptive insulation; swelling/shrinking actuator in body, feathers increase air trapped volume **Relevance to design levels** Modulation by system/material design (plumage, feathers)
House sparrow (Passer domesticus)		
Main principle	**Strategy**	**Mechanism principle**
radiant heat exchange, thermal conductivity change	Thermal adaptation of feather plumage by adaptive air trapping strategies; thermal transmission adapts via volume expanding/shrinking properties.	Air keeping porous structure that adapts kinetically
Key parameters	**Functional purpose assignment (F08)**	**Physical process (V-02)**
thermal conductivity by structure, insulation, regulation of thermal flow, radiant exchange	F08.1: heat loss prevention F08.2: thermal energy control F08.6: energy exchange	V02.2: conduction V02.3: convection V02.5: geometric
Sources, references		
Robinson, D.E., Campbell, G.S. & King, J.R. (1976). An evaluation of heat exchange in small birds. J Comp Physiol B 105, 153–166. https://doi.org/10.1007/BF00691117 da Silva R.G., Maia A.S.C. (2013). Heat Exchange Between Animals and Environment: Mammals and Birds. In: Principles of Animal Biometeorology. Biometeorology, vol 2. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-5733-2_4		

The thermal conductivity of building materials is generally considered an intrinsic and fixed property. In nature, however, adaptive thermal conductivity is the Normal. Strategies in this cluster are ranging from the presented plumage adaptations of birds to foam-producing insects, such as e.g. spittlebugs (Tonelli et al., 2018). The foam provides a thermal microhabitat by regulating temperature transmission and moisture. Similar but much slower due to the high thermal inertia acts the blubber of mammals, such as of e.g. dolphins (Dunkin et al., 2005) or polar bears.

An interesting version for adaptive thermal conductivity presents the ring teeth of squids, which are on the suckers on a squid's tentacles to support the grip on a surface: a proteinaceous film changes physiologically the thermal conductivity of the squid ring teeth depending on ambient conditions (humidity). The thermal conductivity increases when the film becomes wetter (Tomko et al., 2018). This makes the material a switchable thermal conductor, whose strategy is investigated more in depth in Chapter 6.

The best known inanimate adaptive thermal conduction process is also part of this cluster: the phase change process from liquid to solid and back. This occurs when water freezes to ice, or waxes change their consistence (cf. cluster 4). The thermal storage effects of phase change materials (PCM) are well known and already used in the building industry, and, as mentioned already in cluster 4, tested as thermal storage components in façades (Wüest et al., 2020) (Soares et al., 2013). The side effect of the phase changes in natural role models, the deformation, is unwanted. This occurs due to the growth of e.g. crystals (= ice) while changing the phase. A volume change is thus part of the phase change, just as the adapted thermal conductivity. Controlling the volumetric expansion within confined structures in the phase change processes is investigated e.g. by Chandler (2011).

For this work, adaptive thermal conduction is particularly interesting, since the high thermal insulation standards cause an internal heat lock in summer. Heat dissipation through highly insulated building envelopes is thus largely minimized. Adapting the thermal conductivity of insulating layers by volume changes respectively changes in the air trapping layer might support the nightly cooling process in summer.

Cluster 12. Geometries allowing growth	5 items (Appendix 5-1)
	**Exemplary role model:** 59-63_ Growth patterns in 3D structures, e.g. plants, vegetables, bee hives **Short description** threedimensional growth shapes **Relevance to design levels** Modulation by system design

Cauliflower, exemplary for 3D growth patterns using fractals

Main principle	Strategy	Mechanism principle
form stability, growth pattern	cellular units extruded in the 3rd dimension (such as growth patterns applying fractals). 2-dimensional polygonal units that expand in 2D, but have a anisotropy into 3D are e.g. hexagonal designs (e.g. bee hives)	generally multi-directional shape change; limitaion for unidirectional shape changes (e.g. hexagonal structures) since they are transversely isotropic structures; useful when environmental conditions are predictable and structure can be oriented correctly; it has a preferred direction in third dimension.
Key parameters	**Functional purpose assignment (F08)**	**Physical process (V-02)**
Growth, self-shaping deformation, 3D material, cellular solids	None (supportive structure)	V02.5: geometric

Sources, references

Chen at al, (2014). Compressive and flexural properties of biomimetic integrated honeycomb plates. https://doi.org/10.1016/j.matdes.2014.07.021
Zhang et al, (2015). Bio-Inspired Engineering of Honeycomb Structure - Using Nature to Inspire Human Innovation. DOI: 10.1016/j.pmatsci.2015.05.001
AskNature (20.05.2020). honeycomb structure is space efficient and strong. https://asknature.org/strategy/honeycomb-structure-is-space-efficient-and-strong/
Hermann M.(2005): Bionische Ansätze zur Entwicklung energieeffizienter Fluidsysteme für den Wärmetransport, Dissertation Universität Karlsruhe
Fratzl et al. (2015). The mechanics of tessellations – bioinspired strategies for fracture resistance.

Almost all of the identified growth patterns in the list of models are applicable for any functional purpose as long as the system requires a geometry to grow in a 2D or 3D direction. The growth patterns include polygonal anisotropic patterns, such as hexagonal structures, and isotropic patterns, such as fibre-like structures, as well as growth principles, such as tessellations, fractals, lattice structures. All these patterns and principles occur in animals and plants as well as inanimate matter and are analysed in detail, as shown in the exemplary publications by Fratzl et al.

(2016), Porta et al. (2019), or Ball (2009). The examples from cluster 12 are used as supporting system design factors for the development of the functional models.

Cluster 13. Self-shaping and kinetic functions	6 items (Appendix 5-1)
	**Exemplary role model:** 68_rapid motions of plants, e.g. mimosa pudica **Short description** The leaves of the mimosa pudica tilt in seconds when touched. This is initiated by a chemical process (solution changes) in the cells of the leaves **Relevance to design levels** Modulation by system/material design (turgor effect)

Mimosa pudica

Main principle	Strategy	Mechanism principle
motion via turgor/osmosis, chemical process, cell membranes	Adaptation of leaves, rapid folding movements occur as turgor movements (wilting), tropism	Rapid motion by change in turgor pressure in cell (water diffusion through cell walls = osmosis)
Key parameters	**Functional purpose assignment (F08)**	**Physical process (V-02)**
Motion actuator, osmosis, chemcial process	F08.6: energy exchange	V02.2: conduction

Sources, references

Yoël Forterre (2013). Slow, fast and furious: understanding the physics of plant movements, Journal of Experimental Botany, Volume 64, Issue 15, November 2013, 4745–4760, https://doi.org/10.1093/jxb/ert230
Mano, H., Hasebe, M. (2021). Rapid movements in plants. J Plant Res 134, 3–17. https://doi.org/10.1007/s10265-020-01243-7

Another example of kinetic rapid adaptations in this cluster are the stomata on the underside of the leaf. These use a similar biochemically triggered process as the example of this cluster, the Mimosa pudica: a turgor pressure in cells regulated by osmosis, which causes a volume expansion of the cells and initiates the movement (cf. analysis in Chapter 6). Turgor pressure regulation in the cells at the stomata causes swelling or shrinking, which closes or opens the stomata. As in the Mimosa pudica, this process takes place within seconds and is thus a widespread rapid adaptation strategy in the plant world. The principle is interesting, although the scaling and functional level of the osmosis is likely to be a challenge for a transfer. Liquids are less welcome in façade systems due to frost and/or mould risks. In any case, the principle would have to take place in a closed microsystem where the mimicking of the osmosis effect would have to take place. This requires material development, but its applicability to façades would still be questionable due to the moderate nature of osmosis. The topic should be pursued further, but is not analysed in this work.

This challenge also applies to the principle of vasodilation/vasocontraction, another rapid adaptation mechanism that takes place in blood vessels: the diameter change of the vessel walls occurs through vasodilation and vasocontraction, which is initiated by the muscles and fibres of the medium-layered tissue surrounding the vessel wall. The activation occurs through metabolism, i.e. hormones. Depending on the flow velocity of the blood, the pressure and also thermal conductivity adapt. This principle is again based on the Bernoulli effect.

Butterflies use this dependence of flow velocity, pressure and thermal conduction to create a reverse heat exchanger (with an adaptive reversal of the flow direction): the vessels of the wings have a tube-in-tube system with an outer tube that has a liquid and an inner tube that has air flowing through it. When the inner tube expands (due to higher pressure), its diameter increases, which reduces the flow space of the outer tube. This causes an increase in flow velocity (higher pressure) until the direction of flow in the outer tube is reversed. The fluid can therefore flow in two directions, transporting heat from the inside to the outside or vice versa (Tsai et al., 2020).

The flow velocity/shape deformation principle would require investigations in the field of fluid dynamics with material development on a micro scale (capillary tube system). Therefore, it is neglected for the development of the design-oriented functional models in this work. However, the idea is exciting as it could be embedded in material suitable for façades and is therefore further investigated in Chapter 6.

Deformation mechanisms using motion control through osmosis are only one option of rapid activation; deformations by ambient humidity represent another large group of self-adaptive kinetic role models: the common denominator of these role models is that they are bend-dominated structures based on the swelling and shrinking of a fibrous material. The bending depends on the arrangement of the cellulose fibrils; the stimulus to trigger the adaptation process is the moisture. This effect is already well studied and even transferred to biomimetic prototypes, as shown by the hygromorphic materials developed by Holstov et al. (2015), Menges & Reichert (2015) or Grönquist et al. (2019) - to name a few. Deformations based on environmental changes seem to be uncontrollable, they adapt without possibility of control. Their applicability for a controllable behaviour of façades must be investigated in more detail. This effort would require a separate approach to develop solutions. Therefore, these strategies are seen as potentials for future work.

Cluster 14. Shape optimization	4 items (Appendix 5-1)
	**Exemplary role model:** 70_ beak of Tococ Toucan **Short description** Toucan has a big beak relative to body size, which provides a huge surface for heat exchange/transient thermal radiator **Relevance to design levels** Modulation by system design (structural colours)

Toco toucan (Ramphastos toco)

Main principle	**Strategy**	**Mechanism principle**
Heat exchanger, counter-currentsystem and volume/size	Thermoregulation depending on size of beak	surface/volume optimization to increase heat exchange and regulation
Key parameters	**Functional purpose assignment (F08)**	**Physical process (V-02)**
Thermal regulation, non-evaporative heat dissipation	F08.2: thermal energy control F08.4: heat dissipation	V02.2: conduction V02.3: convection (V02.4: evaporation) V02.5: geometric

Sources, references

van de Ven TMFN, Martin RO, Vink TJF, McKechnie AE, Cunningham SJ (2016). Regulation of Heat Exchange across the Hornbill Beak: Functional Similarities with Toucans?. PLOS ONE 11(5): e0154768. https://doi.org/10.1371/journal.pone.0154768

The principle of static shape optimization is well established in nature and in technologies and design. Although this is a passive measure that cannot be adapted dynamically, it has a certain '*dynamic'* effect on changing conditions. As the examples of cluster 7 show, there are different shape optimization strategies depending on the specific needs and the climate region. Cacti, for example, have rib-like structures to increase the self-shading and also to create a thermal boundary layer (together with the spines and hairs). This helps them to regulate thermal exchange with the environment, not to overheat during the day and not to freeze during the cold night.

Especially oversized body parts, as in the cluster example shown or as elephants and rabbits have, are a successful approach to increase the thermoregulatory functions of an animal. The eco-geographical rule, which states "*that related species have developed different characteristics depending on the geographical region in order to adapt evolutionary to the respective climatic conditions*" (Gosztonyi, 2018, p. 171), applies here. The size of the extremities adapts in relation to the climatic region. For example, rabbits in arctic regions have much smaller ears than rabbits in warm regions because their need to dissipate heat is low.

The principle of static shape optimization is well established in the façade and architecture field, with recent application of generic algorithms in parametric design to allow tailored shapes for a specific location and function. No new insights are expected from biological examples; thus the cluster will not be investigated further. However, its principles will be considered for optimization approaches if needed.

5.3 Selection of suitable role models

The selection of suitable role models is done in two steps: in the first step, the two criteria 'useable' and 'transferable' are rated to identify those role models that contain enough information and apply to the translation rules in Chapter 4. In the second step, the defined search fields of Chapter 2 are added to identify those that promise possible solutions for these fields.

5.3.1 Methodology

After the meta-search, the collected role models are screened and clustered into groups with similar adaptation strategies (cf. Appendix 5-1, columns 'meta search rounds'). For this purpose, the key information obtained in the meta-search is set up as following: "*role model name*", "s*hort description*", "*strategy*", "*main principle*", "*principle mechanism*" and "*sources/references*". Furthermore, "*biological class*" and "*biological family*" are added; these taxonomy types are part of the ranking in modern biological classification systems, such as those used by the COL (Catalogue of Life) (Species 2000, 2020). This addition indicates the general occurrence of the strategy. The clustering makes the main features of similar adaptation strategies, such as e.g. colour adaptation by nanostructures or photonic crystals, visible. It also helps to organize the list and identify exemplary publications per cluster for in-depth studies (cf. Appendix 5-1, columns 'key information').

Although at this stage mainly abstracts are reviewed to generate the information, it is considered sufficient to initiate the first step of the selection process, which identifies useable role models for later analysis (cf. Appendix 5-1, column 'useable'):

- Useable? *Is enough information available to assess the role model? (insufficient information, too general information, information leads to a field that has been excluded from investigations will cause an exclusion)*

After the first step in the selection, the information of the role models per cluster is reviewed and representative examples are defined. The publications of these representative role models are selected for closer examination to identify their principles and identify necessary further information leading to a complementary search. This step is intended to increase the effectiveness of the effort, as studying unfiltered all publications would take an enormous amount of time while finally not all of them would be useable. Furthermore, similarities between role models and key publications would also become visible. For example, in the cluster focusing on thermal conductivity modifications, role models that use both biochemical and biophysical modifications were summarized. Only those are seen representative that match with the exclusion criteria defined in Chapter 4 (e.g. processes that do not require new chemical adjustments).

As a second step in the selection process, the transferability of the representative role models is screened based on the study of the available information (cf. Appendix 5-1, column 'transferable'):

- Transferable? *Does the role model suggest a potential that could be transferred considering the design conditions and modelling criteria established in Chapter 4? (for example, role models that lead to new material developments are excluded).*

The evaluation of the transferability is based on a qualitative assessment of whether the principles can be transferred to a functional model for façades using existing materials and construction methods. The evaluation is done by a subjective assessment considering common façade development methods. This means that those principles are considered less transferable that require developments in building services technology or material sciences - even if they possess a high potential. The aim is to primarily select role models for the use of familiar design methods in order to realize short-term solutions. For example, role models that "*modify radiation*" by using nano-scale structures (=structural colours or photonic crystals) or by applying chemical processes are neglected, because this require material development at the nanoscale to function. However, geometric and spatial adjustments of such principles, which could also function on the macro level, are being studied for possible transfer. Of course, the evaluations could be revised depending on the state of knowledge and do not claim to be definitive.

The selection of suitable biological role models is done by identifying those clusters and biological adaptation strategies whose representatives are rated positive in both selection steps (cf. Appendix 5-1, column 'selection') and who comply with the targeted search fields. Only those strategies are taken further for detailed investigations in Chapter 6 that promise new insights. The other selected strategies are considered known well enough to be taken directly to the development of the functional models.

5.3.2 Selected role modelss

Table 5.2 shows all clusters identified in the search process. For each cluster the 'biological class' of representative role models and the 'main adaptation strategy' is shown. Furthermore the two selection steps (cf. Section 5.2.2) to identify useable information and transferrable strategies are added. The rating of these criteria is either '*positive*' (+), '*unclear/possible*' (+-) or '*negative*' (-).

Those strategies that are evaluated positive (dark blue fields) or possible (bright blue fields) for the criterion '*transferable*' are considered for further selection. With this selection step, the result is narrowed down to following ten clusters of similar mechanisms:

- Cluster 04: 'Thermal protection by coatings',
- Cluster 05: 'Surfaces with radiant modifications',
- Cluster 06: 'Selective heat transmission by pigmental attributes',
- Cluster 07: 'Heat dissipation by convective processes at surfaces',
- Cluster 09: 'Ventilation systems',
- Cluster 10: 'Counter-current energy processes',
- Cluster 11: 'Thermal conductivity modifications',
- Cluster 12: 'Geometries allowing growth',
- Cluster 13: 'Self-shaping and kinetic functions' and
- Cluster 14: 'Shape optimizations'.

The detailed rating respectively the full list of identified biological role models can be viewed in Appendix 5-1.

TABLE 5.2 Evaluation of role model clusters.
The rating system for the evaluation is as following:+' means 'positive', '+-' means 'unclear/possible', and '–' means 'negative'. For criterion 'transferable' the rating arguments are added. Those clusters that promise a transfer potential are marked darker blue, those fields that promise a supportive role are marked bright blue.

Cluster		Biological class according to (Species 2000, 2020)	Main adaptation strategy of role model	USEABLE? Available information?	TRANSFERABLE? Potential for objective?
01	Radiant modification by super-thin materials, structural colours	Insects (butterflies, beetles); plants (leaf of dove tree)	Structural colours	+	- colour change objectives, no cooling
			Multi-layered photonic structures	+	- colour change objectives, no cooling
		Birds (blue coloured birds), Lycopods (fern leaves); Crustaceans (copepods)	Thin-film interferences	+	- colour change objectives, no cooling
02	Thermal protection and regulation / hairs	Insects (silver ants); Plants (desert, alpine)	Photonic structure in matter	+	- material development objective
			Micro-structure	+	- material development objective
03	Thermal protection / fur	Mammals (polar bear)	Air keeping structure	+	- static insulator, no cooling
04	Thermal protection / coatings	Plants (desert plants), Insects (cockroaches)	Waxy coatings	+	+- possible if material exists (PCM)
		Quiver tree (Aloidendron dichotomum)	Powder coatings	+	- powder not resistant
		Bark of trees	Multi-layered coatings	+	- material development objective

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Cluster		Biological class according to (Species 2000, 2020)	Main adaptation strategy of role model	USEABLE? Available information?	TRANSFERABLE? Potential for objective?
05	Surfaces with radiant modifications for cooling purposes	Snails (glass snail, peacock begonia)	Nanosctructures	+	- material development objective
		Insects (beetle, butterfly wings)	Positioning of surfaces Emissivity of surfaces	+	+ thermal emission support by geometry
06	Selective heat transmission / pigmental attributes	Reptiles, fish (chameleon)	Selective radiation control	+	- material development objective
		Birds (eggs)			
		Plants (leaves, algae's)			
07	Heat dissipation by convective processes at surfaces	Mammals (trachea)	Regulation by heat exchange process	+	+- potential, needs aerodynamic studies
		Plants (cacti shape)	Heat regulation by thermal boundary layers	+	+- potential, needs aerodynamic studies
08	Cooling by evaporation	Mammals	Evaporation surfaces	+	- not applicable in Central Europe
		Plants (stomata)			
09	Ventilation systems	Mammals (prairie dog)	Open system heat transfer using gas	+	+- potential, needs aerodynamic studies
		Insects (termite mound)			
10	Counter-current energy processes within matter	Animals (blood vessels)	Closed system heat exchanger using fluid	+	+- potential, needs fluid dynamic studies
		Birds (legs)			
		Mammals (respiration system)	Closed system heat exchanger using gas	+	+- potential, needs fluid dynamic studies
		Desert rodents (nose)			

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TOC

TABLE 5.2 Evaluation of role model clusters.
The rating system for the evaluation is as following:+' means 'positive', '+-' means 'unclear/possible', and '–' means 'negative'. For criterion 'transferable' the rating arguments are added. Those clusters that promise a transfer potential are marked darker blue, those fields that promise a supportive role are marked bright blue.

Cluster		Biological class according to (Species 2000, 2020)	Main adaptation strategy of role model	USEABLE? Available information?	TRANSFERABLE? Potential for objective?
11	Thermal conductivity modifications	Mammals (blubber), plants (waxes), matter (water to ice)	Phase change process	+	+- possible, if material exists (PCM)
		Insects Birds' plumage	Adaptive air keeping structure	+	+ dynamic thermal insulation
		Squid ring teeth	thermal conductivity switch	+	+- possible, if material exists
12	Geometries allowing growth	Living organisms	Growth patterns and geometries	+	+ design rule
		Inanimate structures			
13	Self-shaping and kinetic functions	Plants (flexible structures)	Environmentally triggered motion (temperature, humidity, pressure)	+	+- possible, if material exists (SMA)
		Animals (blood vessels)			
14	Shape optimizations	Plants (e.g cacti)	Self-shading shapes	+	+ supportive design rule
		Plants (e.g. living stones), animals (e.g. extremeties)	SA/V ratio optimisation	+	+ supportive design rule
		Sunflower (seeds) Birds (beak)	Exposed surfaces	+	+ supportive design rule

5.3.3 Search scope definition

According to the defined search scope of Chapter 3 (cf. Table 3.5), biomimetic solutions for the selected design measures 'P01: thermal insulation' and 'P08: passive cooling at surface' are sought. For these measures the functional purposes '*F01. Thermal transmission*' and '*F06. Radiative energy*' (focusing on '*F06.1 Radiative emissivity*', '*F06.2 Solar exposure area*', and '*F06.3 Positioning of surfaces*') are assigned, according to Figure 2.16. These purposes are now assigned to the cluster list of Table 5.2 to identify those that may contribute to the search fields.

TABLE 5.3 List of selected clusters assigned to the search fields.
The list shows the selected clusters with the functional principle (=search fields), main adaptation strategy and a representative role model. Those examples that are selected for analysis in Chapter 6 are marked blue with a '+'.

Clusters (selected in table 5.1)	Functional principle (F0x) /SEARCH FIELDS	Main adaptation strategy of role model	Representative example	Analyses in Chapter 6?
C10. Counter-current energy processes within matter	F01 Thermal transmission	Closed system heat exchanger - fluid	blood vessels	+
C11. Thermal conductivity modifications		Adaptive air keeping structure	birds plumage	+
C10. Counter-current energy processes within matter		Closed system heat exchanger - gas	respiratory passages	- known principle, aerodynamic analyses
C14. Shape optimizations		SA/V ratio optimisation	beaks of bird	- known principle
C11. Thermal conductivity modifications	F02 Thermal storage	Phase change process	blubber, water to ice	- known principle
C4. Thermal protection by coatings	F03 Radiative transmission	Waxy coating	plants (desert)	- excluded from search field
C7. Heat dissipation by convective processes at surfaces	F05 Thermal convection	Regulation by heat exchange process	trachea of mammals	- excluded from search field; aerodynamic analyses
C9. Ventilation systems		Open system heat transfer - gas	prairie dog	
C7. Heat dissipation by convective processes at surfaces	F05 Thermal convection	Heat regulation by thermal boundary layers	cacti hierarchy of shape, spine, hair	- known principle, aerodynamic analyses
C14. Shape optimizations		Self-shading shapes	cacti shape	
C5. Surfaces with radiant modifications for cooling purposes	F06 Radiative energy	Positioning of surfaces	butterfly wings	+
C5. Surfaces with radiant modifications for cooling purposes		Emissivity of surfaces		+
C14. Shape optimizations		Exposed surfaces	sunflower seeds, plants (Romanesco)	+
C12. Geometries allowing growth	Design rules influencing adaptation	Growth patterns and geometries	growth patterns	+
C13. Self-shaping and kinetic functions		Environmentally triggered motion	pine cones, mimosa pudica	+

Table 5.3 shows the clusters selected for the search scope (blue fields), and for possible supportive information (lighter blue fields). The table shows the main adaptation strategy and a representative role model in order to choose those for in-depth analyses in Chapter 6.

Only those clusters, respectively representative role models, are selected for detailed analysis, whose principle is not well known or not applied in the façade construction. These are marked with 'yes' in the right column 'Selection for analyses'.

5.4 Summary

The search and identification of suitable role models demands an specific effort in choosing the sources, studying the role models and finally selecting the potentials. The process takes time to read and understand the respective literature and sort out what is not applicable.

During the search and selection process, clarification of terms that are used in the different disciplines is necessary. Many terms are interpreted differently by researchers in physics, architectural sciences or biology (e.g. 'dimension', 'structure'). Thus, some terms, which are used in this work, may deviated from their specific use in the disciplines.

The defined keywords must be constantly complemented for a meaningful search in biological databases. Thus, a certain flexibility in the search process is necessary in order not to restrict the search too much. This process is critical because it can easily become infinite. To prevent this, after a few meta search cycles, similar adaptation mechanisms are clustered to identify strategy typologies. This way, repetition can be avoided, and the number of search cycles reduced.

With the selection steps, another restriction of the process is done: it is necessary to select only those role models for which sufficient information has been found. This selection can be adjusted at any time depending on the available sources. Assessing the transferability of the strategy is a question of existing knowledge and interpretation of the information. For this selection step, a transdisciplinary cooperation with experts from the various fields is recommended. The role model collection of the Bioskin project was elaborated in this sense, from which this work now benefits. A lot of time could be saved through this preliminary work. The selection is finally based on subjective assumptions.

Based on these constraints, the following assumptions can be made: overheating risks can be prevented by specific surface characteristics, i.e. protective coatings, hairs or also by optimising the shape - this applies to the micro- as well as macro-level. The aim is to reduce heat transmission to the inside (reduced heat transfer) or to increase convection (increased heat dissipation). Overheating risks are also reduced by modifying the incident radiation, i.e. filtering or reflecting the wavelength-related (heat) radiation by nano structures on the surface - this happens at the nano level. The aim is to modify radiation in such a way that the heat-relevant wavelengths are reflected or emitted at the surface.

Once a biological system heats up, it is important to dissipate the heat as effectively as possible; this occurs through heat exchange systems, convection or evaporation on surfaces, which is usually done by a combination of measures on the surface and within the system. The repetitive hierarchical geometrical structures (constructive design) are needed measures for most of these functions to work properly. They allow furthermore the system to adapt dynamically (growth) or keep flexible (kinetic motion).

Of the collected 72 role models, clustered into 14 groups of similar mechanisms, the functional strategies from nine clusters are selected (cf. Table 5.2).

Transferability and the defined search scope in Chapter 3 are the decisive criteria for the selection of potential clusters for the further analysis: the criterion 'transferability' follows the established rules in Chapter 4. Those biological adaptation strategies that might reveal new insights will be analysed in Chapter 6. The others are either well known and can be used directly in the functional modeling of Chapter 7 or they would require certain analytical approaches that are outside the scope of this work. Thus following seven clusters are selected for in-depth studies:

- Closed systems using fluid to exchange heat (C10) and adaptive air keeping structures (C11) targeting 'thermal transmission (F01)' principles,

- Positioning of surfaces (C5), emissivity of surfaces (C5) and exposed surfaces (C14) targeting 'radiative energy (F06)' principles,

- Environmentally triggered motion mechanisms (C13) and general growth patterns and geometries (C12) that reveal 'design rules that influence adaptation'.

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Appendices

Appendix 5-1 Total list of identified role models

Online: https://data.4tu.nl/account/collections/5811071

6 [Analyses] Biological concepts

Probably the biggest uncertainty of this work can be found in this chapter. The process of understanding complex functions of a biological organism and the creation of functional descriptions is very demanding. The quality of needed abstraction depends not only on the available knowledge about the organism, but also on the '*translation perspective*' of the knowledge carrier. The specialists' knowhow needed for the analysis of biological role models is often not the same as for the description of biomimetic principles. Therefore, transfer processes and methods in biomimetics must be critically discussed: which questions direct the analyses process and which answers are extracted? The degree of understanding interprets the information. In addition, there are terminology misunderstandings between the domains that can be traced back to different notions of terms. A common understanding of these and the ability to capture the relevant information and framework conditions of both domains is an important factor for biomimetic projects.

This chapter deals with this challenge and proposes a translation system that builds a bridge between biology and technology (respectively façade design) based on parametric structures and a semantic language.

The list of suitable role models, as established in Chapter 5, is based on a review of literature in professional journals, a meta-search of biomimetic databases, and interviews with relevant experts - these sources form also the basis for the analyses in this chapter. Since the author accesses domains far beyond her competence, translation errors are likely to happen. In order to reduce this risk a bit and draw right conclusions about the identified role models, biologists were consulted and coplementary publications were screened in case of ambiguities. The findings, however, should be seen as an attempt to present the developed translation process itself: the systematic method on how to describe and transfer a biological principle in order to make it accessible to technical developments. Possible errors in the translation of the '*how*' and '*what'* of a principle are to be expected, although great efforts are made to avoid this to the best of the author’s knowledge.

The chapter starts with a brief introduction in Section 6.1 and continues to the applied methodology in Section 6.2. The methodology explains the evaluation process for the analyses of the selected principles and the critical transfer process to identify potentials for the generation of biological concepts. The structure of how the concepts are described is developed in such a way that it can be used for the functional model design.

Section 6.3 deals then with the analyses of the biological principles. For this purpose, the functional characteristics of the selected role models in Chapter 5 are examined in depth by detailed literature studies. With the gained knowledge, the role models are then evaluated in Section 6.4 to select exemplary potentials for the translation into biological concepts. These concepts are called 'biological concepts' of which two examples are presented in Section 6.5. The aim of these concepts is to explain the processes, dependencies and design parameters that are relevant for the adaptation process in a structured form that is useable in Chapter 7.

6.1 Introduction

Functional descriptions of biological role models within a biomimetic translation process often form a tightrope walk along expert knowledge and amateurism. The methodological tools and perceptions used to analyse the selected organisms in this work are chosen from the perspective of façade design and physical analysis. For this reason, the understanding of functional principles is already directed and there might be a lack of a scientifically correct description of the mode of operation from a biological point of view. Such descriptions can only be achieved by close cooperation with biologists. Just as with the search, the gained knowledge from the research project BioSkin (Gosztonyi et al., 2013) is used for the analysis. The strategies of the 250 biological role models in the project were examined together with biologists, physicists, mathematicians, architects, engineers and energy experts in various fields in several workshops. These findings were well documented and thus can be taken for this analysis if the respective role model is chosen. In addition, further information is searched to fill the knowledge gaps.

TOC

6.2 Methodology

The transfer work starts with the list of suitable role models from Chapter 5 (Table 5.2). After examining the principles of the role models and extracting the main features, the models' principles are evaluated in terms of their feasibility for the transfer. The identified potentials are then transferred into a semantic structure, the biological concepts (Fig. 6.1). These concepts are used to develop function models in Chapter 7.

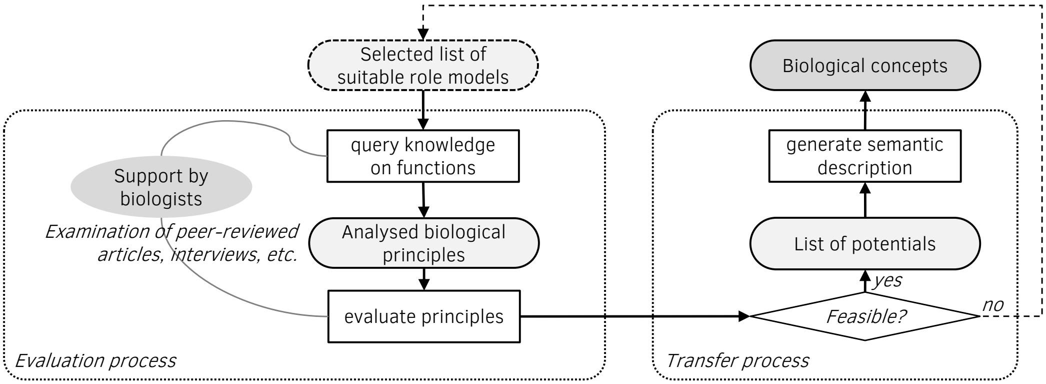

FIG. 6.1 Scheme of the applied process to analyse the principles and develop biological concepts.

The applied method for each step is provided directly in the resepctive section.

6.3 Investigated principles

In the following, the underlying principles of the selected strategies are examined. The examination begins with general considerations about adaptation strategies found in many biological role models (and also considered in technical systems). It then focuses on a better understanding of the selected strategies: thermal transmission modifications, modification of radiation energy (particularly on surfaces), and geometries that allow physical adaptation in various directions and thus adjustable interaction with environment.

Following biological strategies, respectively clusters, were selected in Chapter 5 for an in-depth study (cf. Table 5.2):

- Positioning of surfaces (C5), emissivity of surfaces (C5) and exposed surfaces (C14) targeting 'radiative energy (F06)' principles,
- Closed systems using fluid to exchange heat (C10) and adaptive air keeping structures (C11) targeting 'thermal transmission (F01)' principles,

Environmentally triggered motion mechanisms (C13) and general growth patterns and geometries (C12) that reveal 'design rules that influence adaptation'.

6.3.1 Methodology

The strategies of the selected role models are examined in detail to understand their principles. For this task, peer-reviewed articles in scientific journals within the respective biological discipline are screened and studied. If needed, experts are additional consulted. The goal is to identify the functional key principles, thermodynamic adaptation mechanisms, input factors and output effects. Furthermore, information about the type of process (transition or radiative) and the role between structure and material are collected.

If certain role models have very similar functions and mechanisms, their process is summarised as one. If there is not enough information about an exemplary role model for a deeper analysis of the function, another representative from this group is considered.

6.3.2 General aspects on adaptation strategies

To modify a physical state, several strategies are developed in nature and technology. Some strategies generate solutions that can be used for a wide variety of purposes, such as volume changes or form-adaptive structures. A few of these solutions, more commonly applied in thermal adaptation principles, are presented in the following section.

Adaptation in open and in closed systems

Thermal modifications at ambient conditions seems to be the most common approach for dynamic adaptations in biological role models. Many organisms use local ambient conditions in interaction with heterogenous anisotropic structures that allow changes into various densities, sizes and network typologies to conduct thermal exchange tasks. If they are so-called '*open*' systems (Fig. 6.2, right), they are permeable for the exchange of information, thus they allow direct exchange of matter and energy with the environment, as once defined by the biologist Von Bertalanffy (1950).

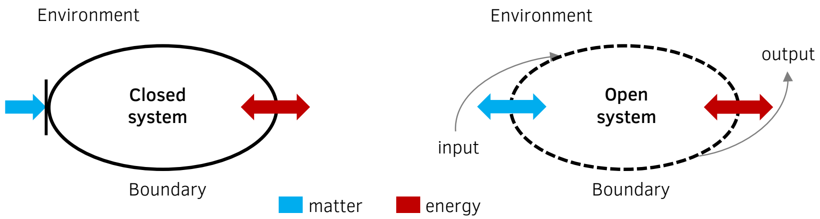

FIG. 6.2 Principle of open and closed systems.
In closed systems, the system boundary allows energy exchange, but no matter exchange; heat can pass the boundaries (e.g. heat exchanger). Open systems allow both energy and matter exchange.

An example for the open system approach is the insects' wing that is able to filter and reflect radiation in certain wavelength ranges through its nano-structured formation (cf. Fig. 6.10). Such photonic structures not only produce genuinely colours but also prevent excessive heat absorption, because the thermal storage capacity of such skeletal structures is much lower than of massive structures.

If they are '*closed*' systems, they allow only energy exchange with the ambient conditions (Fig. 6.2, left). This principle can be compared to the familiar technical analogy of piping systems in building services technologies. They transport liquid or gas in closed structures that exchange energy with the environment through the enclosing surface, but no matter. The flow velocity and direction of the transported gas or liquid in technical solutions is controlled by external pumps. In biological role models, however, these are intrinsically controlled, e.g. by the generation of pressure differences through deformations of the structures. The deformation of the biological 'tubes' is ultimately part of the system that performs the task (e.g. veins and blood vessels).

TOC

Since both system approaches operate at ambient physical conditions (air pressure, temperature, humidity), it requires a smart interaction of functions to modify thermodynamic processes. Structures are built in such way to support these interactions - often on nano and/or micro scale.

Slow and fast adaptations

Adaptations in nature can be fast or slow in both systems, open and closed. Apparently slow processes, such as osmotic processes (e.g. diffusion between cells), can trigger a fast adjustment in closed systems This is, for example, the case in the plant Mimosa pudica (Fig. 6.3): the solutions in the leaf cells (two types of cells, extenso and flexor cells, with two different solutions) changes if triggered (by bio-chemical information). This change in the concentration of the solutions causes a pressure difference in the cells, the turgor pressure. The pressure difference starts an osmosis process, the diffusion of the fluids through the membranes of the cells in order to balance the differences, which causes the kinetic motion. The arrangement and swelling of specific cells in the leaves determine the speed.

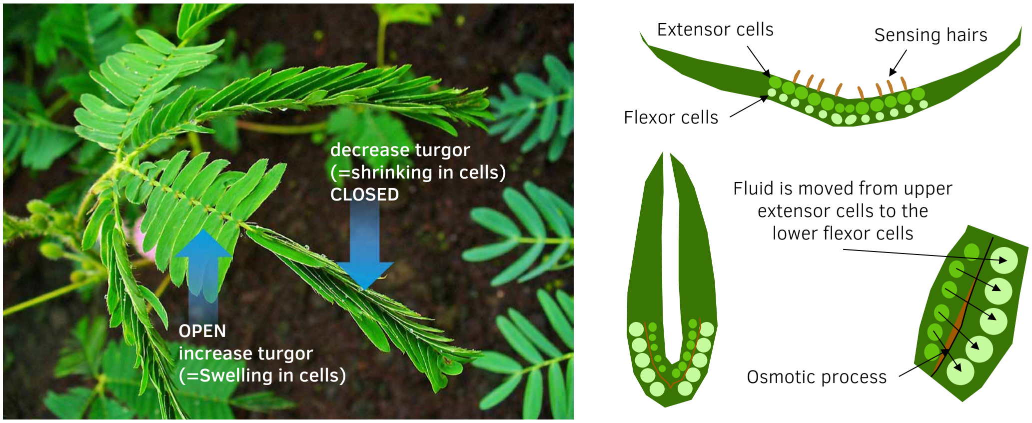

FIG. 6.3 Principle for fast adjustment using slow adaptation processes.
The leaves of the Mimosa pudica closes fast due to the turgor pressure in its cells. The fluid diffuses from the upper extenso cells to the lower flexor cells and vice versa due to the osmotic process. The process is actuated by a concentration change of ions within the two cells. (Left picture of Mimosa pudica by Zell, 2009).

The same applies to other dynamic adaptation strategies in biology (Oliver et al., 2016): it depends on the overall system composition (e.g. asymmetric cellular structure), the attributes of material (e.g. swelling and shrinking of cell walls) and its adjustment parameters (e.g. gradient in cell sizes and order) whether a reaction takes little or a lot of time (e.g. curl up of leaves). For all applies that the effect shall occur with relatively little effort. This can be achieved by making appropriate use of the material properties at all scaling levels.

Sensor, actuation and control interrelation

The actuation, control and sensing capabilities are mostly intrinsic in biological models and are carried out by the same material. A well-known example demonstrating this principle is the shape-adaptive fibre structure of conifer cones that is activated by changes in ambient humidity (Fig. 6.4). The actuator is the varying moisture uptake of the anisotropic fibrous layers in the matrix structure, and the control and sensing are done passively by the degree of moisture saturation in the fibre layers. These contract or expand differently depending on the moisture content. The way the fibres are arranged in relation to each other is responsible for the shape adaptation (cf. hygro-morphic materials by Holstov et al., 2015).

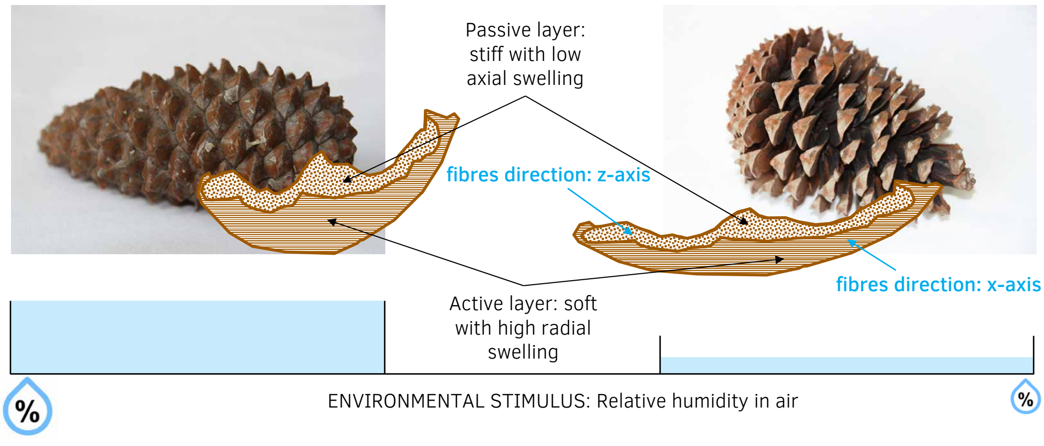

FIG. 6.4 Principle of intrinsic sensor & actuator & control: the form-adaptive conifer cone.
The fibres of the conifer cone are arranged in a 90° degree offset orientation on top of each other and have different properties with regard to moisture absorption, which then cause swelling or shrinkage when the relative humidity changes. The whole sensing, controlling and actuating is done by the fibre attributes.

In technical solutions, actuator, controller and sensor are generally separate components and thus, require individual adjustments, which makes the system more complex and prone to error. Thus, looking at biological role models provides insights on how adaptation mechanism can become intrinsic.

6.3.3 System design rules in biology

Raw materials are limited in nature, or better said, biological composites are limited to combinations between a few carrier materials (e.g. macromolecule, such as cellulose or chitin) and bonding adhesive (e.g. lignin). Nevertheless, an enormous variety of shapes and dynamic functionalities can be found in biological organisms. With the few raw material, biological organisms employ structural arrangements on various scales to develop a system that complies with the needed targets. Geometric order is the key design criterion.

The basic design rule of biological materials is the application of '*heterogeneity*', '*hierarchy*' and '*anisotropy*'. From the cell to a full organism' system, raw material is arranged according to these design guidelines (Fig. 6.5).

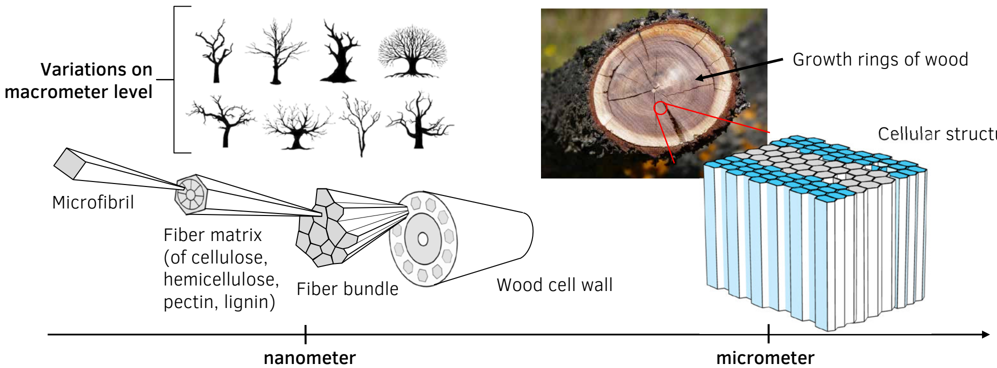

FIG. 6.5 Scheme of the hierarchical anisotropic structure of wood at the various scales.
The scheme shows the specific structure and material employment from the nanoscale (fibril – matrix – bundle - cell wall), microscale (open cell structure), to macroscale (growth rings and tree typologies).

The advantage in this rule is seen in its ability to adapt to growth needs, but also to respond to environmental changes, while using only one raw material and a few adhesives to do so. For each raw material, certain adhesives and rules for the matrix combinations are applied, such as for cellulose material (using pectin, lignin) or crystalline material (using keratin).

Polygonal cell structures arranged in certain patterns that lead to e.g. fibrillation with defined directions (anisotropy), or on a higher system hierarchy, to lattice structures, are found in many role models that need multi-directional deformation capability.

The other already mentioned structure typology are fibrous structures arranged in various layers that enable deformation in a certain direction due to the anisotropic arrangement. Regardless of the geometric arrangement, most combinations are scale-sensitive to conduct morphological or physiological changes, as the examples in Chapter 5 show. In engineered material, this scale-depending hierarchy is not found.

The solutions seem to be comparable if their functional goal and boundary conditions are comparable. For example, those biological role models that aim to colour by photonic measures, such as many butterfly or beetles species, show similarities in their design on the various scales (Kinoshita et al., 2008), but heterogeneity in the solution.

These complex (nano) structures cannot be transferred to functional models within the design conditions defined in this work - mainly because of the scale-sensitive attributes. The scale for transfer is set to the micro and preferably macro scale (> millimetre). However, the criterion ‘scale’ and a possible imitation of some principles found at the nanoscale with comparable boundary conditions applicable at other levels are taken into account when selecting transferable biological strategies.

Thermal transition and geometry

In physics, *thermal transition* is defined as a process that induces a change of phases (from solid to fluid to gas), although in biology it is discussed as diffusion. According to Vogel (2007), diffusion is a physical process that is involved in basically any biological energy exchange process. In general, diffusion is a process where molecules move (or exchange) due to concentration differences in two adjacent areas. This process is again time- and scale-depending and allows a soft adaptation related to the goal. Organisms that rely exclusively on diffusion are rather small and thin, because pure diffusion processes function best on such scales (Vogel, 2007). Osmotic processes in plants, for example, use the diffusion to move their leaves, as already mentioned in regard to the *Mimosa pudica* example (cf. Fig. 6.3).

Thermal diffusivity describes the conduction of heat in transient states, while conductivity and diffusivity are related as quotients. Many biological processes display a combination of diffusion and convection, which makes the mass transport faster. Combined diffusion and convection processes depend on the surface of the '*exchange*' area, resulting in “*excessively surface-rich geometries*” (Vogel, 2007). This applies to many identified organisms, such as e.g. tracheae of mammals (cf. #35, Fig. 6.6, A), which use such excessive surface geometries from the wrinkled geometries of organs, to the fractal surface structures of plants (Fig. 6.6, B and C).

A B C

FIG. 6.6 Biological geometries with excessive surface area while keeping a condensed packed form. Fractal geometries of a human lung (A) and of a Romanesco cauliflower (B) and Fibonacci sequence of sunflower seeds (C).

Such strategies often possess a multifunctional objective, such as the energy exchange with the environment while dense packing into a limited space.

The principle of diffusion is not pursued further in this work as it is a complex material-related process: the process works most effectively on a very small scale and its speed depends on the diffusion properties – both of which fall outside the focus of this work. The excessive surface geometries applied for the convection principle is well known and established a design measure. A proper development and optimisation of this function requires fluid dynamic analysis.

What is definitely taken further is the dependence of a function on the geometric composition.

Adaptive flow and deformations

For an adaptive flow speed in blood vessels, for example, the function of constriction and dilatation is achieved by a structure that allows a cylindric volume deformation. The vascular walls are made of three layers and types of cells, where the smooth muscle cells are responsible for the contradiction or dilatation while the diameter of the vein changes accordingly (Fig. 6.7, A).

TOC

A comparable solution for this contracting and expanding of tube-like structures has been observed by Tsai et al. (2020) in the butterfly wings. The radial vein channels in the wings are supporting the thermal regulation of the thin tissue and reveal a rather astonishing strategy of its circulatory and tracheal system: the veins "*provide pathways for the tidal flow of air and hemolymph*" according to Tsai et al (2020, p. 2) by a central tracheal tube in the middle surrounded by two hemolymph (fluid) channels. The hemolymph flow in the channels frequently changes the direction to transport heat from the wing tip to the body or vice versa. In these channels monitoring cells (=hemocytes) are flowing and checking the flow speed and direction.

To reverse the flow direction a change in volume of the tracheal tube occurs. If the tracheal tube expands by taking in more air, the hemolymph channels contract. The flow direction in the hemolymph channels runs towards the body. When the trachea tube contracts, the hemolymph channels expand and allow the fluid to flow back to the tips, away from the body (Fig. 6.7, B).

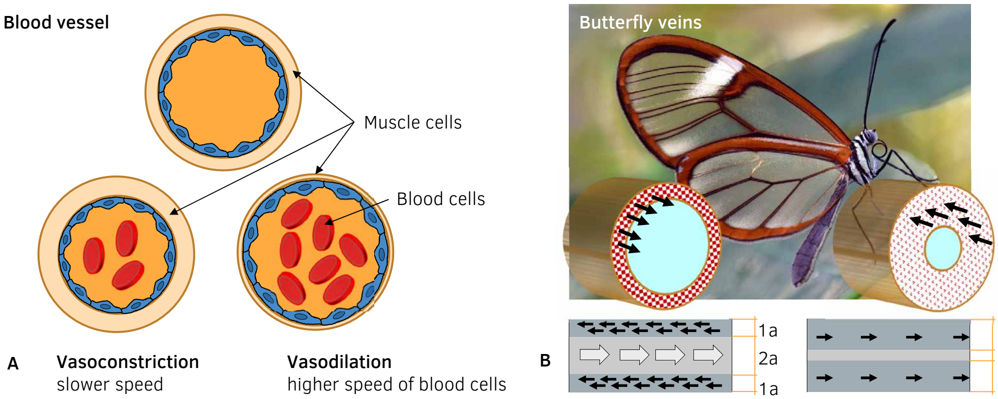

FIG. 6.7 Form-adaptive vessels and veins of animals.
The scheme on the left (A) shows the principle of vasoconstriction and vasodilatation that influences the flow speed of the blood. On the right, the principle of the veins in the butterfly wing (B) is shown with a tube-in-tube system that contracts or expands depending on the gas pressure in the inner tube. The outer tube contains a fluid which again adapts its flow speed and direction depending on the pressure differences.

This smart switch allows to either gain heat or dissipate heat from the body to the wing tips. The contractions and dilations occur within minutes, appearing similar like breathing. The tidal flow '*switch*' works automatic. The authors call this effect "*wing heart*" (Tsai et al, 2020, p. 4).

The finding may be translated into a material development which is therefore not pursued in depth in this work. However, further investigations into the mechanism and a possible upscaling are proposed in order to make this usable for active heat transport in façades.

Patterns and growth designs

The identified patterns and growth designs of the identified biological role models, particular collected in cluster 12, are summarized in Figure 6.8. The combination of geometric units (e.g grid-like patterns) and growth design (e.g. Fibonacci sequences) enable all sorts of functional structures with either selective behaviour (light selection) or an intended growth (bending deformation).

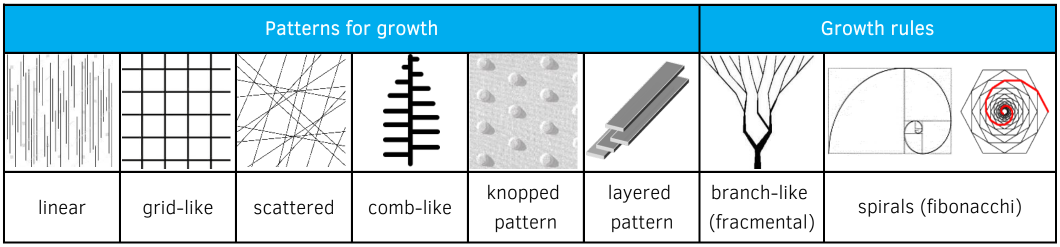

FIG. 6.8 Geometric patterns and growth rules applied in biological examples.

Certain geometries, as already discussed in Chapter 4, provide higher flexibility in deformation and growth, such as polygonal or circular forms. Polygonal shapes are found in role models that build up a shaping structure, which also has to carry loads (lattice structures), circular patterns, such as foam, are found preferably in liquids where adhesion of the cells is important, but no defined form is applicable. The growth design applies to both.

6.3.4 Modification of thermal transmission

Influences on volume changes

Volume changes to modify thermal conductivity can be found in various biological role models, such as volume increase by plumping to reach lower thermal conductivity (e.g. bird's plumage) (Silva & Maia, 2013) (Robinson et al., 1976). The expansion of volumes due to temperature changes of a material (e.g. gas expansion or expansion in phase change processes, Fig. 6.9, A) or volume increase due to pressure changes (cf. the already mentioned wing veins of the butterfly, Fig. 6.9, B) are further processes.

FIG. 6.9 Volume expansion due to thermal expansion of air or kinetic motion.
Sketch A shows an example for temperature triggered volume expansion (balloon) and image B shows an example for volume expansion due to mechanical adaptation (plumage of birds).

Volume changes due to thermal expansion or phase changes also regulate the thermal inertia capacity and therefore, the thermal conductivity. This process is dependent on the ambient temperature and is intrinsically controlled (Chandler, 2011) (Bonales et al., 2017).

Self-adaptive thermal conductivity switch

The self-automated control of thermal transmission in biological material is relatively complex and difficult to replicate. Many organisms must control this actively and fast, such as the plumage adaptation of birds. One fast, self-regulative mechanism in nature is the so-called '*thermal conductivity switch*' that can quickly turn a conductor into an insulator.

For example, investigations about the squid ring teeth's (introduced in Chapter 5, cluster 11) show that the thermal conductivity increases when the proteinaceous tissue becomes wetter. If the humidity decreases, the thermal conductivity decreases as well. This means that thermal conductivity switch works under ambient conditions. The effect ranges from 0.4 to about 1.3 W/(mK) at about 26°C ambient temperature with various humidity ratios (Tomko et al., 2018). The squid ring teeth's are positioned on the tentacles suckers of squids to help them gripping on a surface. They are made of proteins, which are assembled as "*building blocks*" and thus, can be combined "i*n different ways to produce materials with different properties.*" (BBC Science Focus Magazine, 2019). According to Hopkins, the leading scientist in this field (Dumé, 2018), it is possible to program the adaptive property for soft biopolymers by mimicking the control of the network topology between the protein domains (crystalline and amorphous) in soft material. Thus, they can generate thermal switches for synthetic fabrics, based on squid-inspired functions. One possible application is already suggested: athletic clothes that adapt the thermal conductivity according to the sweeting degree of the person.

Engineered solutions of reversible thermal conductivity switches (of polymers) have mostly led to simple on/off switches, since only a relatively small part of the phonon spectrum, which is responsible for the switching, can be influenced. By looking at the biological role models, the technical solutions for reversible thermal conductivity could be improved, and further gradients developed.

A theoretical option for façades would be to embed such materials in façade layers in order to initiate adaptive thermal conductivity depending on the relative humidity in the ambient environment. Thermal switches are, however, still under development and the application potential cannot yet be estimated.

6.3.5 Modification of radiation

In order to be able to address the desired bandwidth of the solar spectrum, the surface structures must be precisely tuned to its wavelengths. A large number of well-studied examples applying this principle can be found in insects, birds and plants, such as e.g. the cuticle of beetles or wings of butterflies to produce brilliant colours (Tsai et al., 2020) (Kinoshita et al., 2008). The way these geometries are designed varies from embedded photonic crystals in tissues, thin films on the surface to specifically designed structures – all of them on the nanoscale. Although nano-scaled solutions are excluded from further transfer to models in this work, the various solutions were collected in Chapter 5 and information specifically useable for the cooling purpose was extracted. It turned out that one example utilizes the effect in combination with thermal emissivity. This finding raised questions about the use of thermal radiation, which is examined in more detail below.

Avoiding excessive solar irradiation is particularly important in extreme hot climate zones or zones with high radiation intensities where overheating is a risk. There are several measures to prevent overheating (reflection, absorption control, emission). Many of the role models explored in Chapter 5 use a protective layer consisting of hair, waxes or films to avoid excessive irradiation.

The strategy of the hair '*protection*' varies according to climate zone and survival strategy: while polar bears, for example, have a dense fur to protect them from heat losses, their hairs are hollow in order to conduct the warming solar radiation to their bodies. The hairy coating of desert organisms, such as e.g. of desert silver ants, on the other hand is highly reflective and formed in triangular shape to reduce absorption and emit heat. The hairs, or better trichomes, of the Edelweiss plant in alpine regions, however, prevent, together with the epicuticular wax layer, from excessive UV radiation by absorbing these wavelengths. The hairs (=trichomes) of plant leaves reflect solar radiation, and also protect from water losses through evaporation. Depending on the plant family, these trichomes play also a role to create a thermal boundary layer in combination with the thermal emissivity of the leaves that can be varied by colours, as exemplarily found in iridescent plants such as the Selaginella ferns (Thomas et al., 2010). These functions are only effective on nanoscale.

An interesting role model that combines colour generation, radiant modification and closed-system thermal regulation at once by using nano-scaled structure-materials are the wings of butterflies (#01, 02, 24, 51 in Appendix 5-1): the temperature regulation of their thin wings is critical because "*minor changes in ambient temperatures having profound effects*" (Tsai et al., 2020, p. 2). As soon as the butterfly wings are exposed to solar radiation and reduced convection while basking, the wings can overheat quick within seconds.

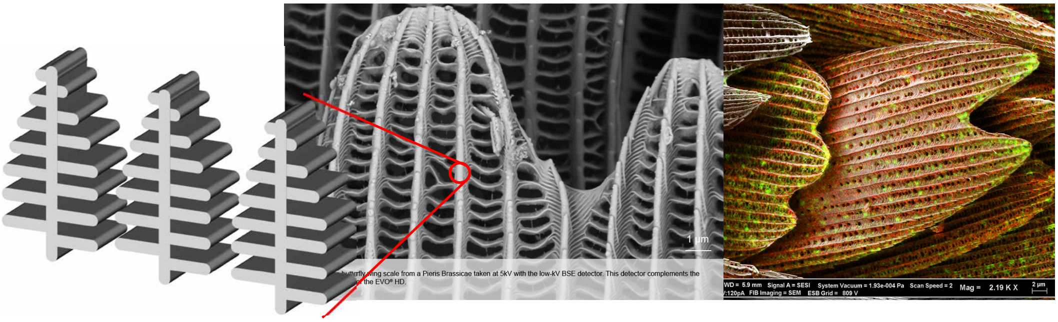

FIG. 6.10 Nanostructure of butterfly wings.
The wing is composed of a hierarchical system of nano-scale structures. (Microscopic images in the middle and left by Zeiss Microscopy, 2012)

It is well-known that the structure of e.g. the butterfly wing creates colours, respectively an optical diffraction, by the specific nano-scale design (Fig. 6.10). However, the various coloured regions also control the thermal absorption and emission along the wavelengths of the solar spectrum.

The principle of thermal radiation applies for this purpose: thermal radiation is determined by solar absorptivity and thermal emissivity of the surfaces of a matter. Spectroscopic measurements and analysis of the common fairy hairstreak butterfly (*Hypolycaena hatita*) done by Tsai et al. (2020) reveal that the heterogenous structure utilizes the thermal radiation spectrum beyond the visible range to reduce the wing temperature. The absorptivity in the NIR wavelengths (λ= 0.7 - 1.7 µm) is much lower than in the visible range. Black wing regions possess an absorptivity of average 0.71, while blue scales have a solar absorptivity of about 0.60. The researchers observed that dark scales do not overheat the wing due to this effect.

Furthermore, the back and front of the wing surfaces contrast in their absorptivity; and in certain positions the wings possess very high thermal emissivity (cf. Tsai et al., 2020, fig. 4). This can be achieved by increased thickness of the chitinous membrane or shortly said, they put the wings together to increase the physical according to Tsai et al (2020). And finally, the butterfly positions the wings towards adjacent 'cooler' surfaces (e.g. leaves, sky) to emit heat more effectively.

With these strategies, the heat dissipation through wings can be controlled, depending on the temperature and emissivity differences as well as the relative position of the wings to the ambient surfaces (Fig. 6.11).

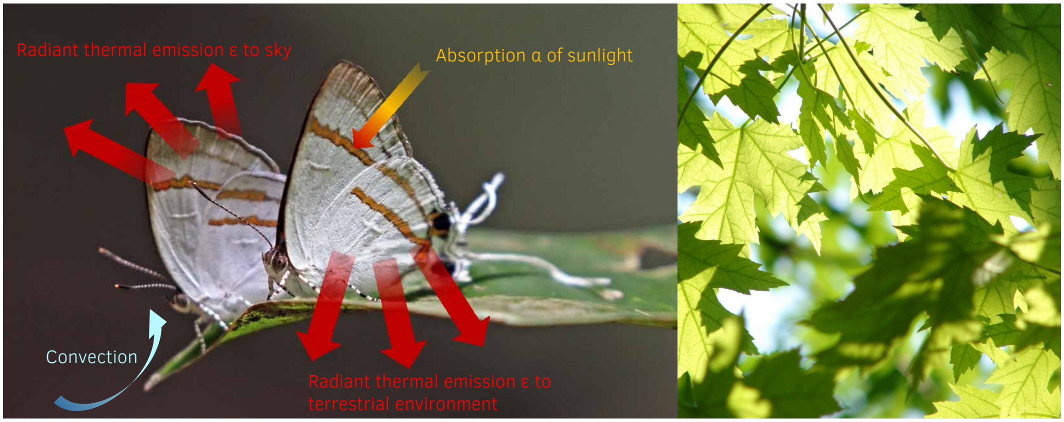

FIG. 6.11 Principles of thermal regulation between ambient surfaces and the butterfly wing or plant leaf.
Left: The arrows point to the physical principles the butterfly common fairy hairstreak (Hypolycaena hatita) applies to keep cool while basking in the sun: to cool down the wing temperature by convection is limited. Thus, the wings are orientated to the ambient surfaces and to the sky in a certain angle to optimize thermal absorption and emission. The butterfly uses furthermore a thermoregulatory flow system in the veins to balance the temperature in the wings.
Right: Leaves use similar mechanisms of thermal emission, convection, and absorption, combined with evaporation to keep cool. (Right image is redrawn from Fig. 3 "Thermodynamics of butterfly wings" in Tsai et al., 2020, p. 5).

Together with the thermoregulatory flow strategies in the veins of the wings and the convective cooling effects, basking of butterflies is possible without severe damages.

Plants show some similarities with the butterfly wing strategy: heat dissipation via thermal flow through the leave veins in order to cool down is limited, and the super-thin leaves are extremely sensitive to solar irradiation and would quickly burn due to lack of thermal storage capacity. Besides the cooling strategy by transpiration, the utilization of thermal emissivity also plays a role (Zhuang, 2014). They also apply varying emissivity's on the front and back side of the leaves to increase the effect. Ullah et al. (2012) and Ribeiro da Luz and Crowley (2007) identified that plants can even be differentiated by their specific thermal emissivity signature that is unique for each plant species.

Most of the role models that display a heterogenous structure with varying solar absorptivity and emissivity do not overheat.

6.3.6 Conclusion

In general, the investigated biological strategies use very few raw materials and additive subsystems to implement the function. They exploit the assets of the material at all scales, and arrange the material in a hierarchical setting so that activation is triggered by the intrinsic material properties. The form then results from the functional characteristics of the adaptation and multifunctional goals (e.g. heat dissipation in super-thin layers, heat regulation of the body through lightweight material that can also be used for flying, etc.). This is probably the biggest difference to technical designs: their form is first largely determined and the activation of adaptation is subsequently inserted by additive subsystems.

Radiant modifications

To modify solar radiation, organisms apply nano-scaled three-dimensional structures made either of one raw material or of a composite of material and adhesives. The objective is to diffract, redirect or reflect certain wavelengths of the visible or thermal radiation. There are different approaches:

- one group requires ultra-light but stable multifunctional structures, such as the butterfly wing. The three-dimensional skeleton structure is responsible for the load-bearing and functional tasks at once (e.g. colour and thermal regulation). They are made of a chitin structure, which is arranged differently in the various regions (gradients in thickness and length). The examples are open systems allowing energy and matter transfer into and through the structure. Other examples with a similar strategy but different morphology are bird feathers,

- another group applies a multi-layered tissue, which serves as a protecting shell to the outside, such as the cuticles of beetles. The fabric-like layers contain on the nanoscale three-dimensional embedded components (photonic crystals) that are tuned to certain radiation wavelengths. With these, the thickness of the structure is less critical than with the former group. The examples in this group try to modify or block radiation as much as possible in that outer layer. Some are closed systems, and some are open systems that allow matter to pass the shell surface (cf. Hercules beetle allow water transfer into the outer tissue in order to initiate a colour change by changing the refraction index).

The scale in both approaches is in nanometres.

Approaches to modify thermal radiation occur by influencing the emissivity of the surface (near infrared wavelengths). Examples targeting at thermal emission adapt the absorption of the surface to generate a temperature difference to the ambient surroundings which increases heat dissipation.

This effect can be confined to specific regions to generate different surface temperatures, which allow thermal convective heat exchange. Thus, a thermal boundary layer is created that either reduces or increases heat transfer. This approach can be found in plant and animal species with feathers, folded surfaces, hairs and spines. The function is composed of a hierarchical system, where the main structure (shape) takes over the task of heat absorption and transmission and the secondary structures (hairs, spines) filter the radiation and produce a kind of thermal cushion. The structure of these hairs is again made of a complex three-dimensional structure in order to influence the radiation like the first group.

Overall, it is observed that the relative position and orientation of such surfaces, as well as their size are crucial for the radiation modification. The criteria of angular dependence of radiation is actively employed by position the surface. The radiation properties of the surrounding surfaces (soil for snails, leaves for butterflies) and the sky also play an important role. This dependence is known but largely neglected in the façade design.

Thermal modifications

Thermal processes of the selected role models can be divided into conductive processes in the matter and convective processes on the surfaces, with few examples using radiative processes (thermal emission). For the first, thermally active multi-layers as outer skins (fat, waxes) and controlled conduction within the matter (heat exchanger channels) regulate the thermal transmission. For the other, hierarchical multi-layered structures in front of the body are composed to control the thermal boundary behaviour (rips, spines, hairs, feathers). The structures of the second appear as '*added*' systems to the organism. Added structures are assumed to mainly provide only one functionality, but they are often multi-functional and serve for further purposes as well (propagation, motion, etc.).

Thermal conduction adaptations use geometric parameters, such as excessive surfaces or volume changing systems. Their actuators are intrinsic. Thermal convective processes employ extrinsic actuators (wind, humidity, temperature) and use the same geometric parameters. A few examples employ biochemical processes (metabolism for muscle power) to activate a volume change, such as birds when raising their feathers to increase the thermal insulation.

While the adaptation mechanisms of multi-layered principles (waxes, coatings, photonic structures) initiate physiological changes, the added or form-depending principles apply more often morphological changes. The structures added to the surface are more fragile to environmental impact than the layered ones.

These examples are composed again hierarchical and anisotropic to allow directional changes. They employ complex designs depending on the type of material, which can become rather sophisticated (e.g. prismatic structure of desert silver ant hairs). The functional scale of the adaptation ranges from nanoscales (when conduction is controlled) to micro-/macroscale (when convection is controlled).

Role of geometry and material

Regarding the geometrical attributes of the organisms, two general approaches seem to prevail:

- Structures that modify radiation or thermal flow are anisotropic and arranged in hierarchies, with different gradients in e.g. thicknesses of the unit (fibre, cell). This allows them to perform the necessary selection or deformation. Radiation-oriented structures are tuned with the wavelengths of the radiation and typically function on the nanoscale. Thermal flow solutions are tuned to the properties of the matter that is transporting the heat. Their role is to build up pressure by changing the volume or to create more heat exchange area by changing the surface. These processes often take place on the micro or macro scale. However, the structure of the adaptable structure (channels) is multiscale,

- The structures are three-dimensional and hierarchically arranged in order to perform the function effectively. To allow adaptation (or growth) they employ polygonal units (cells) or linear layered units (fibre), which are arranged in a repetitive order using sequential growth patterns (Fibonacci) or branch-like patterns (fractmental),

- All structures take over multifunctional tasks: examples that adapt colours in the structure also provide a stable system for motion or growth.

Looking at the relationship between material and geometry, flexible forms (hairs, feathers) are made of fibres, while armour-like protective materials (elytra of beetles, plant surfaces) are made of waxes, chitin, calcareous material or compositions of cellulose.

6.4 Selected potentials

Based on the findings gained from the detailed analysis in Section 6.3, the respectively role models (representing the clusters) are qualitatively examined to identify their transfer potential (Selection step A according to the methodology section).

6.4.1 Methodology

The selection of the potentials occurs on two stages:

A The findings of the detailed literature study are taken to evaluate the transfer potential of the selected list of role models in Chapter 5 (cf. Table 5.2). For this evaluation, assigned criteria describing important features of the four adaptation rules are used (cf. Section 6.2.3, physiomimetic terms). Feasible role model principles can then be identified, which are finally translated into biological concepts.

The assigned criteria are as following:

a for ‘thermodynamic process’

- ‘Functional principle’ (ID: F0x): defines the search fields,
- ‘Control task’ (ID: II-01): identifies type of energy flow strategies. As such, regulation of heat dissipation, thermal storage or heat transmission regulation are interesting strategies for cooling.
- 'Input / Output deviation' (ID: I-03): identifies the climatic situation that induces a change, such as temperaturr differences.

b for ‘adaptation mechanism’

- ‘Response time’ (ID: III-03): provides information about the speed of adaptation. A fast reaction is set as target,
- ‘Adaptation dependency’ (ID: III-07): asks for the type of dependence of local boundary conditions.

c for ‘physical design description’

- ‘Adaptation impact’ (ID: III-08): type of change appearance (morphological or physiological, or both as hybrid),

- ‘Physical characteristics’ (ID: IV-03): describes the particularities of the solution in regards to design-related changes,
- ‘Functional scale’ (ID: IV-04): provides information about the design scale. Potentials for transfer are limited to functions that work on micro or macro scale to avoid new material developments. Principles on the nanoscale are only considered if no new material developments are necessary and suitable materials with the desired properties are available,
- ‘Scalability’ (ID: IV-07): describes the functional scaling limits above which the functionality would no longer be provided.

This step should help to extract those role models that meet the set benchmarks for **adaptation-related** and **design-related characteristics**.

B Additionally, an assessment of all selected role models in Chapter 5 (Appendix 5-1) has been done to evaluate their transfer potential. Only the key information is used for this assessment and no detailed analysis is carried out. Thus, the assessment reveals a higher degree of uncertainty regarding the accuracy of the information, but aims to take into account principles that were not identified as potentials in the first run. Should further role models be added to the group selected in Table 6.1, they will be explored in detail.

a For the assessment, additional criteria to evaluation A are chosen:

- process-related aspects,
  - 'Main functional purpose' (ID: F08),
  - 'Process type' (ID: V-02).

- physical system aspects (ID: IV-03),
  - Material type, assembly and structure,
  - Structure type, dimension and form.

- additional adaptation aspects,
  - Control type (ID: II-03),
  - Operation carrier (ID: II-06),
  - Actuator type (ID: III-02),
  - Response type (ID: III-04),
  - Level of embedment (ID: IV-01),
  - Visibility (ID: IV-05).

This step should enable that unexpected potentials are not lost in the selection process.

Table 6.1 presents the first stage evaluation (A) indicating the assumed contribution to each criterion.

TABLE 6.1 List of potential role models useable for biological concpets.
Those role models that are selected for the generation of biological concepts are marked bold and named "CONCEPT #X".

Parameter list: Selected criteria		Representative role models of selected clusters					
		birds plumage (C11)	butterfly wings (C5)	sunflower seeds, plants (Romanesco) (C14)	blood vessels (C10)	pine cones, mimosa pudica (C13)	growth patterns (C12)
1. Monitoring + 2. Thermodynamic process	Functional principle (F01-F07)	F01 Thermal transmission	F06 Radiative energy	F06 Radiative energy	*Adaptive design*	*Adaptive design*	*Adaptive design*
	II-01: Control task	modulate energy flow	emit energy	gain energy	modulate energy flow; transfer energy	n/a	n/a
	I-03: Monitoring / Input-Output	temperature differences	radiation differences	radiation differences	pressure differences	various	n/a
3. Adaptation mechanism	III-03: Response time	sec	sec	none	sec,min	sec, min	n/a
	III-07: Adaptation dependency	independent of local conditions	dependent on local conditions	dependent on local conditions	independent of local conditions	dependency relies on system	n/a
	III-08: Adaptation impact	morphological	hybrid	morphological	hybrid	hybrid	morphological
4. Physical design description	IV-03: Physical characteristic	air keeping structure	adjusted surface areas	adjusted surface areas	volume adaptive, flexible structure	form-adaptive system	n/a
	IV-04: Functional scale	macro	macro	macro	micro	micro	nano, micro, macro
	IV-07: Scalability	high	high	low-medium	unclear	low	n/a
Selection for biological concept		CONCEPT #1: adaptive thermal insulation	CONCEPT #2: adaptive radiative thermal emission	supportive design rule	ACTUATOR: structural deformations	ACTUATOR: self-adaptive system	supportive design rule

The detailed assessment (defined in the methodology as step B) in regards to all selected role models of Chapter 5 is provided in Appendix 6-1.

6.5 Transferred concepts

Taking into account the prepared systematic of Chapter 4, the transfer of the selected potentials is done by using a process-related language that makes the biological strategies accessible for technical use without sacrificing the functional processes. Thus, as a final step, the development of a detailed semantic structure using physiomimetic terms must be done. This structure is called 'biological concepts'.

6.5.1 Methodology

The physiomimetic terms described in Chapter 4 link the biological principles with the technical, parametric structure and thus bridge the two domains.

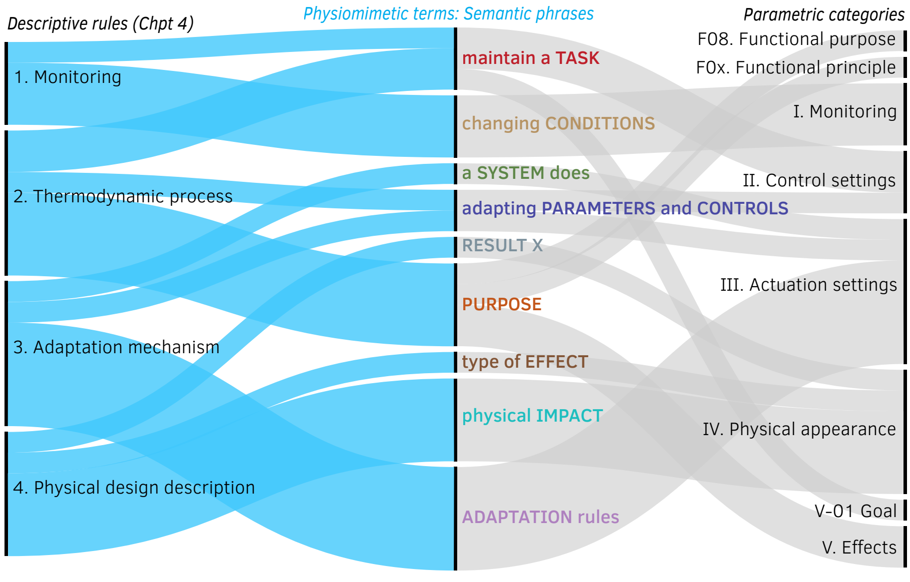

FIG. 6.12 Scheme presenting the assignments of the detailed physiomimetic terms (level 2) to criteria of the parameter categories.

The description of the adaptation process is defined by four aspects, as discussed in Chapter 4. These four descriptive rules (Fig. 6.12, left column) are are linked to specific semantic phrases describing the biological concept (Fig. 6.12, middle column). To each term of the semantic phrases, a specific criteria of the parameter list in Appendix 3-2 is associated (Fig. 6.12, right column).

The semantic phrases are structured as following:

In order to *[maintain a TASK]* due to *[changing CONDITIONS]*, *[a SYSTEM does]* depending on *[adapting PARAMETERS and CONTROLS].*

This action creates *[RESULT X]*, *which* provides *[PURPOSE].*

The adaptation is [ADAPTATION rules] to operate properly.

The *[type of EFFECT]* results in *[physical IMPACT]*. It works *[physical IMPACT]* as long as *[PURPOSE] is provided.*

- The term *[maintain a TASK]* indicates the functional target or the '*task to be performed*', which is analogue to the criteria 'control task' (II-01) indicating the 'functional goal' (V-01) in the parameter list (Appendix 3-2). This term bridges the key search words to the functional task of the change process.

- The term *[changing CONDITIONS]* refers to the monitoring of the nominal and actual values of a status and thus links to the information necessary to describe the initial status (state 1) and final status (state 2) of an adaptation process. It refers to the criteria 'set values' (I-01) and 'actual values' (I-02), and indicates the 'input/output deviation' (I-03). All criteria belong to category 'I-Monitoring' in the parameter list.

- The term *[a system DOES]* describes the adaptation strategy, which indicates the type of adaptation. It is described by the criteria 'task to perform' (III-01) and may be supplemented by some descriptive parameter of category 'IV Physical appearance'. The main criterion belongs to category 'III. Actuation settings'.

- The terms *[adapting PARAMETERS and CONTROLS]* describe the parameters and applicable conditions involved in the change process. This explains the control and adaptation mechanism of the role model by linking the criteria 'actuator type' (III-02) and 'operation carrier' (II-06). By this, the categories 'II. Control settings' are linked with 'III. Actuation settings'.

- The change result is made visible by the term *[RESULT X]*, which provides information about the effect of the final status (=state 2). The criteria linked to this are 'level of embedment' (IV-01) and 'physical impact' (IV-03). The term presents the main features of category ‘IV. Physical appearance’.

- The term *[PURPOSE]* provides information about the principle in regard to the respective thermodynamic process. It indicates the functional purpose that is responsible for the thermoregulation effects by linking the criteria 'functional principles' (F0x), respectively the sub-class 'functional purpose' (F08) with the 'physical principle' (V-02).

- The term *[type of EFFECT]* evaluates the main physical effect in the adapted appearance by the criteria 'adaptation impact' (III-08), which is either morphological or physiological, or even a combination of both. This is an important information in order to know whether spatial changes are expected or not.

- The term *[physical IMPACT]* describes the needed design characteristics that are essential for the generation of functional models. The relevant criteria are of category ‘IV. Physical appearance’, such as 'type of physical impact' (IV-02), 'functional scale' (IV-04), 'visibility' (IV-05), and 'scalability' (IV-07).

- The above described terms provide the core information about the adapted appearance, while the *[ADAPTATION rules]* provide the information about the adaptation process. The criteria assigned to this are 'response time' (III-03), 'response type' (III-04), 'response degree' (III-05), 'adaptation reliability' (III-06) and 'adaptation dependency' (III-07) of the category ‘III. Actuation settings’.

A tabular overview of the semantic description together with the assignment of the adaptation criteria can be found in the selection and evaluation checklist of Chapter 4 (Appendix 4-1).

The choice of this semantic form allows a process-oriented approach to the description of dynamic change processes, including their dependencies and output effects. In comparison, the '*biological data sheets*' developed in the Bioskin project (Gosztonyi et al., 2013) explain the principle without detailed information about the dynamic change process, thus without the use of physiomimetic terminology.

Ultimately, this approach may result in a collection of biological concepts that describe the process and physical impact likewise.

Following strategies are chosen for the generation of biological concepts, according to Section 6.4:

1 **Role model 'plumage of birds'**, assigned to the principle 'thermal transmission' (F01).

2 **Role model 'butterfly wing'**, assigned to the principles 'radiative energy' (F06) / 'thermal emissivity' (F06.1) and 'positioning of surfaces' (F06.3).

The principles of the other analyzed role models are retained as design inputs of the functional models whenever their geometric particularities are helpful.

6.5.2 Biological concept 1: Thermal insulation modification

Adaptive thermal transmission may be achieved by applying smart materials that allow thermal resistance changes, such as e.g. PCM. Experimental studies in the field of façade engineering applied PCM to e.g. create a solar heat storing system (Wüest et al., 2020) or to use it as a thermal storage component (Soares et al., 2013).

An adaptive thermal insulation behaviour by changing the ratio of '*trapped*' air in a system is an approach that used by the role model '*plumage of birds*' (#56 in Appendix 5-1). The concept uses the low conductivity of still air. By changinge the volume the energy flow increases or decreases and thus, the thermal conductivity (Fig. 6.13). The adaptation mechanism points to a geometric solution on micro or macro scale and is therefore interesting as an example for the translation (Fig. 6.14). In the following, the functional approach is explained by using the semantic phrases.

FIG. 6.13 Biological concept #1: plumage of birds controls adaptive thermal insulation.
For heat dissipation, the plumage is fluffed up and the wings are stretched from the body so that the heat can be better dissipated to the environment. In principle, the same mechanism is also applied in winter to increase insulation - but the wings are tight to the body and the plumage is stretched at a different angle. ("Blackbird Swindon" image by Brain Robert Marshall, CC-by-sa/2.0, 2019).

In order to *[maintain a constant body temperature (38°C – 42°C) by modulating the thermal energy flow]* due to *[local temperature differences of T_{body} to $T_{a,e}$]*, *[birds puff up their plumage]* by *[tilting the feathers]* depending on *[energy supply (metabolism)] [activating the kinetic force (muscles to tilt feathers)]*.

This action creates *[an adaptive air keeping cushion] [covering the whole body surface]*, which provides *[a change in the thermal transmission, respectively thermal conduction and convection]*.

The adaptation is *[reversible] [within seconds]*, *[highly dynamic],* and *[adapts gradually] [without dependency on local sources]* to operate properly.

The *[morphological change]* results in *[a visible, spatial] [volume in- oder decrease of the bird's plumage]* with *[a changing SA:V ratio]*. It works *[on macro scale]*, *[is highly scalable]* as long as *[the thermal flow adaptation]* is provided.

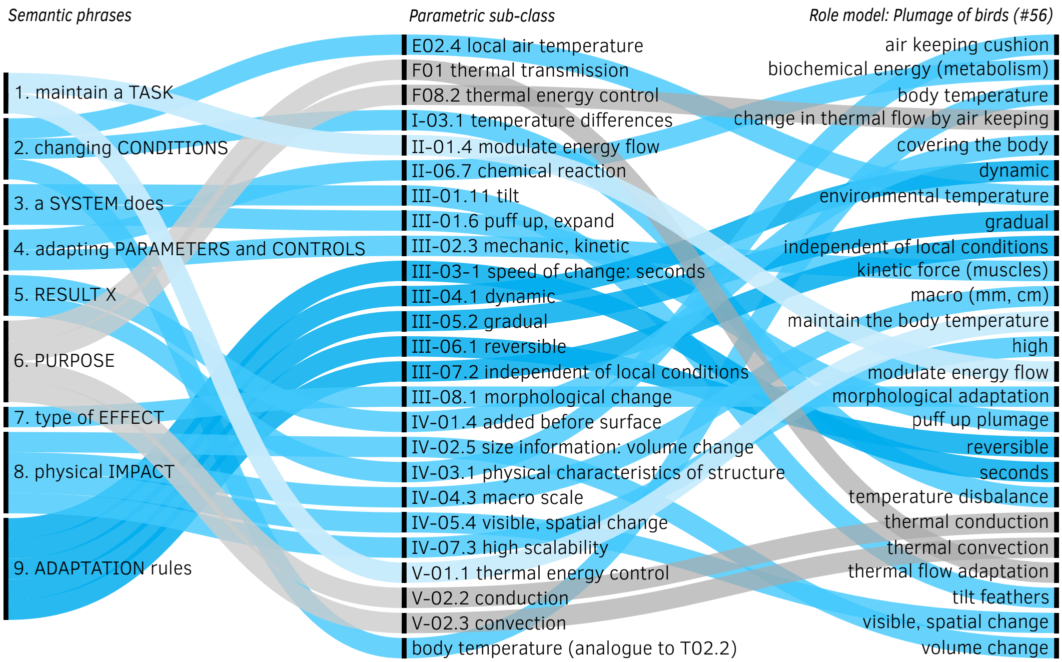

FIG. 6.14 Systematic transfer scheme for biological concept #1: plumage of birds / thermal transmission / adaptive thermal conductivity.
Semantic terms with assigned criteria of the parameter list (Appendix 3-3) describing biological concept #1.

6.5.3 Biological concept 2: Thermal emission modification

Every material emits radiant energy. If this is used for an intentional purpose, it can modulate, for example, radiant heat flow. For example, if the radiating surface is part of a system and the other surfaces are part of the environment (including the sky), the emission effect may support passive cooling by lowering the surface temperature of the system. The emissivities of materials are considered as parameters for physical calculations, e.g. for U-value calculations. However, this is not used intentionally as a function for heat flow regulation.

The role model 'butterfly wings' (#24 in Appendix 5-1) deliberately uses this effect to dissipate heat. The differences in the emissivity of the surface of the wings and the surfaces of the environment are responsible for increased dissipation of heat energy (Fig. 6.15). This is supported by thermally conductive (veins in the wings) and convective properties of the wings. This approach indicates a feasible geometric solution on macro scale, and thus is chosen as a second example for transfer to a biological concept (Fig. 6.16). Here, too, the functional principle and the dependencies are explained with the help of the semantic phrases.

FIG. 6.15 Biological concept #2: monarch butterfly controls thermal radiation.
Butterflies are able to control the temperature of the wings by various measures. One of these is to utilize thermal emission differences between the wings and the surrounding surfaces to dissipate (or gain) heat. The wings are positioned in a certain angle to the surrounding surfaces in order to allow radiative transmission.

In order to *[dissipate heat from the body and wings]* due to *[radiative overheating risks of $T_{body,\ wings}$ to I_s respectively $T_{a,e}$]*, *[the butterfly Hypolycaena hatita adjusts the wings towards surrounding cooler surfaces]* by *[tilting them to a specific angle in order to achieve a change in the thermal emissivity]* depending on *[energy supply (heat transport via blood vessels)]* and *[activating kinetic force to adapt the wings]*.

This action creates *[adjusted surface areas] [with different thermal emissivities]*, which provides *[a change in the energy flow by thermal radiation]*.

The adaptation is *[reversible] [within seconds], [highly dynamic]*, and *[adapts gradually],[with dependency on the surface temperatures of the wings and surroundings]* is to operate properly.

The *[physiological and morphological change]* results in *[an visible, spatial][surface area adaptation]* with *[two or more emissive surfaces]*. It works *[on macro scale]*, *[is highly scalable]* as long as *[different thermal emissivities]* are provided.

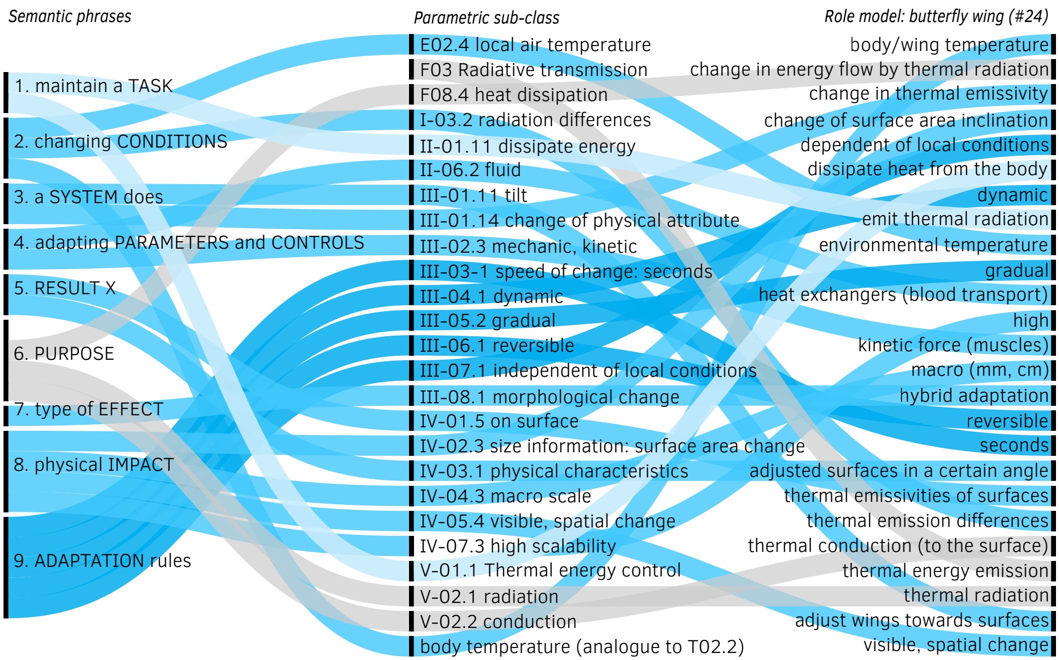

FIG. 6.16 Systematic transfer scheme for biological concept #2: butterfly wings / thermal emission / adaptive heat dissipation. Semantic terms with assigned criteria of the parameter list (Appendix 3-3) describing biological concept #2.

6.6 Summary

The focus of this chapter is on understanding and translating the biological strategies for thermal adaptations. By studying the biological models or repsectively their specific principles, an insight into the processes and interdependencies of the adaptation processes is given. The main challenge is to interpret the literature, as the knowledge and vocabulary in the natural sciences is different from that of façade design and engineering, which could lead to misunderstandings. The support of experts from the relevant fields is therefore very helpful.

Ultimately, from the perspective of façade design and the functional model development, the intention of the organism is less important than the physical relationships for the thermoadaptive process – at least if the chosen principle remains at a certain level of complexity. The concept of the transition process, which was discussed at the beginning of this chapter, served as orientation and also as a basis for the development of the semantic translation, the biological concepts.

For this purpose, only those role models were selected for the creation of the biological concepts that function on macro-scale, do not rely on chemical change processes and preferably apply geometric adaptations. This also relates to the idea of Bejan's 'constructal theory', which states that geometric formations can control the flow of energy.

The chosen strategies apply volume adaptations or adjustments of surfaces to either influence the thermal transmission or thermal radiation intensity. By this choice, the developed systematics in this work can be better tested than more complex examples. These strategies were transferred to a structured semantics that is further linked with the developed parameter list, which helps to systematically develop the functional models in Chapter 7.

6.6.1 Translation challenges

To obtain basic information and conduct an initial selection of potential biological role models, it is often sufficient to study the abstract and conclusion of the respective scientific articles, as done in Chapter 5. However, to understand a role model function, its functional principle, the scale of the effect, needed adaptation mechanisms and boundary conditions must be studied. This step is a rather time-consuming step and shall be conducted normally in transdisciplinary teams.

Studying relevant publications about the chosen biological role models, requires a very high learning effort, since scientific publications in biology are unfamiliar research areas for the author. Whenever needed, expert interviews have been conducted with biologists to better understand some features of the principles. However, some likely well-known references and findings within the field of biology may be missing.

The author could build on the experiences and results of interdisciplinary discussions in the research project BioSkin (Gosztonyi et al., 2013), which the author developed and managed. Therefore some gaps in this regard could be closed, but many uncertainties and missing knowledge remain. The qualitative description is also only rudimentary due to the wide scope and dependencies of the analogies.

At all stages, a certain degree of abstraction must be taken due to the fact that the whole complexity of the organisms are not fully understood and/or cannot be considered.

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Appendices

Appendix 6-1 Assessment of selected role models (selection step 2)

Online: https://data.4tu.nl/account/collections/5811071

7 [Transfer] Functional models

Chapter 7 is dedicated to the development of biomimetic 'functional models', which are a technical translation of the biological concepts in Chapter 6. For this, the semantic description of the biological concepts is transferred to the façade design by using the transfer scheme developed in Chapter 4. The challenge hereby is to transfer the functional processes of the biological concepts in such way that it is useable for the façade design. For this purpose, a process is developed that uses the parametric values by creating design option of these. This is to allow flexibility in the design process. Critical functional principles are evaluated by quantitative analyses. The design results, the functional models, are conceptual drafts with descriptive information at this early design stage. However, this shall provide a sufficient basis for assessing their feasibility and applicability.

After the introduction in Section 7.1, the methodology to generate the functional models is presented in Section 7.2. The two biological concepts of Chapter 6 are then taken to develop functional models, which are presented in Sections 7.3. and 7.4. The aim of these sections is to present the results in such a way that the principles become comprehensible and usable for the early design stage. By doing so, the functionality should still be preserved. The information is prepared on a conceptual level with sketches and descriptions. In Section 7.5, these models are then compared with the prepared use cases of Chapter 3 in order to understand the differences and similarities and to assess their design effectiveness.

7.1 Introduction

The most critical step for a successful utilization of biomimetic research is the transfer of findings from the biological domain to the technical domain, in this case to the façade design. For this, the semantic language must be translated into a technical language in order to obtain the needed information for the design process.

The prepared biological concepts of Chapter 6 provide simplified and abstract drafts of rather complex processes in biology, which in reality have even more influencing factors involved, such as biochemical processes on various scales or local dependencies. However, the abstraction should be designed in such a way that the functional principle remains intact despite the omission of some factors. Many of these factors are too complex to be transferred to a design model, and might not even contribute to the sought functionality. Furthermore, only those concepts are described that follow the defined design rules, meaning that e.g. biochemical processes intiating an adaptation process are excluded from the transfer.

This type of information is now translated back to the façade design by applying the parametric systematics. To generate such models, it requires a certain amount of conceptual thinking with some assumptions that must later be validated. It is crucial to choose those parameters that allow a good qualitative description of the function and later evaluation of the model. Exemplarily for this intention, the presented functional models are based on various assumptions and simplifications to display known physical effects caused by geometric and material assembly. In the end, the development of such models always depends on the involved expert and design knowledge and in this sense always remains a subjective choice.

7.2 Methodology

The applied method for the transfer continues the developed systematics, including the adaptive façade criteria list, the design rules and the biological concepts.
The purpose of this systematics is to preserve the functional pecularities of the relationship between geometry, materiality and influencing factors over the entire translation process. This is also valid for the design of the functional models. Thus, before the models can be designed, the functional intentions derived from the biological concepts and additional outcomes of Chapter 6 are described in technical terms. Possible quantitative or geometric analyses complete this description (Fig. 7.1, I-Intention). From this description, design variations can be created. Each design result is based on various design variants. The models is then created from a best-case combination of these options (Fig. 7.1, II. Development).

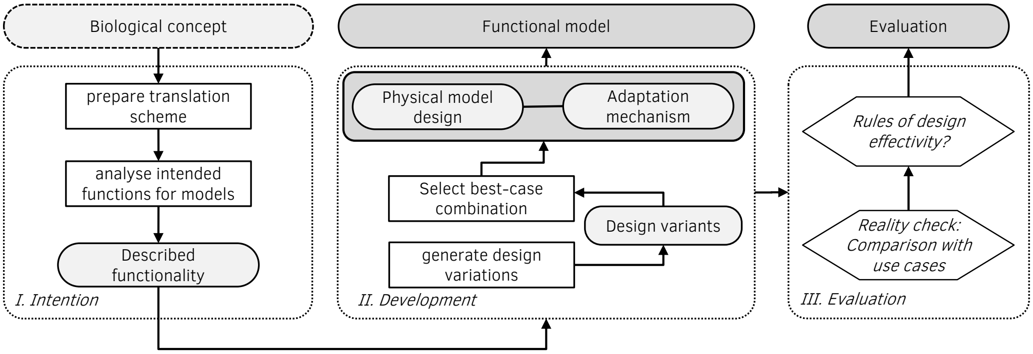

FIG. 7.1 Scheme of the applied process to define the intended functions and to develop and evaluate functonal models

The functional models are finally compared with the prepared use cases of Chapter 3 in regards to their design effectivity and feasibility (Fig 7.1, III. Evaluation).

7.2.1 Description of intended function

The functional parameters of the biological concept must be made accessible for design development by providing a transfer scheme. This is based on the biological concept scheme, which is completed by the rules for adaptation (Fig. 7.2). These rules form the basis of the technical description of the functional model. The illustration of the transfer scheme has already been prepared in chapter 6. It merely provides a complete map and thus serves as a starting point for design development.

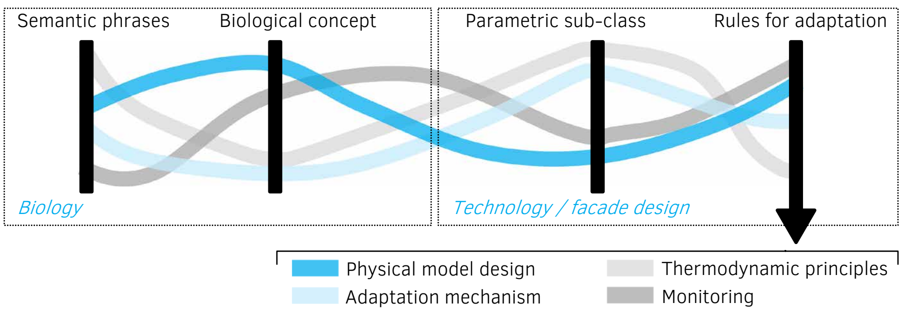

FIG. 7.2 Transfer scheme from biology //*semantic*// to façade design //*technical modelling language*//.

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With this scheme, feasible realization approaches are then discussed and analysed, respectively feasibilites are examined by numerical analyses or design sketches. The intention of this step is to prepare a technical basis of the intended functionality (for the target domain) and the possible related design variations.

7.2.2 Creation of design variants and best case combination

To generate a physical model that works well with the adaptation mechanisms, various design variants are drafted. These variants are set up at various levels based on the provided information from the scheme: possible measures regarding the environmental input/output, physical components and material supporting the adaptation function are considered. For each design variant, the working principle, a visualization of the idea and the same descriptive criteria as for the biological concept are provided:

- Descriptive criteria for the physical design:
  - III-08 Adaptation impact,
  - IV-01 Level of embedment,
  - IV-02 Type of physical impact,
  - IV-03 Physical characteristics of structure or material,
  - IV-04 Functional scale,
  - IV-05 Visibility,
  - IV-07 Scalability.

- Decriptive criteria for the adaptation mechanism:
  - II-06 Operation carrier,
  - III-01 Task to perform,
  - III-02 Actuator type,
  - III-03 Response time,
  - III-04 Response type,
  - III-05 Response degree,
  - III-06 Adaptation reliability,
  - III-07 Adaptation dependency.

- The environmental conditions in which these types work are added by the criteria:
  - I-01/02 Set / Actual values, and I-03 Input/Output deviation.

- Criteria to describe the functional effect:
  - V-02 Physical principle.

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The method applied for the development of the design variants can be compared to a morphological box approach. The intention is to have a choice of design options that meet the functional principle(s) of the biological concept. From this variety of options, a best case combination can be derived that best meets the desired objectives. This allows a certain flexibility in the design process, which is necessary due to constraints in each project (material, time, design intentions, etc.).

7.2.3 Generation of functional models

Physical designs - After developing the design variants and choosing a promising combination, the physical design is developed by sketches and descriptive explanations. This provides the information needed for the realization and includes the morphological and material-related features as well as constructive components.

Adaptation mechanism - The adaptation mechanism is an integral part of the physical design and must therefore be taken into account in parallel. Equally to the physical design, the mechanism is presented by sketches and descriptive information that addresses the adaptive façade criteria.

For the generation of the models, the parametric systematics (Appendix 3-2) and selected criteria of the selection and evaluation check list (Appendix 4-1) are applied.

7.3 Functional Model 1: Heat regulation by adaptive thermal conductivity

The first functional model is based on the biological concept 1 with the role model 'plumage of birds', assigned to the functional principle 'thermal transmission' (F01), particularly on the physical principles 'thermal conduction' (V-02.2) and 'thermal convection' (V02.3). Following the four adaptation rules, the monitoring is hereby focusing on temperature differences (I-03.1) and the physical system reacts dynamic (III-04.1, III-03.1) and reversible (III-06.1) by a 'volume change' (IV-02.5) that creates a modulation in the thermal flow (II-01.4) by an air keeping cushion (IV-03.1) that influences the thermal conductivity (= increase of still air, F08.2). The covering outer layer (IV-01.4) expands or shrinks (III-01.6/7) visible and spatially (IV-05.4) on macro scale (IV-04.3). The actuation is done extrinsically (II-03.2).

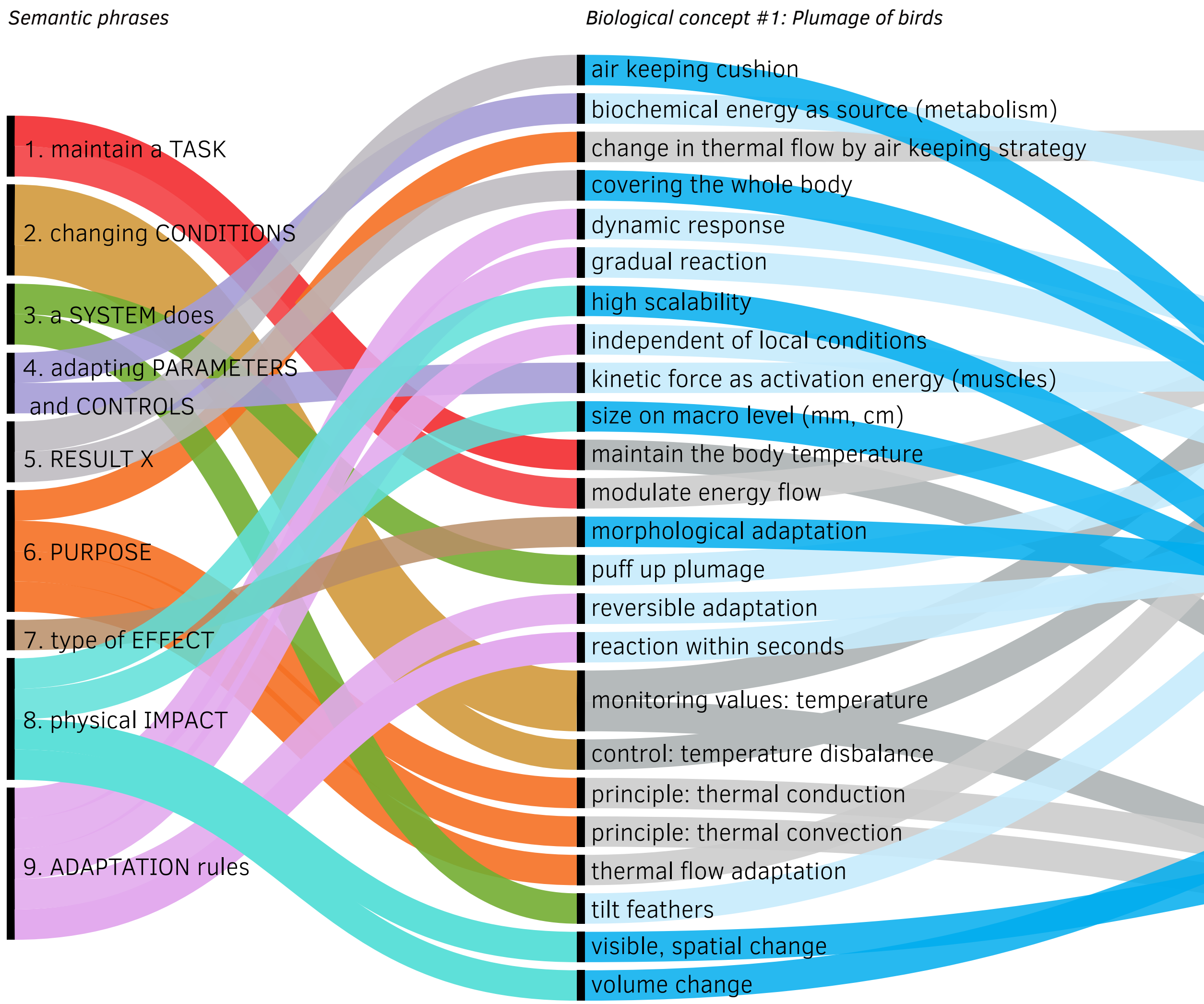
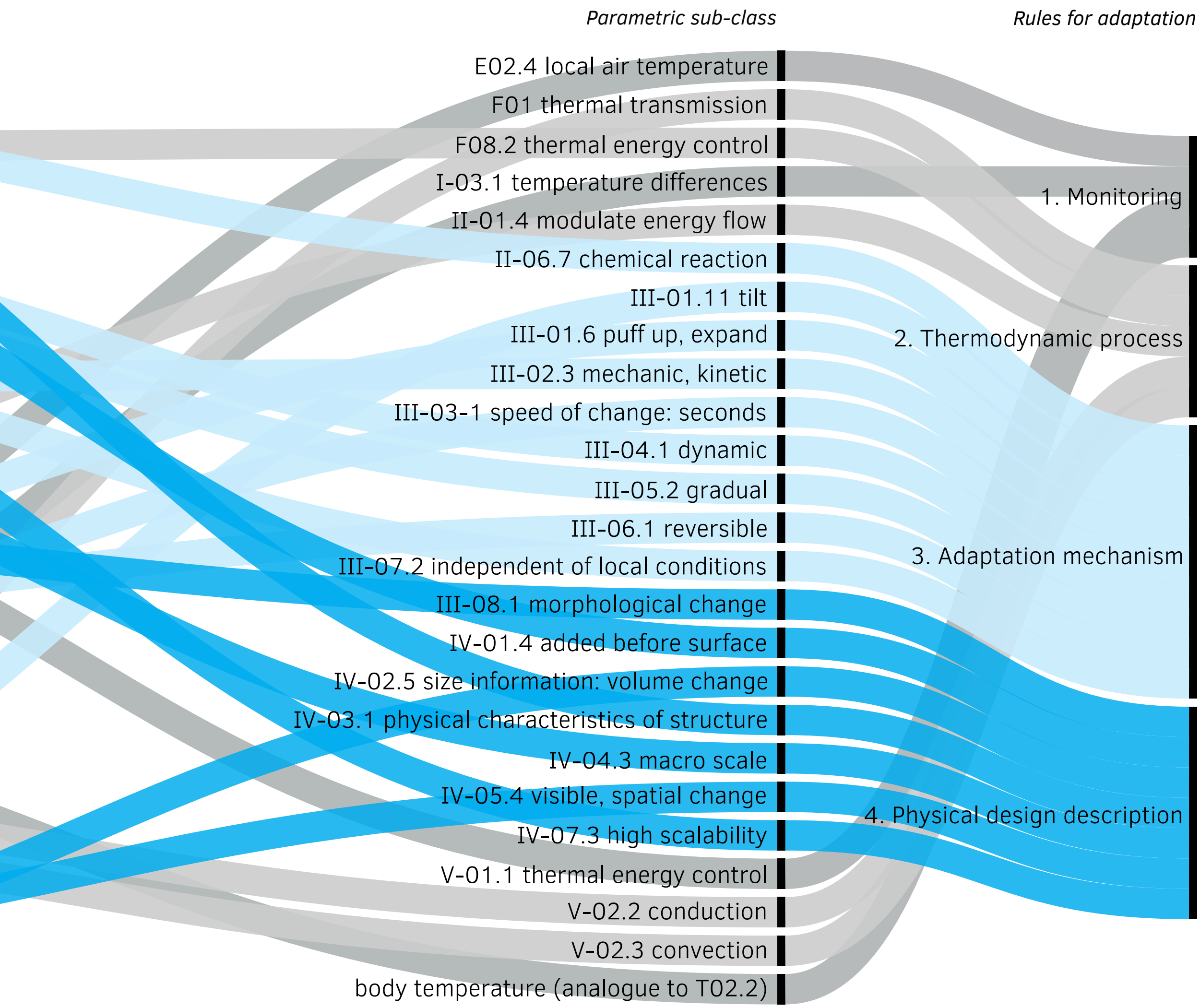


FIG. 7.3 Translation scheme of biological concept #1 following the rules for adaptation.
The semantic phrases (A) are the biomimetic language used to describe the biological concept #1 of thermal conduction adaptation (B). The assignments of these descriptions to the sub-classes of the parametric systematics (C) is needed to keep the function.

The translation scheme presents how the four adaptation rules are linked to the biological concept. It shows the various connections between the languages, as can be seen at the example 'physical design description': this is composed of the physical impact, the type of effect, and the result of the biological concept.



The four rules for the adaptation design (D) support the technical language to describe the functional model.

7.3.1 Description of intended function

The dependency between the thickness or number of insulating layers and thermal conductivity of a material is crucial for the quality of the thermal insulation, as discussed in Chapter 2. For standard products, overall thickness must be increased if thermal conductivity is to be reduced. Chapter 2 also reveals that current high-tech insulation materials aim to reduce the overall thickness and thermal conductivity simultaneously by employing either closed systems (confined vacuum) or highly porous structures (aerogel). This requires energy-intensive manufacturing processes. They are also more fragile in their robustness than conventional ones.

Biological air chushion supporting thermal insulation

Thermally insulating approaches in nature are often open systems that form, for example, a buffer layer, a heat-storing tissue or a 3D structure to create air cavities. To make this functioning, either heat storing materials are applied (blubber with counter-current heat exchanger) or focus is laid on air entrapment (hairs, fur, feathers). In regards to the biological concept, the plumage of birds or penguins is hierarchically structured in layers of different feathers (Du et al., 2007): from the down feathers on the inside to the protective cover feathers on the outside, the plumage protects from extreme climatic conditions. The down feathers are primarily responsible for insulation. The down layer of a plumage consists of elastic, radiant-arranged, very thin feathers that open into numerous, super fine branches, which trap air well and greatly reduce thermal losses (Gao et al., 2007). Thus, down feather possess the “*greatest warmth-to-weight ratio of all natural fibres*” (Fuller, 2015, p. iv). The keratinous feathers are negatively charged by body movement and thus keep distance from each other (low cohesion, which allows to form the down dress with the air cushions (D’Alba Altamirano et al., 2017)).

The mimicry of feathers as insulators for building envelopes has been taken up as conceptual ideas in architecture (Webb et al., 2011) (Gruber & Gosztonyi, 2010) (Pawlyn, 2016) or (Conzatti, 2020). The ideas range from sandwiched solutions with down-like material between layers or an outer 'feather' layer exposed to the environment, which makes it not durable besides the unsolved mechanisms and material attributes.

There are many obstacles to transfer the principle: the type of material that could provide behaviour similar to down feathers has not yet been developed; furthermore it would have to meet rather strict requirements for use on façades, such as for fire protection, weather resistance (UV, water, wind) or mechanical stress. The principle

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of down feathers seems to work best when a free volume change is possible and the super-thin material keeps its low cohesion. This requires a protective layer to avoid wetting by water or adhesions by dirt. Birds also constantly clean their plumage. And finally, the activation mechanism of the muscles must be considered as well.

Thus, a direct translation of the plumage seems not feasible. The idea of changing the thermal conductivity through a change in volume respectively in still air cavities is further pursued. The first approach is to find alternative materials that allow air chambers to change but provide more stability as façade material.

Biological cellulose as insulation material

A more stable structure that can trap air through small chambers could be lightweight cellulose structures. For example, nests of wasps are composed of cellulose layers, whose function is to provide a microclimate and stable habitat at once. The main duty of these nests is to protect thermally and also against water impact, since the '*waxy*' cellulose composite is hydrophobic (Schmolz et al., 2000), (Wainwright et al., 1982). The question is whether layered cellulose, similar to such nests, could achieve sufficient insulation for buildings?

Determining useable values of the thermophysical properties of biological cellulose composites for building physical considerations is very difficult: biological cellulose composites are anisotropic and heterogenous – and as building material of wasps it is enriched with further components (saliva, clay and other mineral components) (Schmolz et al., 2000). Additionally, the thermal conductivity depends on the ambient temperature and moisture content of the material, which differs a lot in the biological role model.

There are thermophysical studies about lignocellulose in nature, the raw material for e.g. wood, grass, or many other plants that is used by the wasps for build their nests. Various types of cellulose have been investigated, from e.g. beech, oak, fir, chestnut by Yapici et al. (2011), softwood by Gupta et al. (2003), or lignocellulose on cell level is studied by Cheng et al. (2014) and in bee hives by Kleinhenz (2008).

Kleinhenz (2008), for example, measured in his doctoral thesis an approx. thermal conductivity (λ) of 0,15 W/(mK) for waxed bee hives. This does not appear to be a good insulator. However, the wax of the hive surfaces controls the heat permeability of the cellulose layers. Although the thermal conductivity in honeycombs is high according to Kleinhenz (2008), bee hives still display a greenhouse effect. The bee pupae in the honeycombs radiate heat in a certain, long-wave IR frequency range, which is reflected back by the waxed walls of the honeycombs. Heat radiation of higher density (i.e. shorter wavelengths) can pass through the walls. In the neighbouring honeycombs, so-called heater bees are residing and warm the pupae in that way. This is an interesting finding to be further studied, as it seems to support the thermal effectiveness of open systems. In the following evaluation, the thermal characteristics of this bee hive material are evaluated as a fictitious insulation material.

Impact of lignocellulose insulation on geometry

To understand the thermal effectiveness of a fictitious linocellulose building material, the data provided by Kleinhenz (2008) about the bee hives is used and a rough calculation is made by the author. For the evaluation of this material, the base case of Section 2.3.4 with a standard insulation (PUR) (Fig 7.5, A) is compared.

The fictitious insulation is a multi-layered and consists of alternating cellulose layers of 1 mm thickness and still air cavities of the same thickness. The material is able to expand by increase the air cavities (Fig. 7.4). It is assumed that the air cavity has still air with a thermal conductivity of 0.025 W/(mK). It is known that still air has a thermal conductivity λ = ~0.024-0.025 W/(mK) at sea level and =°-10C (laboratory value). The lignocellulose has a λ = 0.025 W/(mK) according to Kleinhenz (2008, p. 50).

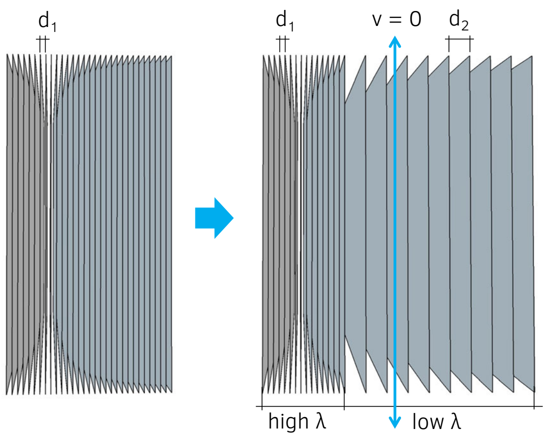


FIG. 7.4 Fictive ligno-cellulose insulation concept.
The sketch shows a multi-layered insulation consisting of cellulose layers with 1 mm thickness and still air cavities of the same thickness (d_1). A possible modification of the thermal conductivity could be achieved by a thickness change of the air cavities (d_2) assuming that the thermal conductivity of the air does not change.
The stage of d_2, high thermal conductivity, could be applied for thermal losses at night; d_1, low conductivitiy, for thermal protection. Air motion is neglected in this model.

The calculated thermal resistance values R of both versions show the following (Fig. 7.5): 135 cellulose layers, or a thickness of 27 cm, would be necessary for the fictitious insulation to achieve a similar thermal resistance like the base case with only 15 cm insulation thickness. This would then allow to reach the Passive House U-value of U= 0.15 W/(m²K) causing the thickness of the cellulose insulation to be 12 cm thicker than for PUR.

Thermal resistance results: $R_{BC,PUR}$ = 6.63 (m²K)/W versus $R_{BC,Cell}$ = 6.64 (m²K)/W).

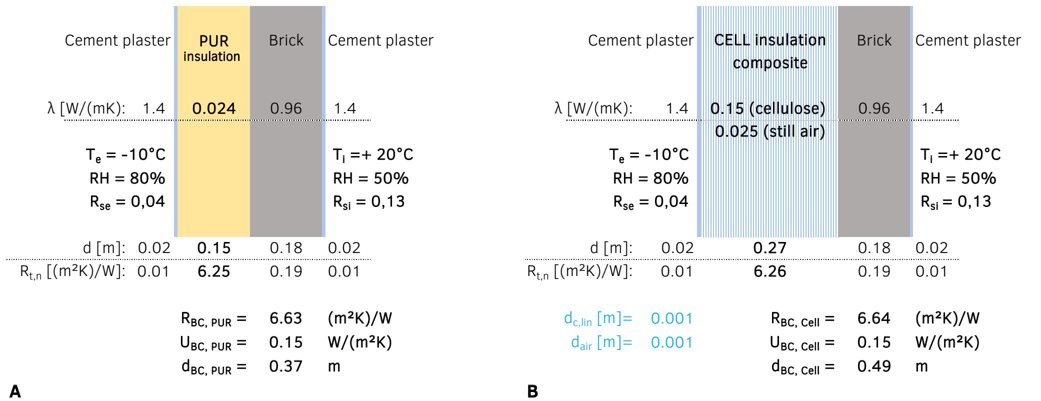


FIG. 7.5 Results of calculated base case with PUR insulation (A) and a fictive cellulose insulation (B).
The assumed model uses the base case of Chapter 2 (Fig 2.17) and adds parallel layered lignocellulose sheets with a thermal conductivity of λ = 0.15 W/(mK), and width of d= 1mm as insulation. With this setting, the base case would require 135 sheets of cellulose to reach the Passive House standard.

Two challenges come with this concept: the increased thickness and the provision of still air with low thermal conductivity. For the first, possible material optimization by adding a coating on the surface in order to reflect heat radiation and lower the permeability, could maybe increase the quality and lower the thickness.

For the second, the air cavities must be designed to avoid circulation to a maximum. The air in the cavities between the layers of the model is assumed to have a low thermal conductivity, which is a laboratory value that does not correspond to reality. This assumption is used for '*still air*' calculations in EN ISO 6946 (2017) In practice, air moves even in closed cavities due to temperature and thus density fluctuations. The thermal conductivity would then be much higher and the result worse. It is obvious that an effective air entrapment is essential for this concept. A chamber-like, closed structure that allows air to be confined in small, closed cells might be a possible solution. The physical behaviour of such structures cannot be analysed in this work, but for further concept development it is expected that the thermal conductivity may be reduced by closed cell structures.

7.3.2 Design variants and best-case combination for FM1

The collected design variants of Table 7.1 show design options that influence the thermal conductivity by material or geometrical interventions. These variations are derivations from the principle found in the biological concept 1 and are supplemented by other biological principles that seem promising to support this approach. The starting point for the design collection targets at volume changes. To enable a volume change, a system must be able to expand / shrink. This may be done by a foldable geometry using linear growth mechanisms (adaptation of e.g. foldable stiff material) or volumetric growth (adaptation of e.g. expandable material). Geometries that allow such volume growth are important supportive design options to consider for the model development.

But also other options are considered in the collection, that are not directly linked to the biological concept itself but may address its principle of thermal conductivity change. Such may be e.g. a change of the thermal storage capacity of materials (adaptation of e.g. phase change materials).

The change of the volume may be activated by extrinsic, kinetic actuators, such as shown in the biological concept, or intrinsic actuators that bend or expand when heated. These actuator types may be initiated by a change in temperature, mositure or mechanical force.

The design variants are arranged according to their change options on material level (design variants #1 to #3), on surface level (design variants #4 to 6) and on system level (design variants #7 to #9).

TABLE 7.1 Design variants for functional model 1.
The design options display various adaptative designs for the purpose "volume change" and adaptive "thermal conductivity".

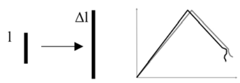
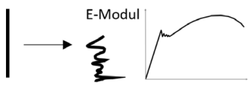
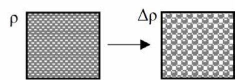
	Design variants	#1	#2	#3
Change on material level	role models	#68, #65	#63, #64, #66	#57, #56, #54, #49
	Design variant name	linear growth in length	growth in all directions	density change
	V-02 Physical principle	.2: conduction	.2: conduction	.2: conduction (density)
	Working principle	change of length - thermally adaptive material	change of volume/surface area by using elastic materials	change of thermal conductivity by change of thermal storage capacity
	Physical design			
	III-08 Adaptation impact	morphological change	morphological change	physiological change
	IV-01 Level of embedment	.1: material	.1: material	.1: material
	IV-02 Type of physical impact	size change in length, width	size change in area	none
	IV-03.2: Physical characteristics of material			
	IV-04 Functional scale	.2: micro, .3: macro	.2: micro, .3: macro	.2: micro
	IV-05 Visibility	visible, spatial change (one direction)	visible, spatial change (all directions)	maybe visible, no spatial change
	IV-07 Scalability	medium (depends on material)	medium (depends on material)	medium (depends on material)
	Adaptation mechanism			
	II-06 Operation carrier	radiation, thermal reaction	thermal reaction, radiation, gas (pneumatic), fluid (expansion), kinetic force	radiation, thermal reaction, chemical reaction
	III-01 Task to perform	.3,.4/.5: extend or stretch/ contract, .8: roll up, .9: wrap up, .10: bend,	.6/.7: expand/shrink, .8: roll up, .9: wrap up	.13: change of phases, .14: change of density
	III-02 Actuator type	.1: thermal, .4: electric	.1: thermal, .2: chemical, .8. pneumatic	.1: thermal, .2: chemical
	III-03 Response time	min	sec - min	min - hours
	III-04 Response type	dynamic	dynamic	static
	III-05 Response degree	gradual	gradual	gradual
	III-06 Adaptation reliability	reversible	reversible	reversible
	III-07 Adaptation dependency	independent of location	independent of location	dependent of surrounding temperature
	applied example	thermally sensitive wires, thermally adaptive polymers	form adaptive materials, systems (balloon, membranes)	PCM material

TABLE 7.1 Design variants for functional model 1.
The design options display various adaptative designs for the purpose "volume change" and adaptive "thermal conductivity".

Cange on surface level

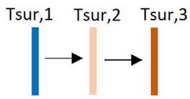
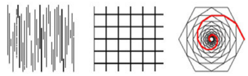
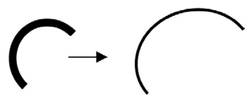
Design variants	#4	#5	#6
role models	#55	#53, #59	#45, #66, #51, #63
Design variant name	thermally adaptive material	adaptive surface structure	adaptive surface area
V-02 Physical process	.1: radiation, .2: conduction	.5: other (geometric)	.5: other (geometric)
Working principle	change of surface absorption / temperature	surface patterns allow growth	surface characteristics allow area adaptation
Physical design			
III-08 Adaptation impact	physiological change	morphological change	morphological change
IV-01 Level of embedment	.1: material, .2: component	.1: material, .2: component	.2: component, .3: system
IV-02 Type of physical impact	none	size change in length, width or area	size change in volume (area)
IV-03.2: Physical characteristics of material			
IV-04 Functional scale	.1: nano, .2: micro	.1: nano, .2: micro, .3: macro	.1: nano, .2: micro, .3: macro
IV-05 Visibility	maybe visible, no spatial change	visible, spatial change (one direction)	visible, spatial change (all direction)
IV-07 Scalability	no limits	depends on geometry	depends on material
Adaptation mechanism			
II-06 Operation carrier	radiation, thermal reaction, maybe chemcial reaction	mechanical force, thermal reaction, maybe chemical reaction	thermal reaction, radiation, gas (pneumatic), fluid (expansion), kinetic force
III-01 Task to perform	.14: change of physical attributes	.1: fold, .2: shift, .4/.5: stretch/contract, .10: bend, .11: tilt	.1: fold, .6/.7: expand/ shrink,
III-02 Actuator type	.1:thermal, 2: chemical, 6: electromagnetic	.1: thermal, .3: mechanical, .6: electromagnetic, .8: pneumatic	.1: thermal, .3: mechanical, .6: electromagnetic, .7: hydraulic, .8: pneumatic
III-03 Response time	min	sec - min	sec - min
III-04 Response type	static	dynamic	dynamic
III-05 Response degree	gradual	gradual	gradual
III-06 Adaptation reliability	reversible (if chemical reaction allows that)	reversible	reversible (depends on material)
III-07 Adaptation dependency	temperature/radiation dependent of sun path	independent of location	independent of location
applied example	thermoactive materials (e.g. paints), colours/absorption effect	self-folding materials, folded shading systems	pneumatic membranes, thermal expansion in assemblies

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TABLE 7.1 Design variants for functional model 1.
The design options display various adaptative designs for the purpose "volume change" and adaptive "thermal conductivity".

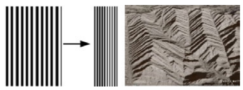
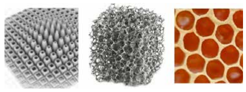
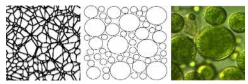
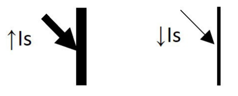
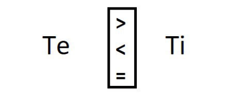
	Design variants	#7	#8	#9
Change on system level	role models	#56, #58, #62, #65	#60, #62	#61, #62
	Design variant name	deformation of width	open cell structure	closed cell structure
	V-02 Physical principle	.5: other (geometric)	.5: other (geometric)	.5: other (geometric)
	Working principle	deformation of geometries in various directions	even or uneven closed-cell deformations	even or uneven closed-cell deformations
	Physical design			
	II-08 Adaptation impact	morphological change	morphological change	morphological change
	IV-01 Level of embedment	.3: system, .2: component	.3: system, .2: component	.3: system, .2: component
	IV-02 Type of physical impact	size change inwidth	size change in length, width or area	size change in length, width or area, volume
	IV-03.1: Physical characteristics of structure			
	IV-04 Functional scale	all scales	all scales	all scales
	IV-05 Visibility	visible, spatial change (one direction)	visible, spatial change (preferably one direction)	visible, spatial change (all direction)
	IV-07 Scalability	medium, depends on layers	medium to high	medium to high
	Adaptation mechanism			
	II-06 Operation carrier	-	-	-
	III-01 Task to perform	.1: fold, .3/4: extend/ contract, .10: bend, .7: shrink	.1: fold, .3/4:extend/ contract, .10: bend, .7: shrink	.1: fold, .3/4:extend/ contract, .10: bend, .7: shrink
	III-02 Actuator type	on material level? .7: hydraulic, .1: thermal (including material attributes)	on material level? .7: hydraulic, .1: thermal (including material attributes)	on material level? .7: hydraulic, .1: thermal (including material attributes)
	III-03 Response time	-	-	-
	III-04 Response type	dynamic	dynamic	dynamic
	III-05 Response degree	gradual	gradual	gradual
	III-06 Adaptation reliability	reversible	reversible	reversible
	III-07 Adaptation dependency	-	-	-
	applied example	layered façade structures	solar active insulation (honeycomb insulation)	membranes, closed cell insulation

TABLE 7.1 Design variants for functional model 1.
The design options display various adaptative designs for the purpose "volume change" and adaptive "thermal conductivity".

	Design impact / conditions	#A	#B	#-
Input/Output factors	change goal	surface temperatures	air temperatures	-
	Working principle	radiation depending energy impact on surface	thermal disbalance between various environments	-
	Visual scheme			-
	Environmental factors			
	I-01/02 Set and actual values	radiation	temperature	
	I-03 Input/Output deviation	temperature differences	temperature differences	-
	applied example	sun intensity (energy, short-wave	temperature changes, air pressure changes	-

Legend
initial design (calculated lignocellulose model)
applied adaptation mechanisms
applied patterns
added for FM 1.1
added for FM1.2

Best-case combination

The coloured legend of table 7.1 shows how and which design variants are considered for the generation of functional models. For the calculation (=initial design), only design variant #7 has been used. Further, two models are developed for the functional purpose: FM1.1 '*hexagonal structure*' that applies design variants #5 and #8, and FM1.2 '*closed-cell structure*', which applies design variants #6 and #9. The adaptation mechanism for both models is either extrinsic and uses design variant #1 or intrinsic and uses design variant #2.

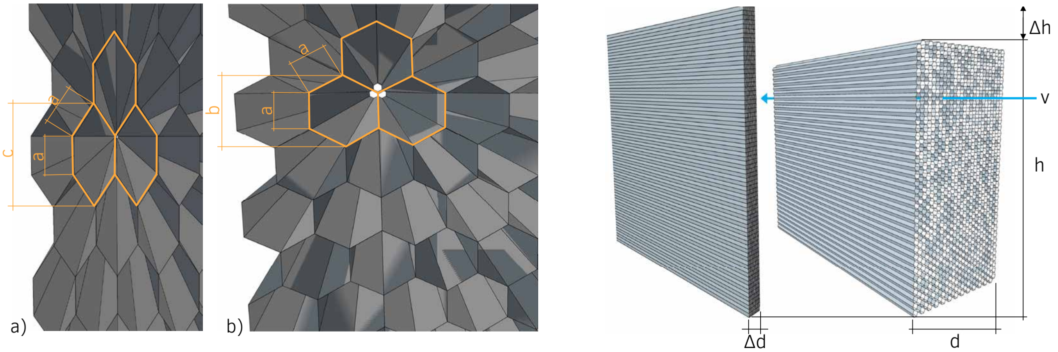
The best case combinations FM1.1 and FM1.2 focus on the adaptability of the thermal conductivity by adapting the air fraction in the system. Care must be taken to allow as little air movement as possible within enclosed air cavities. Additionally, the system must have a certain stability in each adjustment phase. The framework conditions of the environment (defining the sensors and actuators) are set by temperature changes on the surface and/or close to the system environment.

7.3.3 Physical designs

Functional model FM1.1 'hexagonal structure'

To create the functional model FM1.1, the combination of design variants #1, #5 and #8 are applied. This combination would lead to various geometries that change their air cavities by adjusting the thickness of the whole system.

The concept is similar to the calculated model of 7.3.1., but instead of using parallel layers, the model uses an open-cell, chamber-like structure (#8) and combines it with a hexagonal honeycomb patterns (#5). The polygonal structure slows down air motion (v) and thus reduce heat transmission (given that the material is airtight at the faces). The sketch of Figure 7.6 shows how the structure may look like.



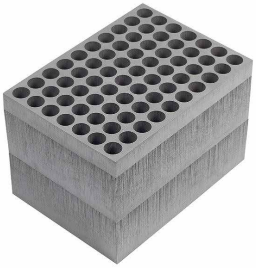
A

B

FIG. 7.6 Sketch of functional model FM1.1 'hexagonal structure'
A: The model adapts the width to reach either high thermal conductivity (a) or low thermal conductivity (b).
B: The change of width (Δd) comes along with change of height (Δh).

The model's construction is comparable to cardboards or similar material that is available on the market. Due to its equal side lengths, thickness adaptation is possible. The effect of the thickness change can be achieved without sacrificing the stability of the system. However, for stiff, non-elastic materials, such as e.g. cardboard, this change goes hand in hand with a change in length: the narrower the wall thickness (Δd), the larger gets the system height (Δh). A growth in height would not be acceptable for an application at building envelopes.

A



B

FIG. 7.7 Image representatives for further material options for FM 1.1
A: Rubber or plastic tubes can can be squeezed more flexible than stiff cardboard materials.
B: Semi-stable squeezable material, such as foam blocks (symbol) that can be deformed.

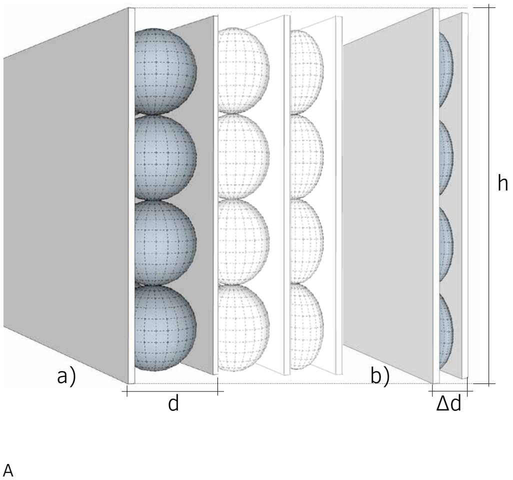
An improvement of FM 1.1 in regards to the retention of the height would require elastic materials that allow thickness changes without changing the heights. Such elastic, shape-adaptive materials consist of either rubber-like materials (gum, plastic, cf. Fig. 7.7, A) or certain foams, functional textiles or poly-membranes that form a sort of body with air cavities (cf. Fig. 7.7, B). These materials must provide or be fitted into a stable structure to allow a directional change in width but stable height. And, the material must remain stable in each transition phase. Due to these material requirements, these options are unlikely to have a chance for realization.

Functional model FM1.2 'closed-cell structure'

Another idea is pursued by the functional model FM1.2 '*closed-cell structure*' (Fig. 7.8). FM1.2 suggests to retain the width-expanding approach but allow a more flexible growth in all dimensions by using a closed-cell structure. The closed-cell structure improves the the air trapping function because of the reduction of air motion in the cells. The size of the cells is limited by production reasons, but should be as small as possible and still allow deformation. For this model, the design variant #9 is chosen instead of the open-cell variant #8.

The cells can have various shapes based on polygonal or circular geometries that allow flexible deformations and growth in all directions. The main advantage of such shapes is the higher tolerance to adapt while keeping the system limits (in this case the height) during the deformations.

TOC



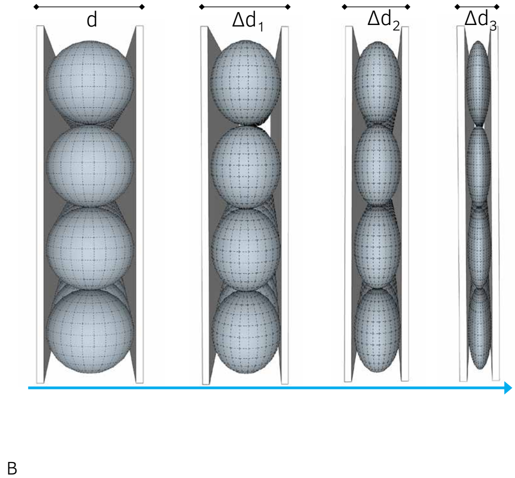
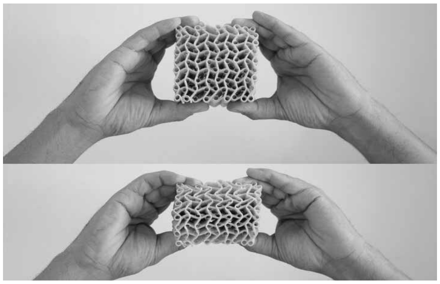
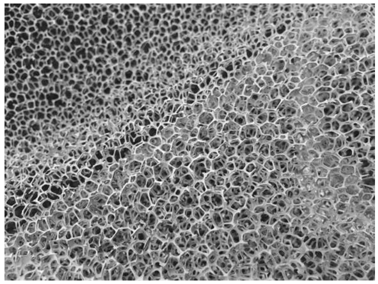


FIG. 7.8 Sketch of functional model FM 1.2 'closed cell structure'
A: The model adapts the cell volumes for low thermal conductivity (a) (thermal protection state) to volumes for high thermal conductivity (b) (thermal transfer state).
B: With the change of width (Δd), the height (h) of the system is not influenced (in contradiction to functional model 1.1).

The specific material attributes of the cells (shown in Fig. 7.8 schematically as balloons) must either elastic or could possibly be folded structures that allow a similar growth behaviour. Threedimensional lattices made of polymer or fabrics may provide possible solutions (Fig. 7.9, A and B). The inner of the cell structures could be divided into further sub-chambers (inner membranes) to reduce air motion to a minimum. The material optimization is not further discussed in this sketch, because it would be matter to further tests in regards to permeability, reflectivity, or elasticity.



A



B

FIG. 7.9 Image representatives for further material options for FM1.2
Possible lattice materials may be made of functional fabrics or polymers, such as exemplarily shown by:
A: 'ZigZAG' - 3D printed flexible woven foam structure made by Oluwaseyi Sosanya, 2014 (Image courtesy of O. Sosanya).
B: Polymer tissue (symbol) that adapts within a shape-stabilizing, squeezable body.

7.3.4 Adaptation mechanisms

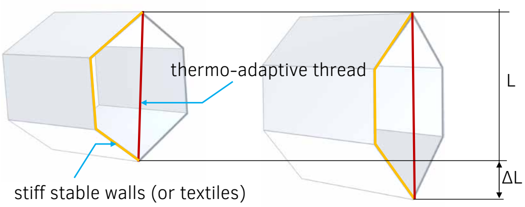
The sensor/actuator system for both functional models FM1.1 '*hexagonal structure*' and FM1.2 '*closed-cell structure*' can be either extrinsic or intrinsic. While extrinsic actuators are familiar measures, such as e.g. kinetic subsystems or pneumatic supply systems, intrinsic actuators are not applied in façade components. The employment of thermo-adaptive or thermally expanding materials to initiate a change provides the advantage of strongly reducing complexity in operation but also the disadvantage of increasing uncontrollability. Nevertheless, it is interesting to look closer into the design options #1 and #2 for intrinsic actuators.

One option for intrinsic adaptation is to apply a thermally-adaptive thread or wire to the hexogonal structure (Fig. 7.10, A). When the wire is heated, a change in length occurs. The coefficient of linear thermal expansion (αL) of the wire or thread must be considered. Functional textiles (e.g. polymer fibres) that form the structure may allow an adaptation by embedded thermo-adaptive threads (Grocholski, 2019) (Ridley et al., 2015).

Another option for intrinsic adaptation may be based on the thermal expansion effects of gases, depending on temperature differences and considering the design conditions of the material (cf. Fig. 7.10, B). Actuator and sensor could be both temperature-dependent and even be the same mechanism. Since thermal expansion in a material is inhomogeneous, the characteristics of the material must match well with the expansion needs. The expansion itself is somehow uncontrollable as it depends on the environmental conditions. And there is a another problem: most materials and gases expand when heated and contract when cooled, whereas gases expand more than materials. This would certainly be contrary to the desired function, where the volume shall expand when its cold in winter, but contract over nighttime in summer to allow heat dissipation. Thus the temperature provided to these cells must be conditioned to reach controllability.

In any case of the expansion mechanism, the volume thermal expansion coefficient (αV or γ) must be considered to choose the right material and gas.

Investigations about possible thermally adaptive materials revealed their ability for possible negative thermal expansion: certain materials contract when heated instead of expanding like most materials do. The best-known example is water in the range of 0°C to about 4°C, but there are mainly metals investigated with such properties (Gong et al., 2020) (Takenaka, 2018) (Miller et al., 2009). A combination of both properties (positive and negative expansion) in matrices would maybe allow a 3-dimensional deformation behaviour as intended.



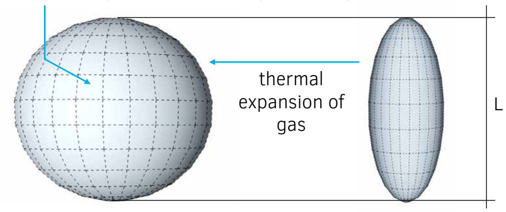


FIG. 7.10 Sketches of the adaptation mechanisms for both FM1 models.
Two options for intrinsic thermal adaptation mechanisms are suggested:
A: Kinetic adaptation effect by applying a thermo-adaptive thread to the structure that deforms it.
B: Shape-adaptive elastic materials interacting with thermally expanding gas.
Both actuators follow the principle of thermal expansion due to temperature/pressure changes: the warmer it gets, the more a material/gas expands.

An extrinsic actuation can be applied by e.g. supplying different air pressures into an elastic structure (amount is depending on system design). Both concepts of Figure 7.10 may also be adapted by such pressure change. The following principle should be considered then: the smaller a cellular unit, the less amount of air needs to be supplied to initiate a change. An even distribution of the air supplement is important.

The '*balloons*' of FM 1.2. could be interconnected by means of stomata-like valves, which open at a certain air pressure and otherwise remain closed. When opened, air exchanges between the chambers and causes the different pressures. In this case, the air flow and pressure of all cells must be controlled ito avoid a chaotic distribution of the gas density.

Two scenarios that combine the physical design with a adaptation mechanism are described below using the parametric classification and a similar description as for the biological concepts (Appendix 4-1). This shall provide information useable for a parametric design tool:

- Intrinsic adaptation for FM1.1: the system monitors the environmental temperatures (outdoors, inside the system, indoors at defined positions) (I.01 – E02.1 and E02.4) and compares it to defined set temperatures (I.02 – E02.1 and E02.4). The monitoring and control can be done by the intrinsic (II.03.2) property of a thermo-adaptive material that reacts to the temperature (calorimetric, I.04.2) and processes (I.05.1), respectively transports the information thermally (I.06.1) within the material structure to launch a physical reaction (III.02.3) by the material property (II.06.6). This reaction is dynamically (III.04.1) and gradually (III.05.2). The material stretches (III.01.4) and contracts (III.01.5) in one direction within seconds (III.03.1). The whole process is reversible (III.06.1) and is dependent on local conditions (III.06.4) if self-reactive (II.05.3). Its adaptation causes a morphological form change (III.07.1). The physical system changes spatially and visible (IV.05.4) on system level (IV.01.3) that impacts the width (IV.02.2.3) and physical properties of the overall structure (IV.03.1). It works on macro scale (IV.04.3) and is medium scalable (IV.07.2) according to the capability of the thermo-adaptive thread.

- Extrinsic adaptation for FM1.2: the system monitors the environmental temperatures (inside the system, outdoors, indoors at defined positions) (I.01 – E02.1 and E02.4) and compares it to defined set temperatures (I.02 – E02.1 and E02.4). The monitoring and control can be done by an extrinsic sensors (II.03.1) that record the temperature level (I.04.2) and air pressure (I.04.5) to process the information electrically (I.05.4) by a subsystem. This information is then transported electrically (I.06.4) to launch a volume changing reaction (III.02.8) by air pressure change (II.06.1). This reaction is dynamically (III.04.1) and gradually (III.05.2). The structure expands (III.01.6) and shrinks (III.01.7) in all directions within minutes (III.03.2). The whole process is reversible (III.06.1) and is independent on local situation (III.06.5) if activated automatic (II.05.2) or manual (II.05.1). Its adaptation causes a morphological form change (III.07.1). The physical system changes spatially and visible (IV.05.4) on system level (IV.01.3) that impacts the volume

(IV.02.2.4) and physical properties of the volume changing material (IV.03.2). It works on macro scale (IV.04.3) and is highly scalable (IV.07.3) if the expansion capacity of the material allows.

The features of the adaptation mechanism for the two functional models FM1.1 and FM 1.2 are described by using the parametric classification list in order to prepare a system for later virtual prototyping (cf. Appendix 7-1).

7.4 Functional Model 2: Heat dissipation by adaptive surface emissivity

The second functional model that is further developed is based on the biological concept 2: 'butterfly wing', and assigned to the principles 'radiative energy' (F06) / 'thermal emissivity' (F06.1) and 'positioning of surfaces' (F06.3).

Following the four adaptation rules, the monitoring is focusing on radiative differences (I-03.2) between surfaces. The physical system dissipates energy (II-01.11) by different thermal emissivities of the systems' surface and environmental surfaces (IV-05, IV-03.1). To increase the emission, the surfaces must be well adjusted to each other (III-01.11, III-02.3). Thus the effect to emit energy is depending on the local conditions (surface temperatures) (III-07.1), but works dynamic (III-04.1), reversible (III-06.1) and is highly scalable (IV-04.3). It is applicable to any surface, because the main design factors are on one hand the inclination of the surfaces to each other (IV-02.3), which is visible and causes a spatial change (IV-05.4). The thermal properties of the surface material (IV-05.1) the other design factor. Furthermore, a subsystem must be considered that transports the heat to the surface (II-06.2, III-02.3). A positive side effect of the system may also be the employment of a heat exchanger as subsystem.

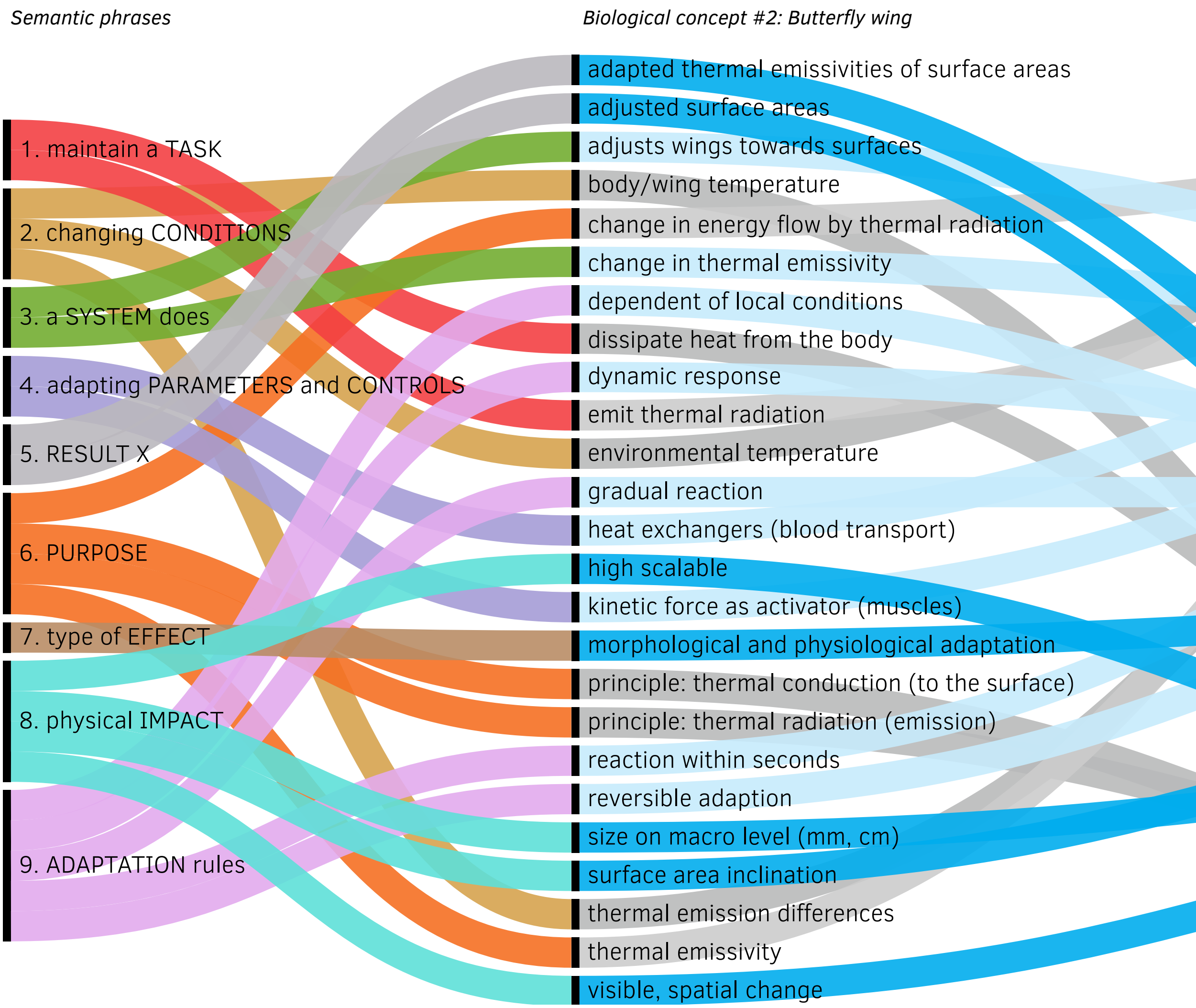
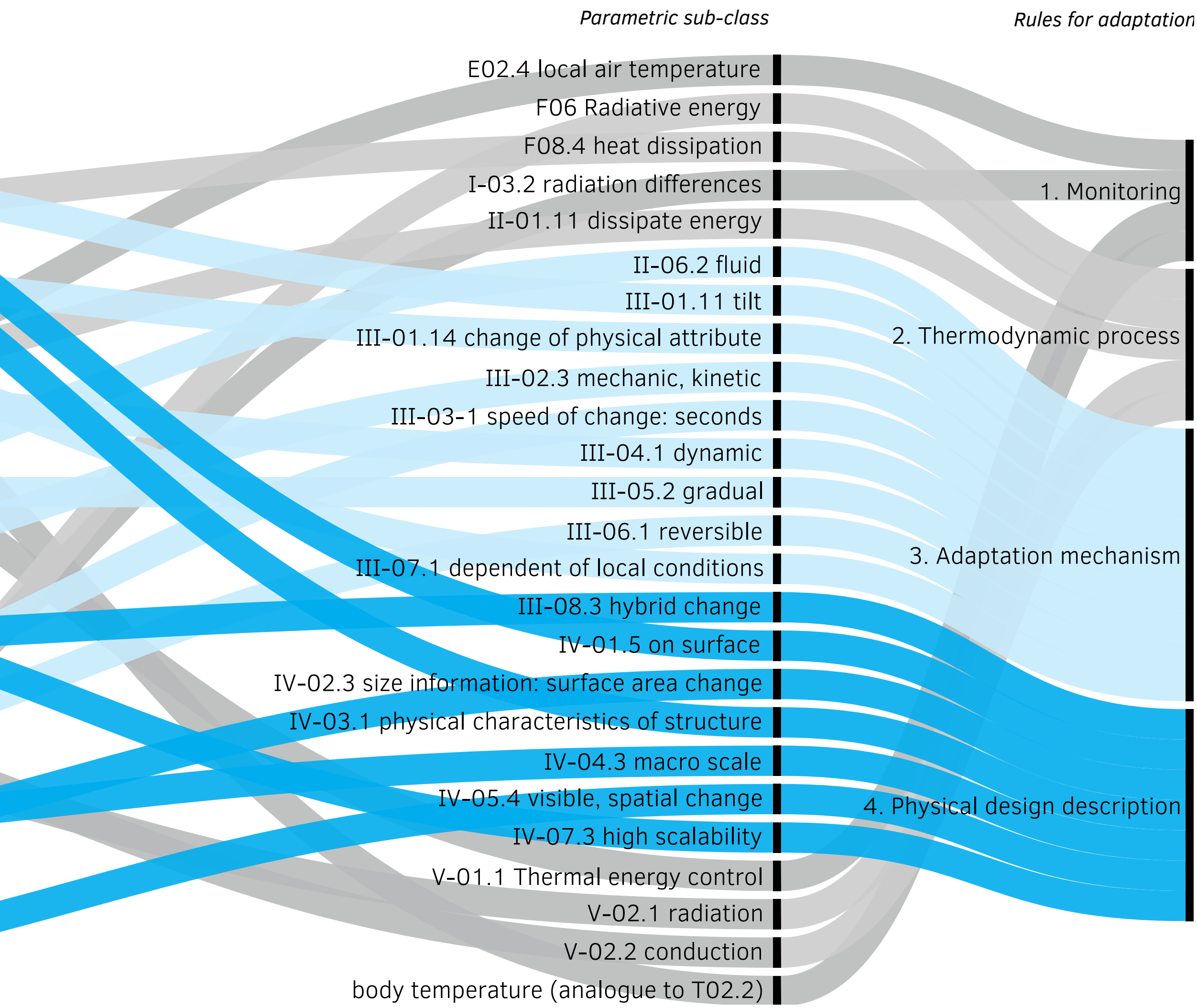


FIG. 7.11 Translation scheme of biological concept #2 following the rules for adaptation.
The semantic phrases (A) are the biomimetic language used to describe the biological concept #2 of the thermal emissivity (B).
The assignments of these descriptions to the sub-classes of the parametric systematics (C) is needed to keep the function



The four rules for the adaptation design (D) support the language to describe the functional model.

7.4.1 Description of intended function

The principle of radiative cooling is not new in the building sector, particularly for cool roofs solutions (Fernandez et al., 2015) (Suhendri et al., 2020) and combined with solar heating technologies (Givoni, 1977) (X. Li et al., 2020). The main activities in this regards are focused on the development of new materials, such as ultra-emissive coatings and paints for daytime cooling, as shown in publications about nanoscaled solutions and metals by (Li et al. (2020), Bijarniya et al. (2020), Jeong et al. (2020) or Pech-May & Retsch (2020), or for nocturnal radiation that is discussed e.g. by Lu et al. (2016).

The concept to achieve heat dissipation by using the principle of thermal emissivity employs three factors: 1) the principle of the view factor (or form factor), 2) the radiative properties of surfaces, particularly the absorptivity and emissivity of thermal radiation and 3) the surface area optimization to allow more emission area.

Surface area optimization

Thermal emissivity is a function of the wavelength of the radiation, temperature and surface characteristics of a material. For an effective emission of heat, the surface attributes are important. Increasing the surface area also increases the heat emission of a material. In nature, the surface area optimization is often combined with other functional aims, such as e.g. solar gains or water uptake. In the technical world, enlarged surfaces are assigned to heat exchange functions. For building envelopes, the surface area tends to be reduced in order to avoid excessive solar radiation and higher heat losses. Further, the overall area of a building is limited.

To increase thermal emission from limited surfaces, two options can be considered:

- roughening the surface (by e.g. sandblasting or anodizing) (Fig.7.12, A),
- applying a thin coating or layer to create a high emissive surface (e.g. powder or high emissivity paints and coatings) (Fig. 7.12, B).

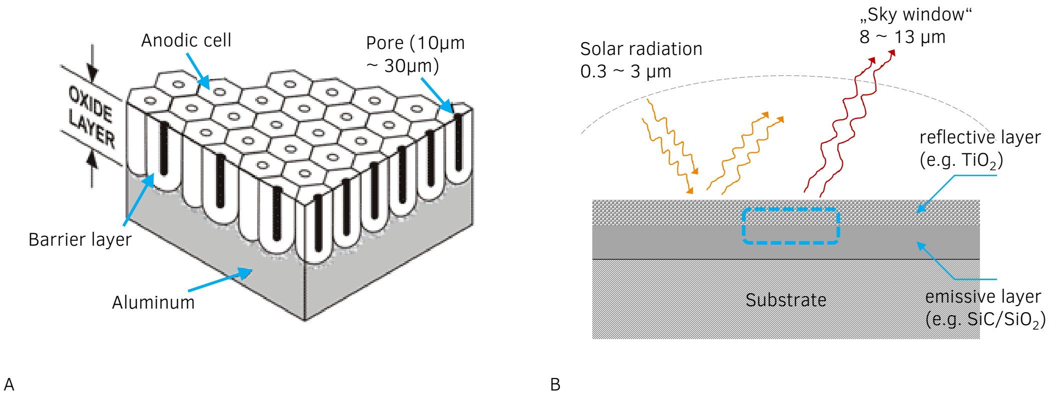


FIG. 7.12 Example for anodized aluminium
Image A shows the schematic construction of anodized aluminium (graphic is adapted from Midstal, 2020) and image B shows a scheme for a double coating design to enhance radiative cooling (graphic adapted from Fig 1 in Bao et al., 2017, p. 79).

Optimized surface geometries for thermal or optical purposes are one of the most widely applied strategies in nature, but also in technology. Heat exchange processes in nature, for example, need a large surface to fulfil their task (e.g. nasal cavities, blood vessels in mammals). Plants, such as e.g. sunflowers, maximize their exposed surface by geometric means (fibonacchi rows) to gain more solar irradiation in limited space. And there are many other examples that use surface enlargements for a physical interaction with the environment.

3D growth patterns

The application of geometric 3D patterns (cf. Chapter 6, Section 6.3) is well researched and established in the field of architecture. With modern parametric design tools and production processes, complex three-dimensional designs can be generated. The functional attractivenes of such patterns is already discovered for adaptive solar shading systems, as shown by the built and conceptual cases in Chapter 3. The solutions reach from triangular 3D forms, as e.g. applied at the shadings of the Al Bahr Towers (Attia, 2017), conceptual origami- or kirigami-like shading concepts (Pesenti et al., 2015) (Pesenti et al., 2018) to complex multi-directional tessellations, like Miura-Ori applying e.g. Ron Resch patterns (Callens & Zadpoor, 2018) (Gonzalez, 2015) (cf. Fig. 7.13). These patterns form adaptive (exposed) surfaces and responsiveness at the same time, which is one to the major goals for responsive design in modern digital architecture. They seem to allow for almost infinite variations in design.

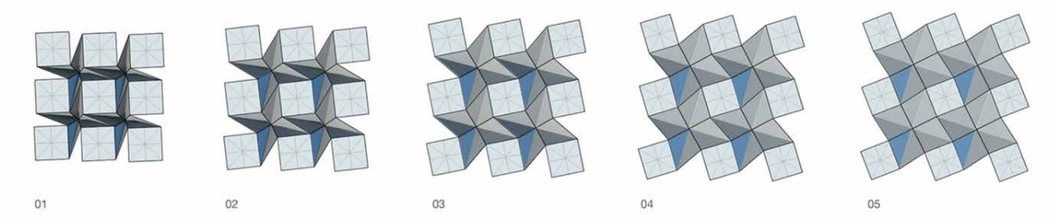


FIG. 7.13 Motion of Tessellation pattern “Water Bomb pattern”, developed by Tomohiro Tachi.
The exposed squre-shaped area of the surfaces changes its orientation gradually with the inclination angle (Image by reRDM, 2013).

The functional optimization of such surface geometries is certainly a critical factor for the functional models, but would take too much time at the current stage. Therefore, it is assumed that surface optimization in regards to thermal emission and other targets will be made once the concept is confirmed as potential.

View factor

Another critical design factor for thermal emission is the relation of the body to the environmental surfaces and their attributes, particularly their radiant properties. Radiation is emitted from any 'surface', including the sky. A specific phenomenon hereby is radiative cooling effect at nights: a certain wavelength bandwidth of the sky 'surface' is utilized where photon can directly escape (emit) into the atmosphere while absorption is rather low. This is known as '*infrared atmospheric window*' or '*(sky) radiative window*'. Its wavelength range is between approx. $\lambda = 8 \sim 13$ µm. The effect is distracted by barriers such as clouds or contamination of the sky, like e.g. greenhouse gases that '*close*' this window because more molecules are absorbed than emitted on their way. So the higher the greenhouse gas concentration, the lower is the night radiation effect, which not only affects buildings efficiency but also nature’s survival.

Figure 7.14 demonstrates the geometric concept of the view factor with two surfaces aligned to each other in certain optimized angle to optimize $dA_1 \rightarrow dA_2$.

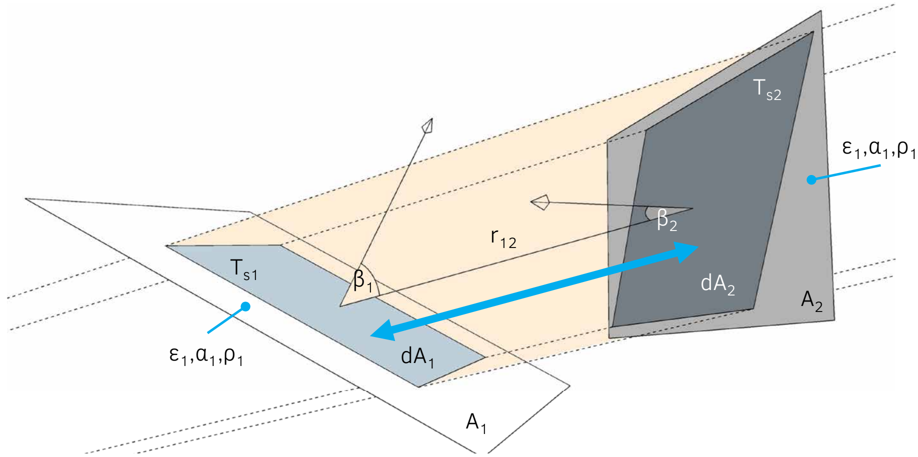


FIG. 7.14 Physical principle for functional model 2.
The sketch shows the concept of the view factor on flat surfaces with the surface areas dA_1 and dA_2 that exchange directly thermal radiation (=emissivity ε, orange field). It can be increased with a higher ΔT between the surfaces.

Radiative properties of surfaces

To increase the heat dissipation of the intended surface A1, the emissivity of this surface but also the temperature difference between surface A1 and A2 in Figure 7.14 must be increased.

Thermal emissivity is achieved by following principle: poor reflection of infrared energy and high radiation of electromagnetic waves from material (which depends on the temperature and waveband of radiation) (Niu et al., 2019) (Tabor, 1979). Furthermore, thermal emissivity of materials is defined by the ratio of the energy radiated from the surface to the energy radiated from a so-called '*ideal emitter*' (black body) under equal conditions. Its value ranges between 0 (= ideal reflector) and 100 (= ideal emitter).

Thermal emissivity is hereby equal to the absorptivity according to Kirchhoff's law of thermal radiation ($\alpha_{(\lambda,\ T)} = \varepsilon_{(\lambda,\ T)}$). Thus, if the absorptivity of a material is higher, the emissivity increases too. A change of the absorptivity can be reach by the surface texture (in wavelength scale) with the goal to decrease the reflectivity. Most non-metals have an emissivity values near 0.9 while polished metals achieve 0.05 to 0.1 (Flir, 2019). Particular paints, electrical tapes and coatings reach 0.9 to 0.95, according to Flir (2019), and hereby the colour does not decide the infrared emissivity but the flatness of the paint.

Thermochromic material

Another approach to influence the thermal emissivity of surface are thermochromic paints or polymers. These are materials with chemical substances that adapt the colour in dependency of temperature (Fig. 7.15). The chemical process is called thermochromism and applied in many products, ranging from medical devices, household goods to toys.

The process is reversible and makes it attractive to consider for this model. However, the change cannot be intentionally controlled.

A B

FIG. 7.15 Example for thermochromic paints applied on walls: 'Thermochromic Wall'.
The thermochromic paint artwork on a wall in London won the competition of 'wall of clash' in 2014. Troels Flensted and Rafael El Baz "*proposed a wall of coloured drips that change colour throughout the day*" (Flensted, 2013) by using thermochromic paint (Image by Flensted, 2013).

7.4.2 Design variants and best-case combination for FM2

The design variants collected for the generation of functional model 2 focuses on adaptation principles around thermal emissivity, either via geometrical or material attributes. Table 7.2 shows several design variations on material, surface and system level, which are again derivations from the principle(s) found in biological concept 2 and other role models supporting the intention.

The basic idea for the design is to adjust surfaces to each in a certain angle that allow a change in the thermal emission of heat. To enable such emission, the two (or more) surfaces must provide different surface temperature (emissivities) to be able to edissipate heat. The change to adapt the surfaces is of kinetic nature. An kinetic adaptation mechanism can be initiated by extrinsic mechanical force or (traditional shading systems) or intrinsic kinetic attributes (adaptation form-adaptive materials initiated by heat or moisture). The change of intrinsic actuators may be initiated by form-bending materials and material properties that change their absorptivity. The thermal emission effectivity can be supported by thermo-adaptive materials.

A specific option that supports the functionality of the biological concept but is not linked directly to the design is a heat exchange system. This delivers the heat from inside to the surface for the dissipation. All design variants are arranged according to their change attributes on material level (design variants #1 to #3), on surface level (design variants #4 to 6) and on system level (design variants #7 to #9).

TABLE 7.2 Design variants for functional model 2.
The design options displays various designs for the functional purpose "thermal emission".

Change on material level

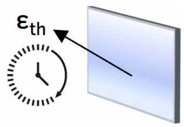
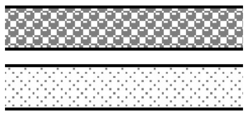
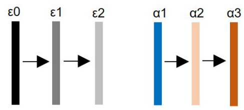
Design variants	#1	#2	#3
role models	#01, #02, #04, #06, #07, #23, #24	#25, #26, #30, #31	#57, #56
Design variant name	thermal emissivity of surfaces	passive change of material absorptivity	active change of material absorptivity
V-02 Physical process	.1_ radiation	.1: radiation, .2: conduction	1: radiation
Working principle	change of thermal emissivity by temperatures	change of absorptivity of material by particles	change of thermal emissivity and absorptivity by films, coatings, pigments
Physical design			
III-08 Adaptation impact	physiological change	physiological change	physiological change
IV-01 Level of embedment	.1: material	.1: material	.1: material
IV-02 Type of physical impact	none	none	none
IV-03.2: Physical characteristics of material			
IV-04 Functional scale	.1: nano, 2.: micro	.1: nano, .2: micro	.1: nano, .2: micro
IV-05 Visibility	no visible, no spatial change	maybe visible, no spatial change	visible, no spatial change
IV-07 Scalability	medium (depends on material)	medium (depends on particles)	high (depends on material)
Adaptation mechanism			
ii-06 Operation carrier	radiation, thermal reaction	radiation, thermal reaction, chemical reaction	radiation, thermal reaction, chemical reaction
III-01 Task to perform	.14: change of physical attributes	.13: change of physical attributes (pigments)	.13: change of physical attributes
III-02 Actuator type	.2: chemical, .1: thermal	. 2: chemical	.2: chemical
III-03 Response time	sec-min	ssec - min	sec - min
III-04 Response type	static	static	static
III-05 Response degree	gradual	gradual	gradual
III-06 Adaptation reliability	reversible	reversible (depends on pigments and material)	reversible (depends on material)
III-07 Adaptation dependency	dependent of location (teperature differences)	independent of location	dependent of location (sun path, temperature)
applied example	coatings, layers, films, any surface material	pigmental matter (black to white)	thermo-adaptive materials (e.g. paints)

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TABLE 7.2 Design variants for functional model 2.
The design options displays various designs for the functional purpose "thermal emission".

Change on surface level

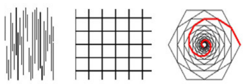
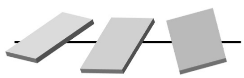
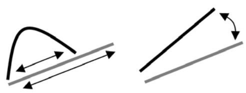
Design variants	#4	#5	#6
role models	#53, #59	#71	#64, #65
Design variant name	adaptive surface structure	linear surface areas	kinetic change of components/surfaces
V-02 Physical process	.5: other (geometric)	.1: radiation	-
Working principle	surface patterns allow growth	change of surface area along a direction (linear)	position change of any kind of component
Physical design			
III-08 Adaptation impact	morphological change	morphological change	morphological change
IV-01 Level of embedment	.1: material, .2: component	.2: component	.3: system
IV-02 Type of physical impact	size change in length, width or area	adjustment of surface area (positioning)	adjustment of positions
IV-03.2: Physical characteristics of material			
IV-04 Functional scale	.1: nano, .2: micro, .3: macro	.3: macro	.3: macro
IV-05 Visibility	visible, spatial change (one direction)	visible, spatial change	visible, spatial change
IV-07 Scalability	depends on geometry	high (depends on system)	high (depends on system)
Adaptation mechanism			
II-06 Operation carrier	mechanical force, thermal reaction, maybe chemical reaction	radiation, thermal reaction, kinetic force	kinetic force
III-01 Task to perform	.1: fold, .2: shift, .4/.5: stretch/contract, .10: bend, .11: tilt	.11: tilt	.10: bend, .11: tilt, .8: roll up
III-02 Actuator type	.1: thermal, .3: mechanical, .6: electromagnetic, .8: pneumatic	3: mechanical, 7: hydraulic, 8. pneumatic, .1: thermal	.3: mechanical, 7: hydraulic, 8. pneumatic, .1: thermal, .2: chemical
III-03 Response time	sec - min	sec - min (depends on mechanism)	sec -min
III-04 Response type	dynamic	dynamic	dynamic
III-05 Response degree	gradual	gradual	gradual
III-06 Adaptation reliability	reversible	reversible	reversible
III-07 Adaptation dependency	independent of location	dependent of location (sun path)	(in)dependent of location (depends on mechanism)
applied example	self-folding materials, folded shading systems	2D sun shades (linear lamella systems)	form-adaptive materials, kinetic systems

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TABLE 7.2 Design variants for functional model 2.
The design options displays various designs for the functional purpose "thermal emission".

Change on sytem level

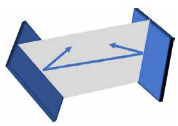
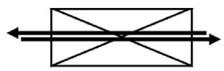
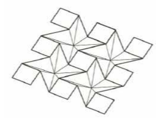
Design variants	#7	#8	#9
role models	#23 (motion of animals)	#48, #50, #51, #52	#59, #62
Design variant name	adjustment of surface areas to each other	change by heat transport (heat exchanger)	kinetic change by 3d folded origami
V-02 Physical process	.1: radiation	.2: conduction (.3: convection)	-
Working principle	change of geometric settings with environment	change of temperature in a certain region	change of form by stretching/wrapping, etc
Physical design			
III-08 Adaptation impact	hybrid change	physiological change	morphological change
IV-01 Level of embedment	2: component, .3: system	2: component, 3. system	.3: system
IV-02 Type of physical impact	adjustment of surface area (positioning)	none	adjustment of positions
IV-03.1: Physical characteristics of structure			
IV-04 Functional scale.	.2: micro, .3: macro	.3: macro	micro, macro (nano)
IV-05 Visibility	visible, spatial change (all directions)	not visible, no spatial change	visible, spatial change
IV-07 Scalability	high	medium (depends on fluid / gas, dimension ducts)	medium (depends on design)
Adaptation mechanism			
II-06 Operation carrier	radiation, thermal reaction	fluid, gas, thermal reaction	kinetic force
III-01 Task to perform	.11: tilt	.13: change of physical attributes (flow attributes)	.1: fold, .6: expand, .10: bend
III-02 Actuator type	.3: mechanical, 7: hydraulic, 8. pneumatic, .1: thermal	.1: thermal, .7: hydraulic	.3: mechanical, 7: hydraulic, 8. pneumatic, .1: thermal
III-03 Response time	sec - min (depends on mechanism)	min (depends on flow speed)	sec - min (depends on mechanism)
III-04 Response type	dynamic	static (hybrid)	dynamic
III-05 Response degree	gradual	gradual	gradual
III-06 Adaptation reliability	reversible	reversible	reversible (depends on material)
III-07 Adaptation dependency	depending of location (surrounding surfaces)	independent of location	indepentent of location
applied example	unknown	heat exchange system (building services)	3D shading systems

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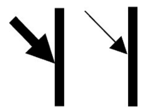
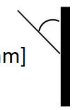
TABLE 7.2 Design variants for functional model 2.
The design options displays various designs for the functional purpose "thermal emission".

	Design impact / conditions	#A	#B	#C
Input / Output factors	**change goal**	**change of surface temperature**	**change of incident radiation**	-
	working principle	radiative energy of surfaces	defined angle dependency and wavelength	-
	visual scheme			-
	V-02 Process Type	change of electromagnetic impact	change of conditions for electromagnetic impact	-
	applied example	sun intensity (energy, short-wave), surface emissivity (sky)	sun ray attributes on wavelength scale	-

Legend	initial design combination
	applied adaptation mechanisms
	applied patterns
	added for FM 2.1
	added for FM 2.2

Best-case combination

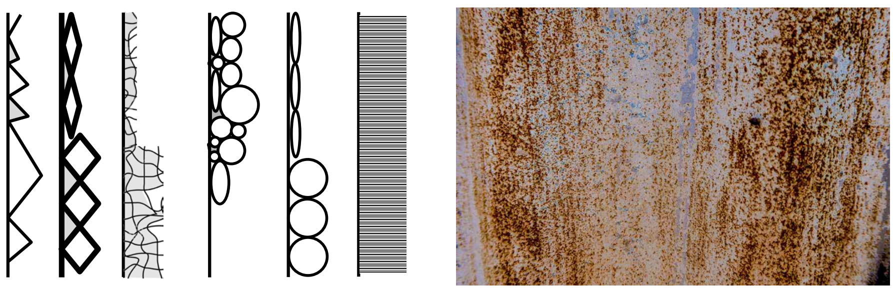
The coloured legend of table 7.2 shows the chosen design variants for the generation of the functional models. The initial design consists of the design variants #1 and #7, supported by the pattern #4. Further, two models are developed: for FM2.1 '*mono-directional thermal emission*', design variant #5 is added, and for FM1.2 '*multi-directional thermal emission*', design variant #9 is added. The adaptation mechanism for both models is either extrinsic and uses design variant #6 or intrinsic and uses design variant #2 and #3. Design variant #6 could also be intrinsic if combined with #2 or #3. Design variant #8 is a special approch dedicated to the heat transport and thus an additional option.

The best case combinations FM2.1 and FM2.2 focus on the optimization of thermal emission by considering the view factor. Additionally, the material's emissivity and system's kinetic adjustments must be designed for the specific location. The framework conditions of the environment (e.g. the radiative window of the sky and/or the surrounding surfaces) is critical for this effect to work and limits its efficiency.

7.4.3 Physical designs

The design variants that form the basis for both functional model FM2 are the thermal emissivity (design variant #1) and the surface adjustments to increase the emissivity of the surface (design variant #7).

The first design variant, thermal emissivity, applies equally to all functional model options, as it is a matter of material optimisation: thermal emissivity of a surface depends on its texture and the thermal material attributes. As already mentioned in the discussion about the intended functionality (Section 7.4.1), thermal emission can be improved by rough surfaces or by increasing the absorption capacity of the material. High emissive material (metals, coatings, paints) is available on the market and even used in the building sector, such as e.g. cool roofs (metal). High tech solutions, however, are more likely to be found at engineering devices (sensors, imaging devices, semiconductors, automotive parts or specific parts in the space industry). The choice of the right material depends in the end on the constructive requirements as building material and its costs. High-tech solutions, such as the heat shield of spacecrafts, which has a high-emissivity coating, are less likely to be applicable than high emissivity paints. New building materials that apply specific surface textures (as shown schematically in Fig. 7.16, A) would have to be developed, but there are many existing materials that can be even used as upcycled parts, such as oxidized metals (Fig. 7.16, B). Thermochromic materials, as already mentioned, would be another option that even allow adaptivity on material level.



A B

FIG. 7.16 Surface characteristics that influence the thermal emission.
A: Various textures of rough surfaces on nanoscale that support the thermal emission.
B: Oxidized metallic surfaces possess a higher thermal emissivity due to their rough surface (e.g. oxidized steel approx. 0.8 - 0.9).

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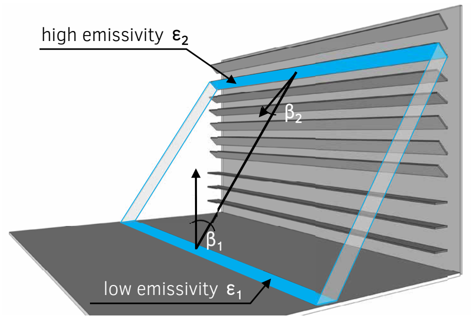
Nature offers also some interesting wavelength-related material solutions that absorb and emit heat energy in a certain range. The leaves of the biological role model #04 'Selaginella fern', for example, change the colour depending on the sunlight intensities. This is caused by thin-film interferences on the leaf' surface.

For the second design variant, two models are created.

Functional model FM2.1 'mono-directional thermal emission'

The first design idea results in the functional model FM2.1 '*mono-directional thermal emission*' for which only a new function to standardized shading slats is added. Three design criteria are applied: first, a specific coating or material must be added on the backside of the slats in order to increase the thermal emission. Second, the position of the units (slats) must be arranged to certain angles at certain times (nighttime) to increase heat dissipation effect (cf. Fig. 7.17, A).



A

B

FIG. 7.17 Sketch of functional model FM2.1 'mono-directional thermal emission'.
A: The principle shows an additional functionality to existing structures: by applying high emissivity coatings to linear shading systems and considering the positioning of the slats, the thermal emissivity could be intentionally used to dissipate heat.
B: To make heat dissipation effective, heat must be transported from inside to the surface. A possible solution may be fluid-transporting pipes, i.e. systems comparable to solar collectors. An example for façade-integrated pipe system is provided by the Solstice Point building in London, which is designed by Nick Baker Architects (Image courtesy by Nick Baker Architects).

And third, which is also a critical part for efficiency of the function, the heat must be delivered from inside to the surface. This could be done by e.g. heat exchanger or pipes integrated in the shading element. A possible application that would fit to this purpose although it has been developed for a different one (gaining solar) are the 'solar thermal venetian blinds' developed as a prototype by Fraunhofer ISE and Priedemann Façade Lab (Haeringer et al., 2020). To integrate solar collectors in façades is not new, and has been employed in building projects, as e.g. in the Solistice Point building in London (Fig. 7.17, B) shows or developed concepts by companies, such as Frener & Reifer (2010), provide.

The model FM2.1 has a rather low intervention level (when the heat transport system is neglected) and could be applied in short term. However, the disadvantage of the FM2.1 concept is the linearity. The adjustment of the slats is limited. The slats only allow the surfaces to adjust around one axis and thus restrict the effectiveness in regards to the view factor (Fig. 7.18). If the system cannot be adjusted to opposite surface following the principle of the view factor, the concept does not work. A more flexible arrangement of the surfaces would therefore be advantageous.

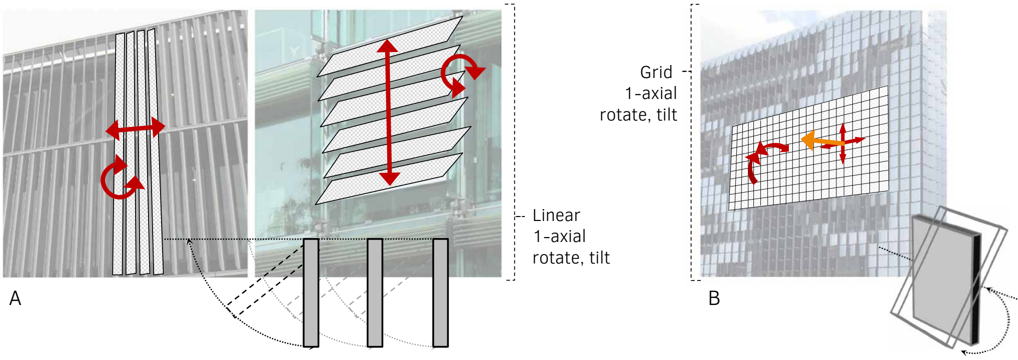


FIG. 7.18 Rotation direction of linear systems.
The examples show linear rotating systems which allow adjustments only around one axis (graphics adapted from Gosztonyi, 2018).

Polygonal (shading) structures are arranged in a wide variety of surface geometries and orientations, as shown already in Chapter 3. For the purpose of heat dissipation, these geometries may better meet the required criteria for the view factor. This leads to the model development of FM2.2.

The function-related criteria for this model, the thermal emissivity of the slat material, the needed temperature difference to other external surfaces and the heat exchange system are discussed in Section 'Adaptation mechanism' of FM2.

TOC

Functional model FM2.2 'multi-directional thermal emission'

There are two options for the realization of FM2.2: it could be either designed as a fixed structure, such as the ArboSkin of the University of Stuttgart (2013) or as a movable solar shading structure, comparable to the three-dimensional solar shading solutions (cf. Al Bahr Towers, Fig. 3.1, A). Both apply design variant #9.

The idea is to generate an origami-like, three-dimensional structure that allows various types of surface exposures and multiple angles of inclination. The shape of the surface areas may be of any polygonal type, from triangular to square-shaped units. Geometric examples based on mathematical modelling are e.g. polygonal tessellations, such as those designed by Ron Resch (Tachi, 2013) (Chandra et al., 2015) (Magliozzi et al., 2017).

Figure 7.19 shows how such structures could work for polygonal tesselations (A) or simple triangular patterns (B): the outward-facing surfaces (orange) are highly reflective and have the task of reducing the solar heat input by reflection. At night, the three-dimensional folded shape opens up and exposes highly emissive surfaces (blue). The surfaces would have to be at a certain angle to each other and to the surroundings in order to increase the thermal emission. Such polygonal tessellation patterns increase the design complexity, but allow a large area in a confined volume.

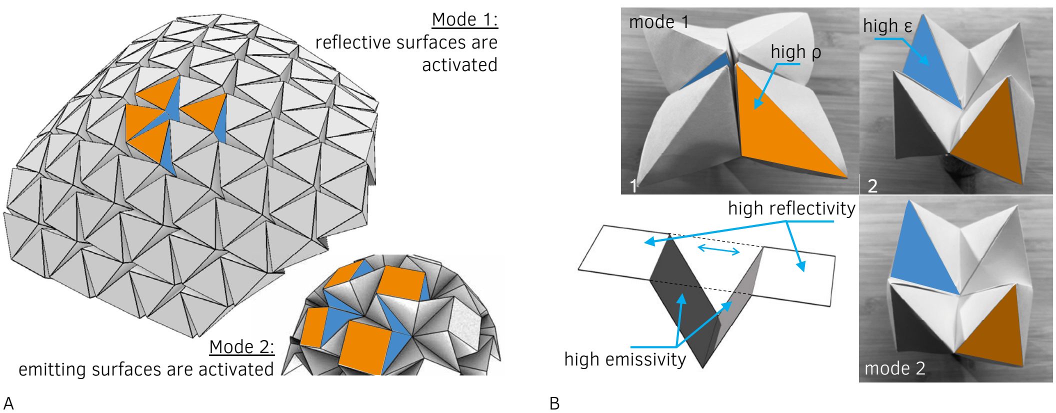


FIG. 7.19 Sketch of functional model FM2.2 'multi-directional thermal emission'.
A: The polygonal tesselation form adapts its 3D structure multi-directionally to expose either more reflective surfaces (marked as orange) or emissive surfaces (marked as blue) (Graphs are adapted from Tachi (2006) and Davidson (2014).
B: In the more simple triangular pattern, the motion of the surfaces is restricted to certain directions.

There are considerable constraints for this model: the distance between the surfaces within the model, the cutting angle in regards to the view factor, and self-shading effects of the system. Further, the interplay between emitting and reflecting surfaces is also rather complex, because it is bound to a certain period of time: the orange fields are exposed during daytime and reflect solar radiation, and the blue fields are active during nighttime when heat dissipation is required. The geometry and material attributes are not (ex)changeable, unless the material properties are switchable.

The application potential of the model can therefore only be assessed after a numerical analysis of the thermal effects in context with the external influencing factors. Therefore, the geometry should be developed by a parametric digital design process. By applying generic algorithms, the geometry and material properties can be automatically optimized depending on the influencing factors. Thus, Figure 7.19 serves only as a illustration of the idea.

Such digital design developments could generate various geometric configurations, whether it is a traditional solar shading geometry whose orientation is to be 'tuned' towards the view factor, or it is an origami structure that allows adjustments of the exposed surfaces in all directions. Interesting biological role models for optimized surface exposure are diverse and extensive in the plant and animal kingdoms.

7.4.4 Adaptation mechanisms

The adaptation mechanism for both functional models FM2.1 '*mono-directional thermal emission*' and FM2.2 '*multi-directional thermal emission*' shall support the thermal emission by adjusting the exposed surfaces.

In order to make heat dissipation controllable, three aspects must be considered: 1) temperature control of the surfaces to achieve the needed temperature difference between radiating surfaces, 2) multi-directional adjustability of the emitting surface to allow effective positioning towards surrounding surfaces for the thermal emission process, and 3) a transport system to transport heat from inside to outer surfaces.

For the first aspect, surface temperature differences may be passively created by e.g. surface properties that possess different thermal absorption capacities as already mentioned or by embedded heat exchangers or phase change materials that actively change the surface temperature.

The second aspect implies a kinetic actuation system for the surfaces. Their directional rotation plays a major role for a flexible use of the model. While linear lamellar systems (cf. Figure 7.18) can only be adjusted via one rotary axis, more complex systems that allow three-dimensional rotary motions also allow a more flexible adjustment with regard to the thermal emission positions. The actuators could be either deployable tensegrity structures or hyrdaulic connetors (Fig. 7.20, A). Or a shape-adaptive layer, which is embedded in the main structure and swells/ shrink, may be another option to adapt the form (Fig. 7.20, B).

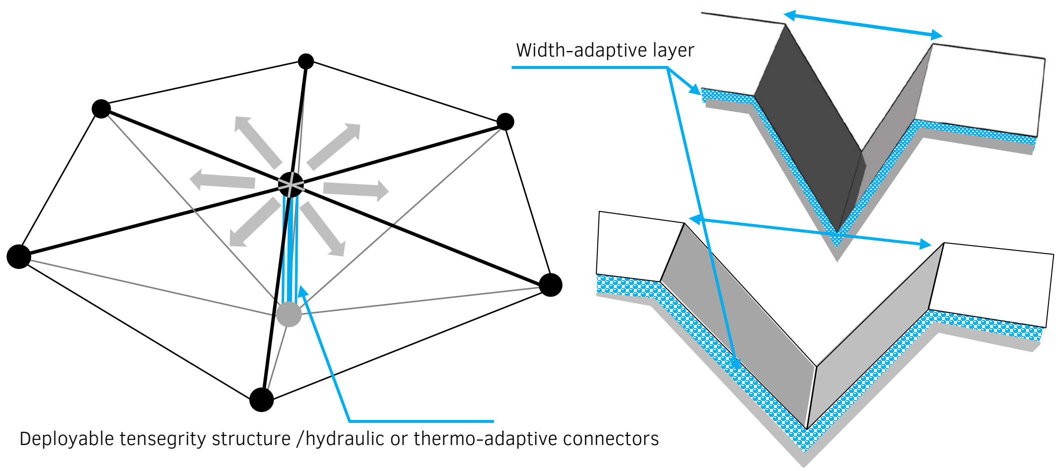


FIG. 7.20 Sketches of the adaptation mechanisms of FM2.
Two options for the adaptation mechanisms are suggested: A) Deployable tensegrity structure with thermo-adaptive material in the horizontal connectors or a hydraulic main connector (blue) or
B) Elastic, width-adaptive layer between the stiffer lower layer mimcking the osmosis process of the Mimosa pudica plant (role model #68 in Appendix 5-1). The elastic layer shrinks/swells and adapts the angle due to pressure on the stiffer layer.

The kinetic actuation may be achieved either by extrinsic mechanisms (kinetic, hydraulic or pneumatic activators) as it is already applied in shading systems, or by intrinsic mechanism (form-adaptive materials) as it is tested in many prototypes. The disadvantage of the second actuation system is its uncontrollability as the reaction effect and time depends on the material and environmental circumstances.

Both actuator principles may also be applied for functional model 1, but their functional goal differs: while the goal for FM1 is to expand or shrink the entire volume and a specific change in direction is not important, an exactly adjustable geometry counts for FM2. This becomes particularly interesting for the multi-directional design of FM2.2. Its motion behaves, according to the origami technique, like a rotary movement. The actuators would either have to pull somewhere at the system or a substructure presses from below against specific pattern points and thus activates the rotary motion.

The principles for heat transport from internal regions to the surface are not investigated because thermal transport mechanisms were not selected for the analyses. It can be anticipated that embedded counter-current systems or phase change material could offer potentials for this. But also systems that mimic vascular contradictions (cf. Appendix 5-1, role model #45, #51) may be interesting.

Two scenarios for adaptive physical designs are summarized below using the parametric classification and a similar description as for the biological concepts. This shall provide information useable for a parametric design tool:

- Extrinsic adaptation system for FM2.1: the system monitors the temperatures on the surface, outdoors, indoors at defined positions (I.01 – E02.1, E.02.3 and E02.4) and compares it to defined set temperatures of the same (I.01 – E02.1, E.02.3 and E02.4). The monitoring and control can be done by an extrinsic sensors (II.03.1) that record the temperature levels (I.04.2) to process the information electrically (I.05.4) by a subsystem. This information is then transported electrically (I.06.4) to launch a position changing reaction by kinetic (III.02.3) motion of the subsystem, which has a force change (II.06.8). This reaction is dynamically (III.04.1) and gradually (III.05.2). The structure tilt (III.01.11) or fold (III.01.1) in defined directions within seconds (III.03.1). The whole process is reversible (III.06.1) and is independent on local situation (III.06.5) if activated automatic (II.05.2) or manual (II.05.1). Its adaptation causes a morphological form change (III.07.1). The physical system changes spatially and visible (IV.05.4) on system level (IV.01.3) that impacts the position of the elements (IV.02.1). The physical properties of the surface material characteristics (IV.03.1) are causing the heat dissipation. This works on micro (IV.04.2) or macro scale (IV.04.3). The system configuration is highly scalable (IV.07.3) as long as the exposure areas and view fields are calculated.

- Extrinsic adaptation system for FM2.2 (with thermo-adaptive material): the system monitors the temperatures on the surface, outdoors, indoors at defined positions (I.01 – E02.1, E.02.3 and E02.4) and compares it to defined set temperatures of the same (I.01 – E02.1, E.02.3 and E02.4). The monitoring and control can be done by the intrinsic (II.03.2) property of thermo-adaptive materials that are embedded directly in the shape. The material records the temperature (I.04.2) and processes (I.05.1) the information thermally (I.06.1) within the structure to launch a physical reaction (III.02.3) by the kinetic characteristics (II.06.8). This reaction is dynamically (III.04.1) and gradually (III.05.2). The shape expands (III.01.6) and shrinks (III.01.7) in the needed direction within minutes (III.03.2). The whole process is reversible (III.06.1) and is dependent on local conditions (III.06.4) if self-reactive (II.05.3). Its adaptation causes a morphological form change (III.07.1). The physical system changes spatially and visible (IV.05.4) on system level (IV.01.3) that impacts the surface area (IV.02.2.2). The physical properties of the surface material characteristics (IV.03.1) are causing the heat dissipation. This works on micro (IV.04.2) or macro scale (IV.04.3). The system configuration is medium scalable (IV.07.2) according to the deformability of the thermo-adaptive material and the required view fields of of the exposed areas.

The features of the adaptation mechanism for the two functional models FM2.1 and FM 2.2 are described by using the parametric classification list in order to prepare a system for later virtual prototyping (cf. Appendix 7-2).

7.5 Evaluation of functional models

In order to make a statement about the particularities of the generated functional models, wo evaluation circles are conducted. First, the similarities and differences of the functional models to established adaptive façades are considered. For this purpose, suitable cases of Chapter 3 are compared to the functional models by rating some adaptation criteria (cf. Checklist, column 'E1', Appendix 4-1). For the analysis the same rating method as for Chapter 2 and 3 is applied. Secondly, an assessment of the design effectivity is applied. For this, the functional models are placed into the visualization of Figure 3.16 in Chapter 3 (=use case evaluation). By both steps, the applicability of the models for the design process shall be assessed qualitatively. A quantitative analyses must be based on detailed models which goes beyond the conceptual early design stage. It would be recommended for future work.

7.5.1 Comparison of functional feasibility

For the evaluation of the functional similarities and differences, studied cases of chapter 3 are compared to the two functional models. The chosen cases, as shown in Table 7.3, represent examples of the selected search scope of chapter 3, which seeks potentials for the design measure '*P01: Thermal insulation*' and '*P08.1 and .2: Passive cooling at surfaces and radiative effects*'. They are chosen on three considerations (cf. Table 7.3, column "type"): adaptative functionality of the solution ('function'), structural approaches for an adaptive behaviour ('structure') and actuator approaches ('actuator').

The relevant parameters to compare the functional models to the selected cases are the same as used for the creation of the models, complemented by "monitoring" (I) targeting at "input/output derivation" (I-03) and following criteria:

- "Control settings" (II) targeting at the sub-class "operation carrier" (II-06), and adding the sub-classes "control type" (II-03) and operation type (II-05).
- "Actuation settings" (III) including the sub-classes "task to perform", "actuator type", "response time/type/degree", "adaptation reliability/dependency/impact" (III-01 to III-08).
- and "Physical appearance" (IV) including the sub-classes "level of embedment", "type of physical impact", "physical characteristics", "functional scale", "visibility" and "scalability" (IV-01 to IV-05, IV-07).

TABLE 7.3 Assignments of the functional models to selected cases.
The column 'type' is taken as common basis for the comparison.

FM	Type		Compared Case #	Sources
FM1	**Function**	kinetic motion	Case #04: Adaptive thermal insulation system, e.g. Thermocollect lamella system	*Schwarzmayer, 2013*
		pneumatic motion	Case #08: Pneumatic membranes for thermal regulation, e.g. Media-Tic Building building skin	*COST FS_12*
	Structure	3D structure	Case #15: Honeycomb structures as thermal insulation, e.g. gap:skin paneels	*Gap solutions, 2017*
FM1, FM2	**Actuator**	SMA	Case #09: Self-responsive SMA in building skin, e.g. Bloom pavillon	*COST M-05*
		SMA	Case #10: Self-adaptive kinetic materials, e.g. Nitinol adaptation concept	*COST M_02*

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TABLE 7.3 Assignments of the functional models to selected cases.
The column 'type' is taken as common basis for the comparison.

FM	Type		Compared Case #	Sources
FM2	**Function**	radiative properties	Case #26: photonic radiator on roof, e.g. analyzed roof-mounted concepts	*Wang et al, Al Obaidi et al, 2014*
		radiative properties	Case #27: Radiant paintings and coatings, e.g. review of ultra-white, emissive surfaces	*Santamouris and Feng, 2018*
	Structure	fold, tilt, 2D	Case #02: Moveable horizontal shadings, 2-dim, e.g. Shading system of Nordic Embassy, Berlin	*COST FS_11*
		fold, tilt, 3D	Case #03: Moveable horizontal shadings, 3-dim, e.g. , zB Al Bahar Towers, AE	*COST FS_40*
		fold, tilt, 3D	Case #11: threedimensional shapes for kinetic motion, e.g. Kumorigami	*COST CS_03*
	Actuator	mechanic	Case #05: Adaptive thermal insulation system, e.g. Daytime radiative cooler Skytherm (Yellot, 1983)	*Raeissi and Taheri, 2000*
		tracing	Case #21: Solar active BIPV, e.g. tracing PV shields of ETHZ (Adaptive Solar Façade)	*Nagy et al, 2016*

Results

According to the comparison of Table 7.4, most of the cases monitor the solar irradiation (few monitor the local air temperature), while the functional models monitor the surface temperatures and local air temperature within or close to the system. Thus, most of the cases target at the macro level (solar radiation), while the functional models target at the micro-level (local temperature environment).

The actuation is equally divided between intrinsic and extrinsic in the cases and functional models. Most of the market-ready cases apply automated operation while the conceptual developments consider self-reactive behaviour. The functional models divide the operation equally, thus provide either self-reaction or automation.

The functional models do favour volume changing adaptation of the structure by expansion/contraction or by extension/shrinking. This is rarely observed in the cases, with exception of the SMA concepts. The structural impact at the cases is mainly a position change (e.g. folding or tilting of the shading components) while for the functional models it is also a volume, area or length change. The same approach as for the SMA cases. All adaptations in the functional model are visible and spatial, while a third of the cases provide physiological changes and thus no spatial adaptation. The scalability of the functional models is high to medium, which equals for the cases.

TABLE 7.4 Comparison results of the functional models with the selected cases.
The 'x' indicates approved information (mentioned in the publications) and the 'o' indicates assumptions on basis of the information.

Evaluation of models / Comparison with use cases		P01: Adaptive thermal insulation						
		Functional models		Cases of adaptive façades (Chpt 3)				
				functionality		struct.	actuator	
		FM1		Case				
		1.1	1.2	#04	#08	#15	#09	#10
I. Monitoring								
I.03 Input/Output factors	I.03.1 Balance deviation of air temperature	x	x		o			
	I.03.2 Differences of surface radiation/temperature	x	x	o		o	o	o
	I.03.3 Solar radiation intensities			x	o			
II. Control settings								
II.03 Control type	II.03.1 extrinsic	x	x	x	x			
	II.03.2 intrinsic	x	x			x	x	x
	II.03.3 both							
II.05 Operation type	II.05.1 manual			o				
	II.05.2 automatic (BMS)	x	x	o	o			
	II.05.3 self.reactive	x	x			o	o	o
II.06 Operation carrier	II.06.1 gas		x			o		
	II.06.2 fluid							
	II.06.5 radiation							
	II.06.6 matter, thermal	x	x	o	o	o	o	o
	II.06.8 matter, force	x			o			
III. Actuation settings								
III.01 Task to perform	III.01.1 fold						o	o
	III.01.4 stretch	x						
	III.01.5 contract	x						
	III.01.6 expand		x		o			o
	III.01.7 shrink		x		o			o
	III.01.11 tilt			o			o	
	III.01.14 change of physical attributes						o	o
	III.01.15 none, indirect adaptive					o		
III.02 Actuator type	III.02.1 thermal	x	x					
	III.02.2 chemical					x		x
	III.02.3 mechanical, kinetic	x		x	x		x	x
	III.02.4 electric			x				
	III.02.6 electromagnetic							
	III.02.7 hydraulic							
	III.02.8 pneumatic		x		x			

	P08: Passive radiative cooling									Criteria frequency applied by	
	Functional models		Cases of adaptive façades (Chpt 3)							Cases	FMs
			functionality		structure			actuator			
	FM2		Case								
	2.1	2.2	#26	#27	#02	#03	#11	#05	#21		
	x	x								8%	50%
							o	o		50%	100%
			o	o	o	o	o		o	67%	0%
	x	x			x	x	x			42%	100%
	x	x		x						33%	100%
			x					x	x	25%	0%
					o	o	o			33%	0%
	x	x	o		o	o	o	o	o	67%	100%
	x	x	o	o			o	o	o	67%	100%
										8%	25%
			o					o		17%	0%
				o					o	17%	0%
	x	x					o	o		58%	100%
	x	x			o	o	o			33%	75%
		x			o	o	o			42%	25%
										0%	25%
										0%	25%
										17%	25%
										17%	25%
	x				o	o	o		o	50%	25%
			o					o		33%	0%
				o						17%	0%
	x	x								0%	100%
							x	x	x	42%	0%
	x	x			x	x	x		x	67%	75%
					x	x				25%	0%
			x	x						17%	0%
		x	x							8%	25%
		x								8%	50%

>>>

TABLE 7.4 Comparison results of the functional models with the selected cases.
The 'x' indicates approved information (mentioned in the publications) and the 'o' indicates assumptions on basis of the information.

Evaluation of models / Comparison with use cases		P01: Adaptive thermal insulation						
		Functional models		Cases of adaptive façades (Chpt 3)				
				functionality		struct.	actuator	
		FM1		Case				
		1.1	1.2	#04	#08	#15	#09	#10
III. Actuation settings								
III.03 Response time	III.03.1 sec	x	x				o	o
	III.03.2 min	x	x	o	o	o	o	o
	III.03.6 none							
III.04 Response type	III.04.1 dynamic	x	x	o	o		o	o
	III.04.2 static					o		
III.05 Response degree	III.05.1 on/off							
	III.05.2 gradual	x	x	o	o	o	o	o
III.06 Adaptation reliability	III.06.1 reversible	x	x	x	x	x	x	x
III.07 Adaptation dependency	III.07.1 dependent on local conditions to function		x			x	x	
	III.07.2 independent on local conditions to function		x	x				
	III.07.3 both (partly dependent, partly independent)				x			x
III.08 Adapt. impact	III.08.1 morphological change	x	x	o	o		o	o
	III.08.2 physiological change		x			o		
IV. Physical appearance								
IV.01 Level of embedment	IV.01.1 material	x	x			x		x
	IV.01.2 component			x	x			
	IV.01.3 system	x	x				x	
IV.02 Structural impact	IV.02.1 positioning			o			o	o
	IV.02.2.2 size information: surface area				o			
	IV.02.2.3 size information: length	x						
	IV.02.2.4 size information: volume		x		o			
IV.03 Physical impact	IV.03.1 physical characteristics of structure	x	x	o	o	o	o	o
	IV.03.2 physical characteristics of material	x	x		o		o	o
IV.04 Functional scale	IV.04.2 micro (nm,mm)	x	x		o		o	o
	IV.04.3 macro (cm, dm, m)	x	x	o	o	o	o	o
IV.05 Visibility	IV.05.2 not visible, change on other level		x			x		
	IV.05.4 visible, spatial change	x	x	x	x		x	x
IV.07 Scalability	IV.07.2 scalability of function (unit, element) low						x	x
	IV.07.2 scalability of function (unit, element) medium	x	x	x	x	x		
	IV.07.3 scalability of function (unit, element) high							

	P08: Passive radiative cooling									Criteria frequency applied by	
	Functional models		Cases of adaptive façades (Chpt 3)							Cases	FMs
			functionality		structure			actuator			
	FM2		Case								
	2.1	2.2	#26	#27	#02	#03	#11	#05	#21		
	x	x		o	o	o	o		o	58%	100%
	x	x	o		o	o	o	o	o	92%	100%
										0%	0%
	x	x			o	o	o		o	67%	100%
			o	o				o		33%	0%
				o						8%	0%
	x	x	o		o	o	o	o	o	92%	100%
	x	x	x	x	x	x	x	x	x	100%	100%
	x	x	x	x					x	42%	75%
					x	x		x		33%	25%
							x			25%	0%
	x	x			o	o	o		o	67%	100%
	x	x	o	o				o		33%	75%
	x	x		x						25%	100%
	x	x	x		x	x	x			50%	50%
	x	x						x	x	25%	100%
	x	x			o	o	o		o	58%	50%
		x					o			17%	25%
										0%	25%
										8%	25%
		x			o	o	o		o	75%	75%
	x	x	o	o			o	o	o	67%	100%
	x	x	o	o			o	o	o	67%	100%
	x	x			o	o	o	o	o	83%	100%
			x	x				x		33%	25%
	x	x			x	x	x		x	67%	100%
							x			25%	0%
		x	x					x		42%	75%
	x			x	x	x			x	33%	25%

Overall, it can be concluded that for the functional models, the monitoring and signal recording focus on local and surface temperature rather than overall air temperatures as applied in the cases. The controls are similar for the models and cases, with both using extrinsic and intrinsic control mechanism. The main difference hereby is the operation carrier that concentrates on material properties with adaptive behaviour at the functional models, while only ~50% of the cases uses this approach. This conclusion can also be made for the actuation: thermal actuation by material behaviour together with pneumatic actuation are the main solutions for the models, while the cases show rather diverse actuation mechanisms. Mechanical actuation applies for both, cases and models.

There is not much differences in the response settings and adaptation reliability: both, model and cases, react fast, dynamic within seconds or minutes and are reversible. The FM2 models, however, depend on the local conditions.

The physical design show mainly differences in the embedment of the adaptive functions, since the models employ material and system adaptability likewise, whereas the cases show much less material and system smartness, but focus on the component smartness.

7.5.2 Comparison of design effectivity

The criteria for the design effectivity have been defined in chapter 3. They were defined as evaluation criteria, because they are critical for a possible implemenation success of the solution – particularly in regards to the complexity in production or design. The aim is now to place the proposed functional models in the same visualization as the use cases in Chapter 3 (cf. Fig 3.16). The placement can only be assumed as the models have not been further developed and tested. However, this shall provide an orientation for the decision against or for a further developpkment of the models.

Following criteria are defined for the design effectivity assessment:

- design complexity (IV-09.1) ('*keep it simple*') refers to the wish to have 'time- and effort effective' solutions in production and maintenance,
- design flexibility (IV-06) and scalability (IV-07) refer to the intention of having a scalable but flexible product, which might be standardized in production but can be applied in any size and position, also allowing a flexible design,

- and robustness/maintenance (IV-08.2) refers to the functional robustness without having too much failure-prone complexity in design and operation. This again also contributes to the '*keep it simple*' wish.

Results

The functional model **FM1.1 '*hexagonal structure*'** appears to need much less maintenance and less complexity in the design process (once the structure is produced) than the use case **B: Kinetic modulation by material properties** to which it can be compared. Its design flexibility and scalability is limited to the capacity to adapt the width and use the effects of the still air cavity. However, the difference is rather small in comarison to the use case B. The adaptation mechanisms are not displayed in the design effectivity criteria, thus it depends largely on the mechanisms whether flexibility and scalability could be improved.

Functional model **FM1.2 '*closed-cell structure*'** is also compared to the use case **B: Kinetic modulation by material properties**. It appears to cause similar maintenance due to the more complex pneumatic mechanism and needed air tightness of the system. Its design complexity appears critical due to the air tightness and difficulty to evenly distribute the air pressure within the system. Thus, it is euqally comples as the use case B. The mechanism needed for th function to work properly probably demands a secondary subsystem – self-reactive actuation must be analysed in detail to assess its effectivity. The scalability and flexibility of the model seem to be a bit better than for functional model FM1.1 depending on the pneumatic material. It seems to be similar to the use case B.

The functional model **FM2.1 '*mono-directional thermal emission*'** can be compared with the use case **A: Kinetic (mechanical) systems**, since it builds on their system and adds material-related and actuation-related functions. This model follows the path of group A rather closely. So there is no big change in the design tasks but only in the choice of material and actuation settings.

And finally, functional model **FM2.2 '*multi-directional thermal emission*'** appears to be the most challenging design, as all criteria are set rather high in the scaling. It can be compared to use case **A: Kinetic (mechanical) systems** and to **B: Kinetic modulation by material properties.** The maintenance and complexity of the system is rather demanding, as it is for group B but less for group A. The design flexibility and scalability of the model seems to be much better than for use case B, but similar to use case A.

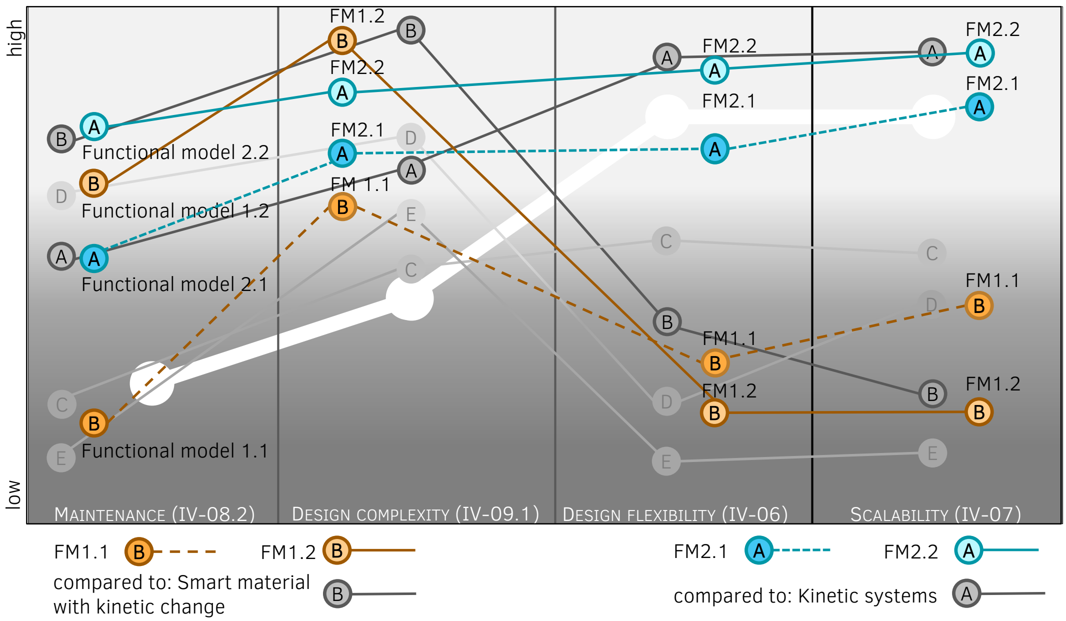

FIG. 7.21 Assignment of the functional models to four design effectivity criteria and compared to the use cases. The white line presents the target.
For the comparison, the visualization of Figure 3.16 in Chapter 3 is used. The grey lines and dots refer to the use cases, whereby only group A and B are compared to the functional models.

It can be assumed that the main advantages of the proposed functional models lies in the actuation effectivity and use of material and system settings to do so; they do not reduce the deisgn complexity and have limits in scale and flexibility. This also corresponds to the biological role models, which function under location-bound and scale-depending conditions. This means that embedded functionality cannot be detached from scale and local influences - at least not when the function is enabled by the physical design.

The comparison must be seen critical because the technical details of the functional models target have not yet been examinated to assess their efficiency.

7.6 Summary

The two functional model sets are testing objects for the systematics and thus are set up as rather schematic models with the goal to use mainly existing materials and known structures. The most difficult task hereby is the correct transfer of the principles to preserve the functionality of the biological concepts and supplemental role model principles. Smart material developments are originally excluded from the translation process, but applied in the functional models, such as e.g. the thermo-sensitive wires which could mimic muscle contraction and expansion. Table 7.3 provides a summary of the main features of the models and references to the biological role models. The parametric descriptions of the functional models sets for FM1 and FM2 are provided as tables in Appendix 7-1 and Appendix 7-2.

The comparison of the functional models with the selected cases highlights the main difference in the approaches: while the functional models mimic the biological role models, which respond to the local dependencies and microclimatic conditions, the cases are mainly detached from such conditions and can be controlled by external systems. This gives them great flexibility and security in the provision of the required indoor comfort and energy performance, but it also detaches them from the climate-sensitive design objectives. Climate-sensitive deisgn means to work with local resources in order to achieve a reduction in energy consumption. The challenge is to take into account the differences between the outdoor and indoor climate, which requires local dependency and acceptance of adjusted comofrt limits. Considering these objectives, the cases arguably perform less energy-efficiently than the models. However, it remains open at this point whether the modern comfort targets can be still maintained with such approach.

The main pelucarity of the functional models is the embedment of adaptive material properties in an adaptive system design; i.e. the interaction of material and system design. Adaptiveness becomes an intrinstic part of the design, but also becomes dependent on local conditions.

TABLE 7.5 Summary of the functional models focusing on functional purpose “thermal energy control” (F10.2)

Description	Functional principle	Biological principles (Chapter 6)
Functional model set 1: Heat regulation by adaptive thermal conductivity		
Functional purpose	F10.2: Thermal energy control (control of thermal conductivity)	Thermal conductivity change, air as thermal resistance
Structure	structure that allows variable thicknesses, change of size/volume and trapping of (still) air	3D structures with volume growth potentials (circular, polygonal forms) – 1 dim to 3 dim
Material	Light-weight material; form-adaptive material, deformations shall be allowed within a defined framing structure. The more flexible deformation are the better (filling the gaps). Expansion/contraction via elastic material	Cellulose, fibre materials, shrinking/stretching material, elastic material
Adaptation	Structure changes its thickness or size/volume = change of air cavities → pneumatic /air pressure intentionally (extrinsic) → Thermal / temperature change causes air expansion (intrinsic)	expansion/contraction of structures
Functional model set 2: Heat dissipation by adaptive surface emissivity		
Functional purpose	F10.4: Heat dissipation	Radiant emissivity, radiant absorptivity, surface area optimization
Structure	Structure that allows high emissivity and surface area adaptations by folding, extend, expanding/ shrinking or: substructure that initiates kinetic motion (traditional shading kinetics)	3D structures with surface area growth potentials (origami tessellations) – 3 dim
Material	high emissivity of the nocturnal surface emitters shall be reached by either structural emitters or pigmental / thin film emitter layers high reflectivity of other parts that are exposed during daytime	Layered, fibres, any material with option to modulate surface properties and adapt geometrically
Adaptation	Structure changes its positioning or surface area inclination → hydraulic, mechanic change of form/position (extrinsic) → form adaptive behaviour of SMA material, must be programmed (intrinsic)	folding, tilting fixed surfaces (shading system); expanding/shrinking, tilting surfaces

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Appendices

Appendix 7-1 Parameter list for functional model 1: Thermally adaptive insulation

Functional Model 1: Heat regulation by adaptive thermal conductivity

FM1-S1	FM1-S2	Category	Sub-class	Function description	
I. Monitoring					
●	●	**I.01 Set values**	E02.1 air temperature	degree of Te, Ti	
●	●		E02.4 local air temperature	degree of air within system	
●	●	**I.02 Actual values**	E02.1 air temperature	degree of Te, Ti	
●	●		E02.4 local air temperature	degree of air within system	
●	●	**I.03 Input/Output factors**	I.03.1 temperature disbalance	air temperatures: Te ≠ Ti	ΔT must be defined
				air temperature in system: $T_{structure} \neq T_{set}$	T_{set} must be defined
●	●	**I.04 Signal recording**	I.04.2 calorimetric	temperature recording	
	●		I.04.5 pressure	air pressure recording	
●		**I.05 Signal processing**	I.05.1 thermal	signal processing happens within material	
	●		I.05.4 electric	signal processing happens in a wire	
●		**I.06 Signal transport**	I.06.1 thermal	thermal transport within material	
	●		I.06.4 electric	electric transport within wire	
II. Control settings					
●	●	**II.01 Control task**	II.01.4 modulate, regulate	temperature differences in regions	
	●	**II.03 Control type**	II.03.1 extrinsic	external sensor	
●			II.03.2 intrinsic	material-inherent, thermo-sensitive property	
	●	**II.05 Operation type**	II.05.1 manual		
	●		II.05.2 automatic (BMS)		
●			II.05.3 self.reactive	Shape memory effect of thread	
	●	**II.06 Operation carrier**	II-06.1 gas	information is carried by air	
●			II-06.6 matter, thermal	information is carried within material property	

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Functional Model 1: Heat regulation by adaptive thermal conductivity

FM1-S1	FM1-S2	Category	Sub-class	Function description
III. Actuation settings				
•		III.01 Task to perform	III.01.4 stretch	length adaptation of materion (SMA) in one direction
•			III.01.5 contract	
	•		III.01.6 expand	area adaptation of material in all directions
	•		III.01.7 shrink	
•			III.02.3 mechanical, kinetic	
	•		III.02.8 pneumatic	
•		III.03 Response time	III.03.1 sec	
	•		III.03.2 min	
•	•	III.04 Response type	III.04.1 dynamic	
•	•	III.05 Response degree	III.05.2 gradual	
•	•	III.06 Adaptation reliability	III.06.1 reversible	
•			III.06.4 dependent on local conditions to function	
	•		III.06.5 independent on local conditions to function	
•	•	III.07 Adaptation impact	III.07.1 morphological change	
IV. Physical appearance				
•	•	IV.01 Level of embedment	IV.01.3 system	
•		IV.02 Structural impact	IV.02.2.3 size information: length	
	•		IV.02.2.4 size information: volume	
•		IV.03 Physical impact	IV.03.1 physical characteristics of structure	adaptive part stays fix but configuration changeable
	•		IV.03.2 physical characteristics of material	adaptive part must be elastic
•	•	IV.04 Functional scale	IV.04.3 macro (cm, dm, m)	
•	•	IV.05 Visibility	IV.05.4 visible, spatial change	
•		IV.07 Scalability	IV.07.2 scalability of function (unit, element) medium	
	•		IV.07.3 scalability of function (unit, element) high	

Appendix 7-2 Parameter list for functional model 2: Thermal emissivity surface

Functional Model 2: Heat dissipation by adaptive surface emissivity				
FM2-S1	**FM2-S2**	**Category**	**Sub-class**	**Function description**
I. Monitoring				
●	●	**I.01 Set values**	E02.1 air temperature	degree of Te, Ti
●	●		E02.3 surface temperature	degree of surface areas (system, environment)
●	●		E02.4 local air temperature	degree of indoor air
●	●	**I.02 Actual values**	E02.1 air temperature	degree of Te, Ti
●	●		E02.3 surface temperature	degree of surface areas (system, environment)
●	●		E02.4 local air temperature	degree of indoor air
●	●	**I.03 Input/Output factors**	I.03.2 Differences of surface radiation	temperature of surfaces: $T_{sur,e} \neq T_{sur,\ system}$ T_{set} must be defined
●	●	**I.04 Signal recording**	I.04.1 photometric	radiation recording
	●	**I.05 Signal processing**	I.05.1 thermal	signal processing happens within material
●			I.05.4 electric	signal processing happens in a wire
	●	**I.06 Signal transport**	I.06.1 thermal	thermal transport within material
●			I.06.4 electric	electric transport within wire
II. Control settings				
●	●	**II.01 Control task**	II.01.11 emit, dissipate	surface temperature emission
●		**II.03 Control type**	II.03.1 extrinsic	external sensor
	●		II.03.2 intrinsic	material-inherent, thermo-sensitive property
●		**II.05 Operation type**	II.05.1 manual	
●			II.05.2 automatic (BMS)	
	●		II.05.3 self.reactive	Shape memory effect of thread
●	●	**II.06 Operation carrier**	II-06.8 matter, force	change is induced by tension

>>>

Functional Model 2: Heat dissipation by adaptive surface emissivity

FM2-S1	FM2-S2	Category	Sub-class	Function description
III. Actuation settings				
●		III.01 Task to perform	III.01.1 fold	position of surfaces of 3D shadings, 3D structures
	●		III.01.6 expand	area adaptation of material in all directions
	●		III.01.7 shrink	
●			III.01.11 tilt	position change of shading (e.g. lamellas), 3D structure
●	●	III.02 Actuator type	III.02.3 mechanical, kinetic	
●		III.03 Response time	III.03.1 sec	
	●		III.03.2 min	
●	●	III.04 Response type	III.04.1 dynamic	
●	●	III.05 Response degree	III.05.2 gradual	
●	●	III.06 Adaptation reliability	III.06.1 reversible	
	●		III.06.4 dependent on local conditions to function	
●			III.06.5 independent on local conditions to function	
●	●	III.07 Adaptation impact	III.07.1 morphological change	
IV. Physical appearance				
●	●	IV.01 Level of embedment	IV.01.3 system	
●			IV.02.1 positioning	position of stage 1 and 2of surfaces
	●	IV.02 Structural impact	IV.02.2.2 size information: surface area	
●	●	IV.03 Physical impact	IV.03.1 physical characteristics of structure	adaptive part stays fix but configuration changeable
	●		IV.03.2 physical characteristics of material	adaptive part must be elastic
●	●	IV.04 Functional scale	IV.04.2 micro (nm,mm)	
●	●		IV.04.3 macro (cm, dm, m)	
●	●	IV.05 Visibility	IV.05.4 visible, spatial change	
	●	IV.07 Scalability	IV.07.2 scalability of function (unit, element) medium	
●			IV.07.3 scalability of function (unit, element) high	

8 Conclusion

8.1 Introduction

The goal of this dissertation is to find a method to transfer biological principles for thermally adaptive façades based on geometric rules in order to reduce technical complexity - and without compromising functionality. This method is based on a stringent, parametric system of lists, schemes and classifications, which should support the transfer and keep function and design in a correct relation during the process. The dissertation is divided into three main objectives: first, the goals for thermally adaptive façades are established. Secondly, the transfer system and transferred models are developed. And thirdly, the results are tested for their design effectiveness, i.e. the reduction of technical complexity by the use of geometric design. These objectives are reviewed by the answers to the research questions.

8.2 Answers to the research questions

In order to find out to what extent and by which means constructive measures can take over technical functions for thermal adaptation, biological analogies with comparable intentions were sought, selected and transferred to technical concepts. In order to enable a function-oriented transfer of the biological role models, a systematics had to be developed that takes equal account of the constructive and material-oriented parameters as well as the functional criteria for the adaptation process. These parameters must also be tangible for an applicable implementation in the early design stage. The key questions account to the complexity in this intend: both the search, creation and evaluation of functional adaptation strategies, as well as the development of the transfer systematics require a high degree of abstraction.

The leading hypotheses that guided this intention were:

- **Reduction of the additive approach in current adaptive façades**: in adaptive façades, the number of assembled components can be reduced by using biomimetic solutions with integrated functionality.

- **Reduced need of new material and smart device developments**: biomimetic solutions can be realized by using standard design methods and existing materials - only the way of designing determines the functionality.

- **Reduced gap between design and adapative functionality in the façade design due to biomimetic approaches**: a function-oriented systematics would overcome the gap between design and adaptive functionality and provide a stronger role to design. This systematics can be best developed on the basis of climate-sensitive and parametric methods.

The research questions were derived from these hypotheses. The answers to these questions, and thus to the hypotheses, are given below.

Can the technical complexity of thermally adaptive façades be reduced by applying biomimetic approaches?

The question is addressed by following sub-questions:

A What are the challenges for thermally *adaptive* measures of façades?

Technically seen, it can be said from the investigated information on (passive) constructive façade design measures in Chapter 2 and thermally-adaptive solutions in Chapter 3, that particularly the measures '*thermal insulation*' and '*glazing*' are the most controversial challenges. Their main tasks result in contradictions regarding the targeted cooling purpose: while high thermal insulation quality is needed for cold seasons, it is disadvantageous for hot seasons. This contradiction also applies to the day/night shifts in summer or whenever the temperature difference between indoors and outdoors reverses. However, there are no market-ready solutions to solve this contradiction. Tendencies to use phase change materials to delay the thermal flow speed are tested on prototype level but do not promise a solution in this regard.

Glazing's face the same problem: they should provide daylight quality all year round, and allow maximum solar energy gains in the cold season while minimum solar energy gains in the warm season. This can only be solved by shading or a material-

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inherent reduction of solar radiation. An reduction of the radiation means a reduction of daylight. In the last 20 years, many product developments targeted this problem. Market-ready products, such as switchable glazing's, are applied in building projects since a few years. They resolve the contradiction to some extent, but not completely. However, the discrepancy is much smaller than with the thermal insulation problem. New developments, such as long-wave (thermal) selective films, promise an even better solution for the glazing's problem in the near future.

Other design measures such as thermal storage and thermal boundary layers, passive cooling strategies applied on the outer surfaces of façades or geometric form optimizations may possibly contribute to cooling, but their influence his unclear. Their challenge is a methodologically one: comprehensive dynamic flow simulations would have to be done to evaluate their potential for cooling - especially in the context of a façade structure including e.g. the thermal insulation layer. Concepts, such as e.g. '*breathing walls*' that deal with the air cavity of multi-layered systems, are interpreted very differently. This example shows that a major challenge in thermally adaptive façades is also the definition of 'adaptivity' itself and its targets. It is relatively unclear what functional increase in efficiency is expected for most of the measures that are currently associated with thermal adaptation.

From the performance analyses of adaptive façade features carried out in this work, it can be said that heat dissipation is the least considered function of current adaptive façades, while overheating prevention is the most often considered. Thermal energy control measures are targeted by use of smart materials and multi-layered solutions; overheating prevention and solar gains are addressed more by kinetic solutions, whereby geometric optimizations were sought more for aesthetic rather than functional reasons. Smart materials without kinetic adaptation mechanism seem to be more robust, as they need little maintenance in operation. Kinetic systems and some multi-layered systems using fluids are considered least robust in this context.

Developments move towards the employment of smart (self-adaptive) materials embedded in façades, whether they are controlled intrinsically or extrinsically. The combination of such materials with external controls in standardized or customized façade components seems to increase the challenges in the design, construction and operation enormously. The main challenge, seen not only by façade planners but also by other stakeholders in the building sector, are the maintenance and reliablity over the lifetime of the system.

The wish to '*keep it simple*' must be taken into account for adaptive façades, be it the flexibility to create various appearances or to strive for economic effectiveness. Acceptance by the facility management and users is also a decisive criterion. Costs, user satisfaction, and development efforts are interchangeable in their ranking, but ultimately form the decision for all of these criteria. From the perspective of stakeholders other than architects and planners, and taking into account the market share of adaptive façade measures, it can be concluded that (complex) adaptive façade designs are appealing (particularily for light-tower projects) but limited for a wide implementation. So the question about their challenges is closely linked to the economic and technological realities, and perception about their benefit.

B Which criteria support the evaluation of technical complexity of adaptive façades?

Identifying distinct criteria that describe the technical features of adaptive façades depends to a certain extent on the perspective of observation. The criteria developed in this work have been based on the idea of defining not only performative or technical characteristics but also design relevant information. Thus, the technical complexity is described by various criteria:

First, the efforts required to develop the system (design complexity), to assemble and implement the system (implemenation complexity) and to run the system (operation complexity) are defined as sub-criteria in the main class 'IV-09 complexity' in the 'adaptive facade criteria list' of Chapter 3. While operation complexity can ultimately be assessed in the stage of prototyping or implementation, the other two criteria can already be assessed in the planning phase. The design complexity is essential especially in the early design stage, which is crucial for the development of the functional models, the target of this work. Thus, the design complexity can be found in all assessment stages of the transfer process in this work. The complexity criteria are supported by further criteria, which were considered critical in the literature review on success factors for adaptive façade planning. They are summarized as '*design effectivity*' criteria and consist of following:

- *Flexibility*: design configuration flexibility linked to modularity, standardization/customization, easy exchange of parts,
- *Scalability*: scalability of a unit, element or system to be useable in various applications,applicability to various project sizes,
- *Robustness in mainentance*: system design that affects the maintenance effort and redundancy, such as 'simple' solutions and easy replacements,
- *Design complexity*: time- and effort-efficient design by use of existing materials and construction methods, support by digital tools for the optimization.

This criteria set has been defined in Chapter 3 and 4 and is part of the parametric '*adaptive façade criteria*' list (Appendix 3-2 and as checklist in Appendix 4-1).

This set of criteria was taken as benchmark to compare the functional models created by the biomimetic transfer process in Chapter 7 with existing façades solutions summarized as use cases in Chapter 3.

C What are the baseline aspects for *(*thermal*)* adaptability in biology and technology?

The major functional goal of thermally adaptive façades is to enable a responsive behaviour in order to control energetic flows. Four aspects for adaptive façade systems have been identified from the literature review in Chapter 3: monitoring settings, control system, actuation system and physical settings (=physical body). These four aspects were also found as relevant in the general considerations about *adaptation* in Chapter 4 and in the biological analogies in Chapter 5. Thus they define the basis for the generation of adaptation criteria that describe both fields. These criteria were summarized in the adaptive façade criteria list (Appendix 3-2) and serve as the technical language in the transfer process developed in this work.

While the monitoring and the control system are linked to the degree of intended and influenceable change behaviour (or ability of self-reaction) and are information-related, the actuation system describes the technical setup for the change process and is the link between the information and the mechanism of the physical structure.

From the evaluation of the existing adaptive façade solutions, it can be said that information-related settings are less embedded than added to the physical 'body', the façade structure. It was also found that the reliability for any adaptation, the degree of controllability or automation, is an important criterion for the success of the solutions. The type of control in façades that directly affect the comfort situation ranges from user-centred to fully automated types. However, these are almost always directed by external monitoring that is not necessarily connected to the adaptation system. This differs from biological role models, where automated and manual processes are also applied but are always closely linked to the adaptation system. The criterion 'controllability' is considered as a critical baseline aspect for both fields and thus a part of the 'effects' category (V) in the parametric list.

In contrast to technical solutions, biological solutions apply other time frames to adaptations. Adaptation in nature is an evolutionary lengthy process, while 'adjustments' are dynamic, demand-oriented 'smaller' changes. This difference reveals one of the main adaptation characteristics for biology and technology: time is the game changer for any adaptive process. Adjustments in nature have restricted framework within which change may occur. This narrow framework also defines the search scope for the analogies. However, it must be mentioned that these adjustments are the result of both evolutionary adaptation, resulting in corresponding morphologies, and dynamic adjustment mechanisms. Thus, the relationship of geometry and material must be considered to get a full picture of biological adjustment strategies. The design aspects that describe the balance of stability of the structure and flexibility in change, are another important baseline to describe adaptability in both fields.

The rules of the physical design depend on the materiality and constructive design (=geometry). This dependency was roughly examined in Chapter 2 by identifiying the relationship between material and geometry in the current passive design measures. Subsequently, they were then explored in greater depth in the evaluation of the selected biological role models, and the findings were finally applied in the creation of the functional models.

D Are biomimetic solutions for thermally adaptive façades less complex?

The evaluation of the investigated adaptive façades cases in Chapter 3 revealed that the complexity in the design is rather high for almost all defined types of adaptive façades, while the flexibiity, scalability and robustness is rather low. The qualitative assessment result is visualized by Figure 3-16 in Chapter 3. This evaluation was then repeated in Chapter 7 on the created functional models, which demonstrate biomimetic approaches to thermo-adaptive features. The result revealed that the biomimetic models do not massively reduce the complexity.

One reason for this is the use of kinetic mechanisms. The attempt to avoid new material development resulted in adaptations that had to take place through morphological adaptations. Morphological adaptations may take place via kinetic mechanisms that control individual parts or via generic material deformation. Ultimately, it depends on the material properties whether the complexity of the design can be reduced. This cannot be definitely assessed at the stage of this work.

The physical design aspects in both fields follow hereby the paradigm of design and implementation effectivity: standardized parts shall keep the design and production efforts low while customized approaches shall allow the desired flexibility. Such configurations are complex. Biological configurations show a sophisticated design of the structure iteself on another scale that embeds the adaptive function. Technical systems use the additive approach because it is currently not possible to implement function on nanoscale in order to control thermo-adaptive processes.

The functional models would have to be further technically developed and tested in a next step. An in-depth study on smart materials that can adopt adaptive properties would also be necessary for the optimization of such models. Based on the findings, especially the in-depth studies of the biological models, it can be said that enabling smartness in materials reduces the complexity of the design as defined in the engineering field, but does not reduce the complexity of the inherent function. The question of how controllability can be guaranteed also remains open. The interweaving of these criteria is the basis for simpler solutions.

What role do geometric strategies play in the modulation of thermal energy?

A Do biological role models use geometric design rules for thermally adaptive functions?

This question can only be partially answered as it relates to the studied role models in this work. Of the 72 identified role models grouped into 14 functional clusters, those strategies that were extracted for closer analyses reveal a close connection to geometric rules: overheating risks can be prevented by selective surface characteristics that reduce direct solar irradiation, i.e. protective waxes, hairs or self-shading shapes. The strategy behind these purposes is to reduce the conduction to the inside and increase convection on the outside - it is done by a customized surface design that allows a control over both. Thermal energy regulation principles also use geometric parameters, such as thickness or volume changes. The modification of radiation is also applied for heat dissipation, i.e. emitting the wavelength-related (heat) radiation. In order to be able to emit the desired bandwidth of the thermal radiant spectrum, the surface structures must be precisely tuned to its wavelengths. Thus, this effect takes place at the nano-level to work. Finally, an effective dissipation of heat needs the combination of heat exchange systems combined with excessive surface areas. Thickness plays also a crucial role: the thicker a material is, the less thermal emissivity is applied as active heat dissipation strategy. The thinner a material is, the more crucial such mechanisms are because of the lack of thermal storage capacity and the associated risk of rapid overheating (and burning). Such materials usually have a highly sensitive and critical multifunctionality and therefore need to be precisely designed, which makes them difficult to transfer to façade systems.

In general it can be said that geometric (structural) aspects play a crucial role for most regulating approaches, either by enabling growth and thus (adaptive) deformation, or by enabling a change in thermal flow, which is usually due to the contact with the environment and thus dependent on the surface characteristics.

The overall insights made in this work in regards to the role of geometry in biology are as following: structures that modify radiation are often skeletal, arranged anisotropic and in hierarchies using the '*right*' material, which allows the needed properties to be arranged, such as e.g. different gradients in thicknesses of the unit (fibre, cell). By this approach, biological organism perform the necessary action and adapt dynamically on wavelength scales. Radiation-oriented structures are tuned to the wavelengths of the radiation on nanoscale. Structures that modify thermal flow are usually working with thermal storage capacities, heat transport mechanisms and excessive surfaces. They are tuned to the properties of the matter that is transporting the heat. Thus they are applied on micro or macroscale. Their geometric rule is to modify the heat exchange area, the surface. To allow adaptation (or growth) they employ polygonal units (cells) or linear layered units (fibre), which are arranged in a repetitive order using sequential growth patterns (Fibonacci) or branch-like patterns (fractmental). All solutions, either radiant or thermal flow ones, take over multifunctional tasks: examples that adapt colours in the structure also provide a stable system for motion or growth.

Finally, it should be noted that thermal processes in biology combine morphological, chemical and behavioural processes at once. Therefore an extraction of the geometric parameters would not be sufficient to investigate the behaviour of organisms. For this work, however, an attempt is made to omit these relations and to study the role of geometry as a factor for thermodynamic processes. The role models are chosen based on the assumption that a sole transfer of the structural factors may already affect the thermal task positively.

B To what extent and by which means can constructive measures of façades take over functions for thermal adaptation?

As concluded in sub-question A, the role of the constructive measure for thermal adaptation depends on the functional goal: it is about regulating the thermal flow, surface area optimization plays a significant role. An adaptation of the surface areas done by constructive measures means to deal with kinetic mechanisms or smart materials. Here is the interface of construction and materiality. This interface becomes even more critical for radiative goals. The constructive settings shift hereby to nano scale, and thus become part of the material design. On macro scale, the orientation and optimal positioning of the surface area remains a task of the façade

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design process. As a conclusion from the findings it can therefore be stated that constructive measures rely on the right material. Then they are a decisive factor for the efficiency of thermal adaptability.

C Can the gap between design and functionality (for adaptation) be reduced by using biomimetic design approaches?

The discrepancy between the role of design and adaptation can definitely be reduced by taking into account the thermodynamic processes. Current façade solutions are largely disconnected from this potential; adaptation is too little adjusted to the microclimatic phenomena and too much controlled by external subsystems that do not capture these conditions.

It is not a novelty that constructive measures, as i.e. in many vernacular buildings, have an impact on thermal performance. It does not seem self-evident to tune adaptive features of the façade equally, whether components or whole systems, to environmental effects. If these are more related to the micro-climatic situation, they could more effectively respond to changes. A great opportunity to overcome this gap is promised by digital parametric analysis tools that can capture and correlate such characteristics, the tasks and the boundary conditions. Parametric design seems to be the only option to integrate design into the functionality because the complexity increases enormously with this intention.

This work attempted to make the role of geometry tangible by using parameters and schemes along the whole process. The weakness of these tools is the unvalidated behaviour in regards to the functional purposes, which is discussed throughout the transfer process. As the objective of this work was to set up a systematics in order to establish a function-oriented design of biomimetic concepts, the validation step is certainly a follow-up task to be done. However, it can be concluded that the design can be greatly optimized by applying findings from biomimetics as long as the correlation of material and geometry is maintained.

Can a standardized systematic process support the transfer of biological principles for thermal flow modulation to façade design?

A How can functional characteristics of biological role models be preserved when transferred for the use in the façade design?

The intention of this work was first to identify the functional characteristics and second to keep them in a correct relationship to each other throughout the transfer process. This applies also to the transfer of the biological role models: in order to be able to preserve their functional characteristics, a kind of translator language had to be set up.

The result of the identification of functional characteristics was the creation of a parametric list featuring the criteria for thermal adaptation. This list was started on the level of functional purposes of thermal design measures in Chapter 2, and completed on the level of adaptation settings in Chapter 3. In Chapter 4, the thermodynamic priciples and geometric features were investigated in detail in order to check and possibly adapt the parameter list also with regard to the biological characteristics. Thus, a rather comprehensive list with several classes, subclasses, each with a unique ID, was created.

The result of the correlation of each criteria was the creation of schemes (using the alluvial diagram method) that visualizes the relationsships between the criteria. This scheme started as well in Chapter 2 with the links between the thermal measures and their functional purposes, and continued to the rules for adaptation, showing the five categories of the adaptation and their associated criteria. The scheme is also applied for the functional role models and helps the evaluation of these with the prepared use cases.

Both methods, the parameter list and the schemes, also form the basis to describe the biological role models. However, since schemes and parameters were created from a technical understanding and cannot be directly applied to the terminology of scientific publications in the natural sciences, a translation language had to be added. The literature review on methods for such transdisciplinary translation work revealed that semantic languages can serve as a bridge. The semantic approach enables a context-dependent description of adaptive phenomena.

A defined sequence of semantic phrases (*physiomimetic terms*) was therefore prepared to describe the adaptation process of the biological role model. The key words in this sequence were linked to the parameters to establish a reference to the criteria list. This way, the biological model could be described in sentences, behind which the technical criteria for a parametrisation could be found. The link between the adaptation rules, the semantic phrases and the parameters was visualised by a separate scheme (Chapter 6, Figure 6.2).

B What are the critical aspects for the transfer process in the established context?

There are several aspects to consider. In Chapter 2, the main parameters for assessing the functional performance of passive design measures were identified. These parameters are used to identify the search fields for the analogy search. Their setup is necessary in order to avoid searching too broadly and getting lost in the process. Thus, they guide and restrict the search questions essentially, and as a consequence control the analogy search substanially. A critical reflection on the definition of the search fields must be done, because a possible anticipation of (expected) analogies may be possible.

Attention must also be paid to the way they are contextualized to each other. This means, for example, that the influences and functional purposes of the design measures may be different to the biological role models. So that this is not anticipated, the criteria have been listed individually and not immediately placed in context to each other. A deviation of the context can thus occur with the biological role models.

In Chapter 3, the adaptation criteria for facades are set, which are used to describe the adaptation process. They are arranged along five aspects (which are discussed in question 8.2.1, B), which also define the framework for the description of the biological role models and the creation of the functional models. To assess this framework, some parameters from the adaptive facade criteria list (Appendix 3-2) were used as constant evaluation criteria ('design effectivity') during the process. The main challenge was to choose the right parameters. For the first attempt as provided in this work, the design critical ones were selected that were argued by the market perspective on successful adaptive facades.

In Chapter 5 to 6, the analogy search and analyses occurred. The critical aspects for this step is obvious, as the author left her own knowledge domain and studied publications in unfamiliar fields. Misunderstandings or misinterpretations of the phenomena are rather possible. The question is whether it is essential to fully understand the '*intention*' of the organism or whether it is enough to recognise and adopt the universally valid physical principles that an organism must also apply.

The last step in Chapter 7 was dedicated to the creation of functional models. This step is a creative process and adds design generation methods - with the advantages and disadvantages in terms of retaining functional features. This step leaves room for interpretation of the identified strategies. This leads to a subjective choice of design options and assembly to a model, which can vary greatly. A critical evaluation of the models must be done through functional numerical analysis and prototyping. This did not take place within this work. Therefore, to a certain extent it remains open whether the selection of design options and the models function correctly and are applicable. Their robustness, applicability and some aspects of the flexibility can thus not be assessed at this stage. This applies also to the criteria of group V, the implementation effects. A conceptual assessment has been done by comparing the design effectivity criteria of the models to the established use cases. It can be said, however, that this step served more to evaluate the procedural implementation and less the actual applicable solutions.

In conclusion, it can be said that there are critical aspects in all phases of the transfer process, as it was highly complex and many assumptions and subjective decisions had to be made. These limitations can be objectified if several people work on the process. The criteria definition is then more sharpened through different approaches. A digital approach, possibly using artificial intelligence methods, would also be an option, but at the moment it still seems to be a unjustifiable effort for the target task, the early design stage.

C How effective is the parameterized systematics for its applicability in the early design stage of adaptive façades?

Above all, particulary the semantic schemes for describing biological concepts illustrate the dependencies between physical and functional processes relatively well. The structure of the scheme is strictly ordered and also includes a mapping to the parametric criteria catalogue. In this form, this method can be a good choice for a quick explanation in the early deisgn stage where numerical analysis or in-depth studies cannot be done. The schematic approach also allows an abstracted explanation and at the same time it enables the comparison of different role models' principles. The effectiveness of the semantic scheme must be evaluated by more data transfers (more role model explanations). Together with sketches of the functional principle as a viual aid, the scheme should be tested in field - in architectural office. The scheme is still rather '*technical*' as it works with words and IDs.

The prepared parameter list seems confusing from an external point of view. It is intended as a backend tool and should run in the background when the systematics is implemented. The definition of the search fields and question, the search itself

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and the transfer are then based on keywords and semantic phrases that are linked to the respective parameters. The effectiveness of this approach is only evaluated conceptually in this work. To evaluate the parametrics, it would be necessary to build a digital environment. This is given as a recommendation for future work.

The main advantage of the systematics is to provide a structured tool for all phases of the transfer, from the search field identification towards the design development, that allow a clear mapping of functions and correlations, and thus allows the observation on how these correlations vary depending on the type of strategy.

It was also an attempt to develop a function-oriented approach to shift the focus from the obvious to the functional. Thus, the systematics in its present, still improvable raw form serves as a kind of training for a function-driven view for biomimetic transmissions. It shall reveal the physical fundamentals and geometric rules that lead to the thermo-adaptive results. Its applicability ultimately depends on the data available, whether in the form of a large set of biological concepts or design options that need to be prepared. The preparation of this data is an essential criterion for applicability. Suitable options could be selected via keywords. Digitalising the data could also be a great advantage in this respect.

In conclusion, it can be said that the attempt to develop a strict systematics for subjecting the biomimetic transfer process not to the artistic freedom but to the regime of thermo-physical processes has succeeded as a theoretical concept. For an actual applicability, this would definitely have to be developed further.

8.3 Recommendations for future work

The list of recommendations for future work grew steadily during the course of this work, be it the required numerical analyses of biological models, functional models or development of further concepts and models; or be it a detailed examination and further development of the proposed systematics by field tests.

The intention of the work was to develop a systematics that serves as a function-oriented guide for the translation of biological principles to thermo-adaptive façade concepts. The developed systematics itself is a discussed draft, but still needs refinements and a validation. There are many uncertainties in the systematics that could not be resolved due to the needed constraints of this work.

Quantitative assessments of the functional models would ask for mathematical modelling of processes, functions and dependencies. A correct mathematical-physical twin of biological processes and/or a correct model of the technical models with all influencing and decisive parameters is considered an interesting starting point for a follow-up project. This would also have an impact on the structure and effectiveness of the systematics. The systematics itself should be digitised in order to be able to identify and adapt problems in the implementation. Ontologies combined with parametric design tools would be an interesting approach. The actual identified phenomena, such as deformations due to volume change, could serve as a starting point to set up such digital environment.

8.4 Final remark

"*I'm glad I did it, partly because it was worth it, but mostly because I shall never have to do it again.*" – Mark Twain

This quote describes very accurately the first impulse after completing a work that touches so many interrelations and disciplines. Writing a dissertation in a transdisciplinary field not only promotes awareness of one's own narrow professional limits, but also an understanding of the difficult handling of highly complex processes that are better solved in appropriate teams and settings. And yet it was impressive to study and reflect on the many individual achievements in the transdisciplinary fields of biomimetics and adaptive façades design and engineering. The question of how to effectively collect and structure the existing swarm knowledge is probably the hottest topic of our time and yet the biggest task in the age of digitalization.

To compile complexities (of nature or technology) and make it available for planning is indeed promising, although it seems to be beyond human capabilities. Novel methods in the digital field of Artificial Intelligence, such as Machine Learning, offer a tempting outlook to structure and analyse large and complex data and to identify patterns. Linking databases and knowledge with such methods would be a highly exciting task that is certainly already in the starting blocks.

Curriculum Vitae

Susanne Gosztonyi works in the field of performative buildings with focus on energy efficiency, climate-sensitive design strategies and responsive façades. For this, she combines methods from the disciplines of architecture and construction, building technology and biomimetics in order to investigate suitable strategies for sustainable building solutions. She conducted several research projects on biomimetics and façades, such as the research projects '*BioSkin - Research potentials for biologically inspired energy-efficient façades*' or '*Biomimetic potentials - Innovative biologically inspired key technologies for 'Plus-Energy buildings of the future'* ''. Furthermore she was active participant in the COST Action '*Adaptive Façades Network*' and in several EU projects and IEA Tasks focusing on energy-efficient, solar buildings.

Susanne works as lecturer and research group leader at the Lucerne University of Applied Sciences and Arts in Switzerland since 2018. Before that she worked as a scientist and project manager at the Lund University, Energy and Building Design, in Sweden between 2014 and 2017, and at the Austrian Institute of Technology (AIT) in Vienna between 2005 and 2013. She also conducted a Master course at the University of Applied Sciences Technikum in Vienna from 2010 until 2014 and had several lectures at Austrian universities between 2008 and 2014. Before moving to research, Susanne worked as an architect for international architectural offices in Europe, Australia and South America between 1994 and 2007. The many questions gained from the practical experiences and her entrepreneurship in the area of energy-efficient buildings until 2007 paved her way from practice to research.

Susanne Gosztonyi holds a BSc/MSc degree in architecture from the Vienna University of Technology and completed post-graduate studies in the Master programme '*Climate Engineering*' from the Danube University Krems in Austria. Parallel to her jobs, she pursued her Ph.D at the TU Delft, Architectural Engineering and Technology in the field of '*Design of Construction*'. She is active as advisory board member and expert evaluator for EU programmes and scientific conferences, and conducts peer-reviews for scientific journals since 2010. Furthermore, she is an active member of the European Façade Network efn.

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Physiomimetic Façade Design

Systematics for a function-oriented transfer of biological principles to thermally-adaptive façade design concepts

Susanne Gosztonyi

Adaptive façades are designed to actively regulate the exchange of material and energy flows and thus improve the balance between comfort and energy consumption. However, their technical complexity leads to higher development efforts, maintenance and costs, and ultimately fewer implementations.
Embedded adaptive functions could be an opportunity to reduce these drawbacks. If embedded adaptivity is to work within a design, the particularities of geometry and material arrangements must be considered. Nature offers fascinating models for this approach, which frames the objectives of this doctoral dissertation. The dissertation examines both adaptive façades and biology criteria that support a *function-oriented* transfer of thermo-adaptive principles in the early design stage. The research work discusses whether the technical complexity can be reduced by biomimetic designs and which role geometric design strategies play for thermo-adaptive processes.

The research work is divided into three phases, following the top-down process in the discipline biomimetics, supplemented by methods from product design and semantic databases. The first phase is dedicated to the analysis of the contextual framework and criteria of façades aiming at thermal adaptation.
Further, transfer systematics are developed that guide the analysis and selection process. In the second phase, analogies in biology are collected that appear suitable. Selected examples are examined to identify and systematically describe their functional principle. Two exemplary descriptions herald the third phase, in which functional façade models are created and evaluated.

The result of this research work provides a conceptual approach to generate function-imitating biomimetic façade designs, so-called *physio-mimetic* façade designs.

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