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Designing Transformation: Negotiating Solar and Green Strategies for the Sustainable Densification of Urban Neighbourhoods

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Abstract: The current need to redevelop post-war residential settlements opens up the opportunity to exploit the potential for densification and for the climatic and energetic activation of building envelopes through greenery and photovoltaics. The question arises as to which design strategies help to identify and balance relevant solar, green, and densification interventions that would lead to new qualities in the built environment. This work relies on a threefold research by design approach to acquire this knowledge base. Within a research-based design studio, four teams of master's students in architecture faced the design task in a case study of an inner-city perimeter block development in Munich, thus covering the first two phases of the research by design process: Phase 1—pre-design, comprises a shared knowledge literature research, among other things, and concludes with specific research questions for the subsequent phase; Phase 2—design. Here, design concepts answer the research questions and are iteratively adapted and evaluated in an interdisciplinary expert discourse. Phase 3—post-design, synthesises the design proposals into design strategies. By gaining insights into the benefits and disadvantages of solar and green interventions, the research provides designers and urban planners with strategies to design the practical transformation and upgrading of urban residential structures.

Keywords: climate-oriented design; integral design strategies; building greening; building-related photovoltaics; research by design; informed decision; decarbonisation; climate change adaptation

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1. Introduction

Cities are faced with the major challenges of climate change and a growing urban population.

Increasing heat stress enhances the demand for climate adaptation measures to improve climate resilience, thermal microclimate, and human health [1,2]. Climate protection is equally important in reducing global warming to a minimum. In urban areas, solar energy is the largest renewable energy source that can be flexibly exploited by photovoltaic installations. While photovoltaics and building greenery compete for scarce urban surfaces, synergies between the measures may arise, and hybrid systems featuring solar and green components may allow for a bifunctional use of the available surfaces [3–6]. Moreover, growing cities experience an increasing shortage of living space, which can most sustainably be countered by redensifying existing districts in an urban context [7].

Post-war residential urban structures are a common district typology in Germany, with low sensitivity to architectural interventions and considerable redensification and solar potential [8,9]. Their microclimatic situation typically entails moderate or punctual heat stress risks [10,11]. The buildings often show far-reaching deficiencies concerning their design and energy performance as well as in their contemporary usage requirements. The upcoming need for redevelopment and renovation opens up the opportunity to exploit the existing potential for vertical and horizontal redensification and for the climate and energy activation of the building envelope through greenery and photovoltaics.

This transformation towards carbon-neutral, climate-resilient, and liveable urban structures requires creative and integral rebuilding and further construction of the building stock with innovative ideas and interdisciplinary cooperation. However, current redevelopment concepts are not very innovative and usually entail non-detachable thermal insulation systems [12]. Moreover, knowledge gaps and reservations regarding innovative interventions, such as building-integrated photovoltaics and building greenery, often prevent their application [13,14]. Hence, standard practice only considers these measures for rooftops and new construction projects.

Several past and ongoing research projects deal with the topics of redevelopment, building greenery, and building-integrated photovoltaics: Hild and Müsseler [15] exemplarily investigated the complexity of the redevelopment and valorisation of post-war German settlements, stating the need for objective information in order to conceive adequate reconstruction concepts while appreciating the existing building stock. Semprini et al. [16] discussed the topic of deep versus shallow renovation, with the conclusion that retrofitting is a multi-objective optimisation problem. Lucchi and Delara [17] developed concepts for the deep refurbishment and revitalization of a residential neighbourhood in Milan within an university architectural design studio, with a focus on the social aspects of the redevelopment project. Further research projects focus on the urban green infrastructure: Brasche et al. [2] analysed the demand for climate adaptation measures and their effects on post-war settlements, providing spatial greenery concepts for different post-war district typologies and insights into political planning processes; meanwhile, Erlwein and Pauleit [18] attempted to balance outdoor thermal comfort and housing demands. The authors conclude that the loss of existing street trees has the greatest negative impact on outdoor thermal comfort. With regard to climate protection, Aguacil et al. [19] examined the implementation of building-integrated photovoltaics during the renovation processes within three different design scenarios and in relation to five performance indicators. Farkas et al. [20] identified general, functional, and formal architectural integration issues for building-integrated photovoltaics.

However, the complex problem of negotiating solar and green strategies and redensification measures in an architecturally ambitious way has only been partly targeted. To date, no satisfactory and holistic solutions have been identified. Moreover, the available database that can aid in the making of informed and well-founded research-based planning decisions is still small.

Consequently, these two leading research questions arise: How can the transformation of urban neighbourhoods be developed and designed while negotiating the demands for climate adaptation, climate protection, and redensification? Which information and metrics lead to informed design decisions?

Due to their complexity and interdisciplinarity, the research questions cannot be adequately answered with purely analytical scientific methods. Therefore, a research by design approach is applied—similar to the design-driven didactic approach utilised by Lucchi and Delara [17]—to identify innovative design solutions, but without direct interactions with the inhabitants. The research questions are tackled exemplarily for one project area during a design experiment, within the framework of an interdisciplinary master-level design studio for university students of architecture; generalisable design strategies are subsequently deduced from the students' design proposals. By gaining a deeper insight into the benefits and conflicts of solar and green interventions, and by suggesting relevant design strategies in the context of the redevelopment and densification of urban neighbourhoods of the post-war period, this research provides the impetus and inspiration to architectural designers and urban planners for designing the practical transformation and the qualitative upgrading of existing urban residential structures. Apart from reflecting the potential of design to produce scientific knowledge, the educational role of the studio in developing the students' skills and the potential of research-based learning as a teaching method [21] through an interdisciplinary project are discussed.

2. Materials and Methods

2.1. Materials

The selected project area of Augustenstrasse is in the central Maxvorstadt district of Munich and runs from northeast to southwest. Most of its 49 buildings were destroyed during World War II and reconstructed during the post-war period. Their eave height is 18 m, and the attics, now mostly converted, provide additional floor space. In the post-war building stock, saddle roofs and hipped roofs at intersections predominate, while the historical buildings erected before World War II also feature mansard roofs. The roof inclinations vary from building to building, and the façades are mostly plastered with regular arrangements of apertures. The ground floors mostly accommodate small retail shops and restaurants, while the upper floors are dedicated to residential use.

During the reconstruction process in the 1950s and 1960s, the street space of Augustenstrasse was partly enlarged by five metres to allow for more space for the growing traffic volume, which means that the new buildings were set back by 5 m. However, this measure has not been fully put into practice, as several pre-war buildings remain at their original location. Hence, several protrusions and recesses of buildings lead to an irregular building line. Nowadays, an offset of the building line back to its pre-war state represents an unused potential for horizontal redensification: The relocation of the building line increases the ground floor of the buildings by 36% on average and provides a theoretical potential of up to 38,000 m^2 of new floor space in the entire Augustenstrasse area, provided each building is six storeys high [22]. Furthermore, the distance between buildings on opposite sides of the street currently amounts to 22 m. By relocating the building line back to its original location, the street space would be narrowed down to a width of 17 m [22].

2.2. Methods

Due to the need to balance the different demands of climate protection, climate adaptation, and living space while guaranteeing high aesthetical quality and meeting social needs, the nature of the research assignment is a so-called 'wicked problem'. A wicked problem does not feature a comprehensive problem formulation and cannot be solved with one ultimate solution. Thus, wicked problems cannot be tackled by regular thinking and conventional scientific research approaches, but rather require counterintuitive thinking [23–25]. Therefore, the research questions are addressed through a research by design approach. The research by design process is inspired by the iterative working methods applied by designers and architects that consider multiple perspectives and dimensions. Thus, it is used as an innovative way of acquiring scientific knowledge and is defined as follows:

'Research by design is any kind of inquiry in which design is a substantial part of the research process. In research by design, the architectural design process forms a pathway through which new insights, knowledge, practices, and products come into being. Research by design generates critical inquiry through design work that may include realized projects, proposals, possible realities, and alternatives. Research by design produces forms of output and discourse proper to disciplinary practice, verbal and non-verbal, that make it discussable, accessible, and useful to peers and others' [26].

This broad definition underlines the wide range of applications for a method that is under constant development and aspires to become scientifically accepted, but which remains ambiguous. Thus, Roggema [23] concretised the research by design process by structuring it into a threefold approach: The pre-design phase (providing the basis for the design process), the design phase (testing spatial potential and developing design concepts), and the post-design phase (producing new insights and knowledge helpful for a wider audience).

The first and second phases of the research by design process, according to Roggema [23], have been applied within the framework of a master-level design studio; there are 12 students involved, supervised in an interdisciplinary way by three professorships of Building Technology and Climate Responsive Design, Architectural Design, Rebuilding, and Conservation and Green Technologies in Landscape Architecture at the Technical University of Munich. The students worked in groups of three, and each group dealt with one part of the Augustenstrasse. The authors worked out the post-design phase upon completion of the design studio (see Figure 1). This research approach is in line with the didactic approach of the studio, which integrates concepts of research-based teaching. Despite the real-life context of the case study, a realization of the designs was not planned and is beyond the scope of this research work.

1. Pre-design phase

The start of the pre-design phase was marked by disciplinary lectures introducing the students to building greenery and building-integrated photovoltaics (BIPV). This way, the students with architectural backgrounds were familiarised with the primary topics of the design task, and the expansion of their knowledge allowed them to adequately deal with the complexity of the assignment. With this information in mind, the students conducted literature research in parallel teams. Each team covered one of the following topics: the challenges and opportunities of the post-war building stock, climate resilience in urban districts, the benefits of BIPV and building greenery, and design strategies for hybrid systems. Subsequently, they shared their newly gained knowledge with the other students via presentations and short research papers. From the didactic point of view in the research-teaching nexus, this phase pertains to the 'inquiry learning' type of teaching method, which is aimed at independently acquiring existing scientific knowledge and preparing research findings, hence improving the students' academic writing skills. Here, the research question serves as a didactic tool to stimulate the students' learning [27]. Based on previous research and on-site inspections of the project area, the students analysed the neighbourhood based on its strengths, weaknesses, opportunities, and demands, both analytically and graphically. The on-site inspections increased the students' observational skills and comprehension of local occurrences and helped them to get a grasp of the character of the project area. The insights gained from these explorations led to the development of concise research questions, future design directions, and focal points for each group of students.

2. Design phase

The design phase started with an analysis of built examples with integrated photovoltaic and greenery measures that serve as references and inspiration for starting the actual design process. During a virtual excursion, the students could interview experts in BIPV and ask relevant questions, hence gaining valuable insights from experienced engineers. Based on the previous explorations, the students developed design concepts as preliminary answers to their research questions. While sketching and drawing the different design concepts, the critical reflection and evaluation of the ideas commenced, and the students began to improve their ability in visualizing their design ideas. The concepts were evaluated, modified, and re-evaluated in an iterative process, with several interdisciplinary plenary discussions, poster sessions, and consultations in small groups. The interdisciplinary discourse with professors and experts from urban greenery, building technology, and design and reconstruction, covering the fields of city planning, design, and engineering, supported the advancement and sharpening of the design concepts and fostered the students' creativity. The students needed to defend their design ideas against perspectives that prioritised either the use of greenery or the intensive application of photovoltaics, or ones that focused on the provision of additional affordable living spaces in inner-city districts. Thus, they acquired argumentative skills valuable for their future professional life as architects. Furthermore, the demands and potential for climate adaptation, climate protection, and additional living space were assessed and balanced based on the calculation of green volume, solar yields, and additional living space, which made the designs comparable. Consequently, a sound argumentative basis for each intervention was found, leading to informed design decisions. The entire design and evaluation process was documented to retrace the motivations and backgrounds of each design decision. Research and design are interwoven during the design phase, while research and design interests influence each other [23]. In contrast to the 'inquiry learning' type of teaching method, this phase relies on 'research-based learning', according to the classification of Rueß et al. [27]: The students undergo a complete research process, pursuing a specific question. Here, the function of the research question is to create new knowledge and scientific findings.

3. Post-design phase

The post-design phase began following completion of the design studio. First, the design concepts were systematised into design strategies as a final synthesis of the work. The results were not meant to present an ultimate solution for one dedicated location, but rather conceptual deliberations that offer support in capturing the different aspects of the wicked problem. Moreover, the degree of transferability of the concepts to other districts with similar typological features and patterns was investigated. Oral interviews with the students participating in the design studio and written feedback in their final documentation allowed for a reflection on the design process, thus leading to the identification of key aspects and suggestions for improvement.

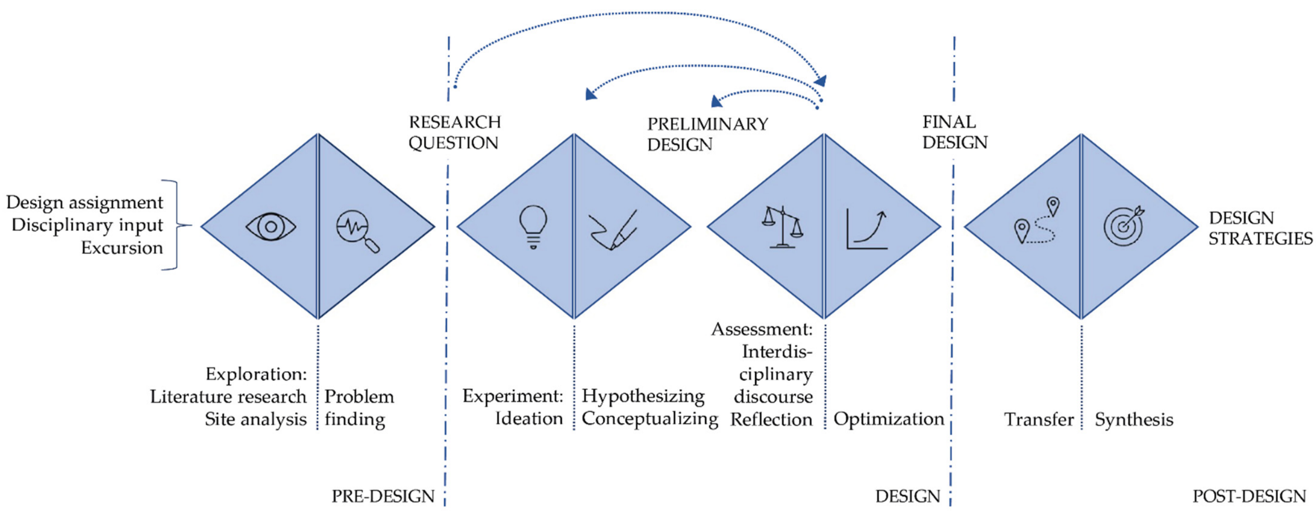


Figure 1. Methodology of the research by design process as applied in the present research.

3. Results

3.1. Pre-Design Phase

3.1.1. Literature Research and Development of Leading Questions

In parallel to the district analysis, the students were asked to perform an extensive literature review concerning the following topics:

Post-war buildings and districts: drawbacks and improvements in the existing building stock

Post-war buildings with a high potential to provide affordable living space typically feature small apertures but large opaque surfaces, deficient living standards, and scarce private open spaces. Repetitive building structures surround monotonous open spaces, which lack design and function. These drawbacks and the uniform resident structures lead to a generally negative perception of post-war districts. Even though dilapidated constructions require immediate redevelopment measures, several barriers prevent upcoming renovations: the diverging interests of inhabitants and owners, high investment costs, and the increasing complexity of renovation processes reduce the motivation for deep refurbishments. Hence, cost-effective, fast, and standardised methods are required for district-wide redevelopments. These methods might also lead to the envisaged valorisation and redensification of post-war districts without undesired gentrification as a side effect [12,28].

Climate resilience: local microclimate within urban districts

The Intergovernmental Panel on Climate Change (IPCC) defined resilience as 'the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions' [29].

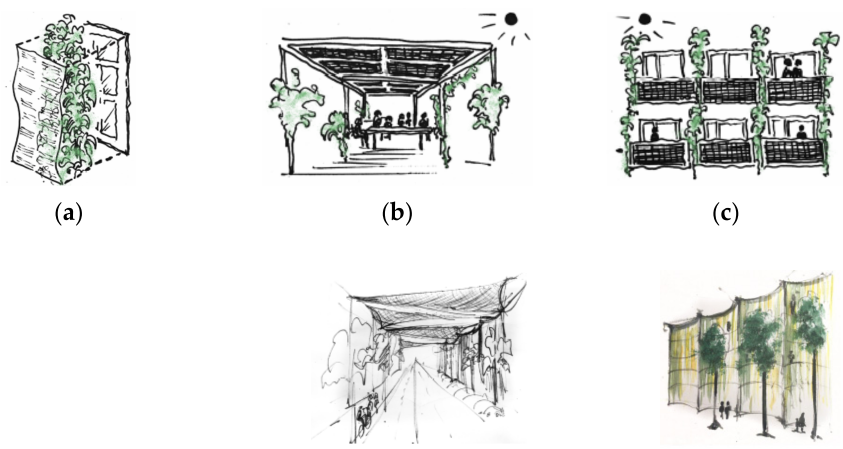
A great variety of measures for improving climate resilience, climate adaptation, and local microclimate within urban districts can be found in the existing literature. Mostly, these measures include the implementation of additional green volume. However, the effective transferability of interventions requires site-specific analyses and strategies to react to climate change [2,30].

Benefits of building greenery and building-integrated photovoltaics in urban districts: socio-spatial impacts and performances

An analysis of the benefits of building greenery and BIPV has led to the conclusion that the complex and expensive construction of hybrid systems can hardly be justified. Consequently, the separate implementation of both technologies is favoured. However, the evaluation does not consider spatial efficiency, and future concepts of hybrid systems might alter the result of the analysis [4,31,32].

Holistic evaluation of building greenery and building-integrated photovoltaic installations for developing hybrid systems

The students developed a methodology for comparing systems for building greenery and BIPV. Even though the comparison was challenging due to fundamental differences between the two systems, the evaluation helped to reveal their potential and benefits. Moreover, it supported the process of creative ideation for developing effective hybrid systems. Using this, the students developed several ideas for beneficially combining photovoltaics and greenery into hybrid systems (see Figure 2). However, intelligent combinations of both systems require an in-depth comprehension and a thorough knowledge of both technologies, and their mutual interactions and the exploitation of synergy effects do not necessarily lead to fundamental advantages [6,32–34].



(**a**) (**b**) (**c**)

(**d**) (**e**)

Figure 2. Ideas for hybrid systems: (**a**) Transparent photovoltaic curtains in front of vertical greenery systems; (**b**) Photovoltaic shading above roof gardens; (**c**) Balconies with green separations and photovoltaic balustrades; (**d**) Photovoltaic shadings above the street space; (**e**) Transparent photovoltaic curtains around existing street trees.

These topics cover the relevant aspects related to the primary assignment and provided the students with the background knowledge needed to deal with the multi-layered task. The literature review and the district analysis were then synthesised into three distinctive research questions:

1. How can post-war neighbourhoods with building greenery and building-integrated photovoltaics be upgraded while considering socio-spatial and financial aspects?
2. How can the separate arrangement of building greenery and photovoltaic modules in façades be used to optimise their ecological, economic, and social benefits?
3. Which architectural/functional, planning, and decision criteria are relevant for solar and green strategies?

3.1.2. Site Analysis

The analysis of the project area revealed several weaknesses typical for German districts erected during the post-war period, as evaluated in [9] and in the parallel literature research (see Section 3.1.1). In the case of Augustenstrasse, some weaknesses are related to the building level: The buildings feature low storey heights, construction deficiencies, and deficient living standards typical of post-war buildings, hence requiring deep renovation. The open space exhibits special characteristics due to the amendment of the building line: the partial shifting of the building line leads to heterogeneous open spaces and chaotic pedestrian zones. The impression of disorder is intensified by the varying façade appearances, eave heights, and aperture dimensions. Typical for perimeter block developments is the high degree of soil sealing. The only vegetation type present in the open space are individual street trees that provide shading and cooling through evapotranspiration, but which also significantly reduce the solar potential on the façades due to their height of ten–twelve metres.

Thus, one general ambition for the redevelopment concepts across all student groups is the transformation of the heterogeneous appearance of Augustenstrasse into a homogeneous, consistent street scenery in a resilient and sustainable manner.

3.2. Design Phase

In the following section, three selected projects developed in the design studio are presented. For each project, the preliminary design concepts are first described; then, the final design solutions are presented; finally, the designs are evaluated in terms of the exploitation of potential, the meeting of demands, and concerning the aesthetical appearance.

3.2.1. Modular

The ‘Modular’ project by Katharina Broghammer, Philipp Neumann, and Sarah Reithmeier is strongly related to the first research question, which seeks to identify financially affordable solutions with added values in social terms while applying building greenery and BIPV. Due to their large of green volume and the provision of benefits such as fostering biodiversity, providing recreational cool spots during heat waves due to shading and evapotranspiration, and contributing to the well-being of residents and pedestrians, one aim of the designers was to conserve the existing street trees. Hence, the first step in the design phase consisted of identifying options for exploiting the available potential of a structural extension resulting from the relocation of the building line while respectfully dealing with existing green infrastructure.

This approach led to two different preliminary design concepts: The first one arranged the added building mass in a honeycomb-shaped structure around the existing trees. The second one placed ‘energy towers’ in front of the façades, thus providing private open spaces for the inhabitants, while also creating additional surfaces that could be climatically and energetically activated by photovoltaic and greenery integration (see Figures 3 and A1). The flexibility of the concept and the minimally invasive intervention into the building stock led to the further pursuit of the idea of the energy towers (concept (b)).

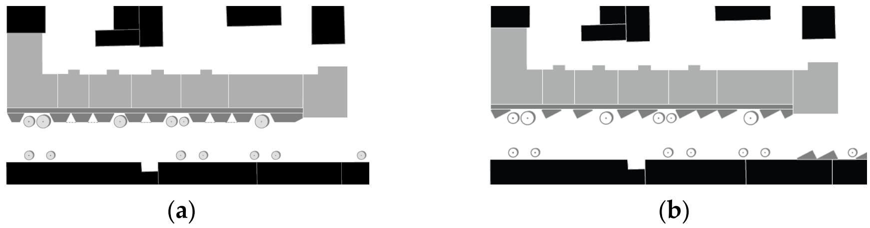
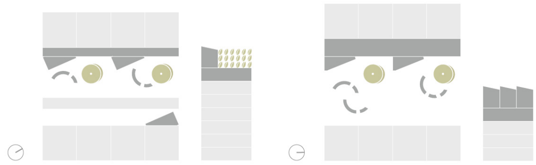


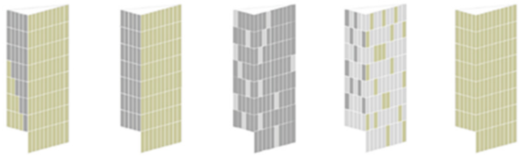
Figure 3. Preliminary design considerations for 'Modular': (**a**) Honeycomb structure; (**b**) Energy towers.

In particular, the topic of prefabrication and the possibility of easily adapting the design to further building dimensions was stressed by the interdisciplinary discourse, thus leading to the final design (see Figure 4): The energy towers are based on a planning grid that takes up the typical dimensions of post-war residential buildings as identified in the previous literature research. The simple lightweight construction comprises few elements and can easily be adapted to individual heights and widths. The surfaces are individually covered with photovoltaic and green elements based on the intrinsic demands and potential of the building and its surroundings. The vegetation is planted into plant troughs and grows upwards along vertical, horizontal, or crossed ropes. The individual choice of plants based on a portfolio of suitable vegetation offers a certain singularity and allows for customisation by the residents. The photovoltaic modules are mounted on a metal supporting structure. The rear of the panels is clad with timber, thus providing a comfortable ambience on the newly created balconies. In addition, modular housing boxes as a vertical redensification measure on the rooftop offer additional floor space and thus provide an answer to housing shortages. The elements are differently sized in order to flexibly meet the needs of various household sizes. Next to the roof apartments, semi-public greened open spaces provide recreational areas for the inhabitants while at the same time increasing the amount of greenery in the inner city and contributing to improved water management.

Accordingly, the designers provided a conceptual answer to their research question: solar and green retrofitting in the context of modular horizontal and vertical structural extensions allows for an affordable implementation of the integrated measures for the enlargement of floor space and climate action. The minimally invasive interference with the building substance, the simple construction and mounting procedure, and the standardisation and integration of cheap greenery systems guarantee feasibility and offer a financially affordable solution. Prefabrication enhanced by digitalisation allows for installation without residents having to move out. The energy towers as plug-in machines with an independent supporting structure include their own water and energy cycle and combine all the relevant functions, even those of urban surfaces. Case studies on inner-city and suburban districts have proved their transferability to and applicability in a broad range of post-war neighbourhoods. At the same time, customisation creates identification, and the occupation with vegetation and exposure to greenery leads to positive psychological impacts. Private and semi-private open spaces enhance social interactions and hence provide additional social benefits. Achieving the aims of feasibility and social added-value may counter the risk of gentrification. Individual and diversified façade landscapes improve the aesthetical quality of Augustenstrasse while conserving the initial character of the street canyon.

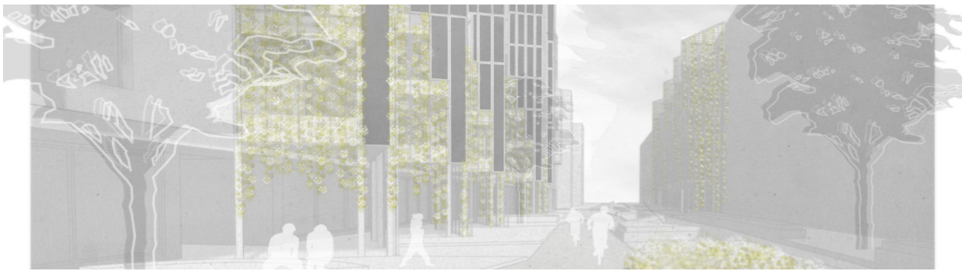


(a)



(b)

(c)



(d)

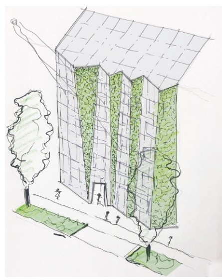
Figure 4. Final 'Modular' design: (**a**) Energy towers for inner-city and suburban districts; (**b**) Climate and energy activated customisation of energy towers; (**c**) View of Augustenstrasse with energy towers; (**d**) Rendering of Augustenstrasse with energy towers.

3.2.2. Mosaic

The 'Mosaic' project by Malaz Attar, Simon Perez, and Pinar Sel focused on the second research question, which tries to optimise a separate arrangement of building greenery and BIPV in order to ideally exploit their respective benefits. Hence, the preliminary design concepts investigated the monofunctional use of photovoltaic and greenery: In one concept, the lower three storeys of the buildings are covered with climate active greenery, while the upper storeys and the roofs are used for energy activation with photovoltaics. The second concept increases solar exposure by receding the upper storeys into terraces. Likewise, the third concept aims to increase the incident solar irradiation. Here, the façade is vertically folded, thus optimising the orientation of the façade surfaces towards the sun (see Figure 5).

(a)

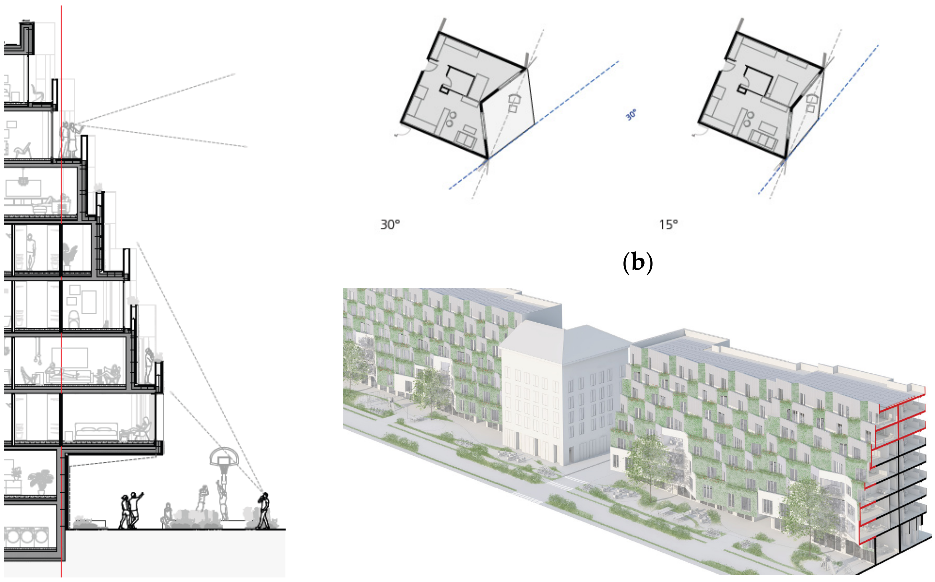
(b)



(c)

Figure 5. Preliminary design considerations for 'Mosaic': (**a**) Application of photovoltaic modules and greenery on the existing buildings; (**b**) Terracing of building façades; (**c**) Vertical, prismatic folding of building façades.

All three design concepts were further pursued, systematically combined, and iteratively developed while considering the opinions and advice of different experts (see Figure 6). Identical to the design project 'Modular' (see Section 3.2.1), the preservation of existing street trees was prioritised, and the added building volume was erected at an adequate distance from the vegetation. The façade's terrace-shaped protrusion into the additional five metres of open space available in Augustenstrasse provides additional floor space and private balconies for each apartment (Concept (b)). Moreover, the folding of the façade, as conceived in the preliminary design concept (c), increases the façade area and optimises its orientation to solar irradiation. The folding of the façade follows specific rules that are defined in an iterative process (see Figure A2), including interdisciplinary discussions and the students' critical reflection of their own work: The lower storeys focus on the northern orientation with building greenery, thus increasing the amount of climate active vegetation that is more beneficial for human outdoor thermal comfort when applied close to the pedestrians. The façades of the upper storeys are predominately oriented towards the south, thus enlarging the already higher solar potential in the upper part of the buildings (Concept (a)). The definition of angles for the folds also considers the layout of the apartments and balcony dimensions. The balancing of increasing solar and green potential while maintaining appropriate floor plans leads to folding angles from 15 to 30°.



(**a**) (**b**) (**c**)

Figure 6. Final design of 'Mosaic': (**a**) Sectional drawing; (**b**) Folding angles of the façade; (**c**) Perspective drawing (sectional).

Even though the students took intuitive decisions based on aesthetical considerations rather than providing arguments for their design based on quantitative assessments, the 'Mosaic' design provided one answer to the research question raised: The separate arrangement of building greenery and photovoltaic modules is optimised iteratively with regard to ecological, economic, and social benefits, thus demonstrating the potential of the monofunctional use of each surface. The ecological benefits are enlarged by using each surface according to its potential and the arising demands. As this approach leads to high solar yields, it simultaneously optimises the economic profitability of the design. Social demands are addressed by providing psychological benefits resulting from a large amount of greenery and an increase in social interactions due to various view connections between the buildings and the open space, from private balconies, and from additional floor space while considering sufficient illumination in the lower storeys. This major intervention into the existing building stock bestows the project area with an entirely new, modern, and vibrant appearance while negating its initial character.

3.2.3. Under the City Roofs

During their literature research regarding the development of hybrid systems with building greenery and BIPV, the students Arvid Kaminski, Maria Rau, and Robert Wittek discovered that these systems are highly complex and expensive in terms of construction while only providing minor additional benefits (see Section 3.1.1). They concluded that a separation of the two technologies might be more reasonable. Hence, in their project 'Under the city roofs', they addressed the same research question as that addressed by the students from the project 'Mosaic': They also pursued the goal of identifying solutions for the separate arrangement of building greenery and BIPV, although they followed a different approach. They developed the concept of only exploiting and optimising those surfaces with the highest solar potential (=rooftops) for photovoltaic installations, with the façades providing potential for the installation of vertical greenery systems. Encouraged by expert inputs, they created a prominent photovoltaic roof with cantilevers running along several metres, thus projecting the entire solar potential calculated for façades onto the rooftop. After several constructional studies, including timber framework and metal constructions, the newly designed rooftop above the vertical redensification of two storeys took the form of a timber-constructed, shifted sawtooth roof. Thus, surfaces created with high solar potential using renewable construction materials is combined with a high-quality outer appearance that references traditional alpine architecture and architecturally appealing indoor spaces. The newly created attic is semi-public, with offices, roof gardens, sanitary facilities, and kitchens. Horizontally, the existing building is enlarged by 2.5 m, and additional floor space and balconies for each storey are provided. Guided by metal wires, climbing vegetation trails the new façades clad with timber panels. The conservation of existing street trees and the planting of new ones complete the greenery concept, hence increasing biodiversity and the residents' exposure to greenery and improving the local thermal microclimate (see Figures 7 and A3).

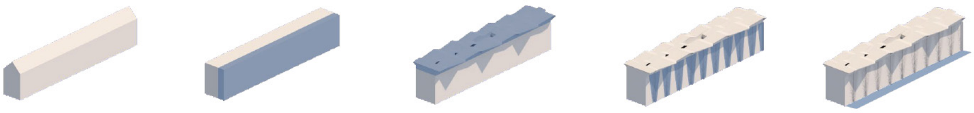
Thus, by following the same research by design approach, the designers found a different answer to the same research question: While the 'Mosaic' project focuses on maximising the potential of the façade surfaces, the project 'Under the city roofs' stages the roof as a protagonist in their design.

This idea is consequently honed by the enlargement of the energy-active roof area with a prominent, cantilevering sawtooth roof that provides high solar yields, but which also grants Augustenstrasse a distinctive but harmonious 'alpine' appearance. Simultaneously, the open space is altered, with the roof providing rain and solar protection, but eventually also hindering ventilation. The horizontal redensification of 2.5 m is the result of a process that balances the provision of additional floor space while guaranteeing sufficient illumination for the lower storey and designing attractive street spaces. The vertical greenery systems result in a green and liveable appearance of the open space. They are also made perceptible inside the buildings due to the large apertures, improving both the buildings and the open space and contributing positively to the residents' mental health due to an enhanced exposure to greenery.

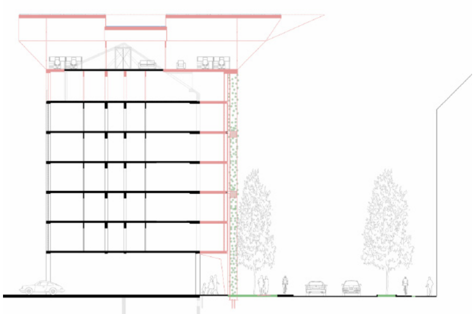
3.3. Post-Design Phase

3.3.1. Design Strategies and Transferability

The aim of the research by design process is to identify some general conclusions. However, the design is always focused on a unique situation; in our case, the focus is on one exemplary street canyon and its intrinsic layout, demands, and potential, as this approach provides a more intuitive access to the complex design task. The design concepts are further synthesised into general design strategies to gain universal knowledge. Due to the underlying typological approach, the strategies identified can then be transferred to other buildings and districts of similar typologies, and the architectural design turns into research. Based on the students' designs (see Section 3.2), three main strategies have been carved out:

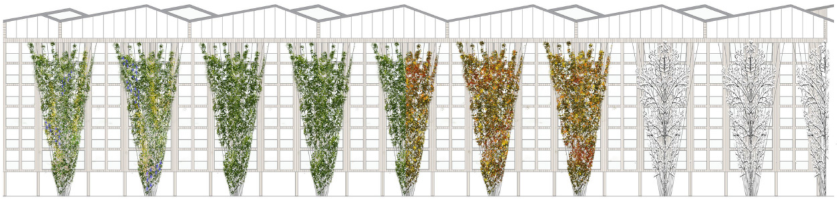


(**a**)



(**b**)

(**c**)



(**d**)

(**e**)

Figure 7. Final 'Under the city roofs' design: (**a**) Development steps of the design concept 'Under the city roofs'; (**b**) Sectional drawing; (**c**) Rendering of the final design; (**d**) Seasonal variation of vegetated façades; (**e**) View of Augustenstrasse.

Modular kit for districts

The 'Modular kit for districts' design strategy is based on the findings of the 'Modular' project. Different, ideally prefabricated components for the vertical and horizontal extension of existing buildings provide additional floor space and new private and semi-public open spaces. The type and quantity of the modules can be individually selected and implemented, depending on the district's intrinsic demands for additional living space as well as its potential. Moreover, each of the modules is autonomous and can feature climate and energy-active elements. Again, the arrangement of photovoltaic and green elements may be determined according to the demands for climate adaptation and the potential for climate protection measures. Thus, architects and planners receive a basic modular kit that can be adapted and designed individually. As the existing building layout is only slightly modified, the modular kit presents a minimally invasive and financially affordable strategy that can be applied to many building types due to its flexibility of size and dimensions. Hence, it represents a viable strategy even though the available potential is not maximally exploited.

Enlarging active façade areas

The 'Enlarge active areas' strategy was drawn from the 'Mosaic' project. It is based on the active approach of increasing the envelope area while ideally optimising its orientation to the sun, instead of utilizing passive strategies that minimise the A/V ratio to reduce the heating demand. At the same time, additional floor space and private open spaces are provided. However, the reasonable enlargement of active areas requires deep knowledge concerning building energy demands, solar potential, and the benefits of greenery systems. Compared to the previous design strategy, the folding of the façades presents a maximally invasive strategy that fundamentally alters the appearance of the buildings. It changes the initial character of the district into a homogeneous, consistent street scenery and can lead to considerable solar yields and contribute to the urban green infrastructure. The basic strategy is transferable to similar building types. However, major customisations due to the deep interventions are required.

Enlarge active roof areas

The 'Under the city roofs' project served as an inspiration for the 'Protagonist energy active roof' design strategy. This strategy is based on the idea that each surface should be used according to its major potential. Thus, photovoltaic and greenery interventions are strictly separated, and the rooftop is reserved for photovoltaic applications. The rooftop area is enlarged to increase the solar potential, thus leading to a cantilever roof that dominates the appearance of the building. The form of the roof—from sawtooth roofs, such as in the design studio, to conventional flat roofs—can be determined individually, based on requirements relating to the use and dimensions of indoor spaces and the envisaged outer appearance of the building. The strategy is easily transferable and adaptable to other buildings without requiring any profound knowledge. The architects and planners have the flexibility to design the façade and to integrate greenery systems into the vertical surfaces as the roof makes a large contribution to climate protection. This leads to the maximum exploitation of the building's existing potentials, in particular concerning solar potential, in a resilient manner while positively changing the district's appearance.

Apart from these basic strategies, some strategic interventions have been identified within the design concepts, their iterative development, and discussions (see Table 1).

Table 1. Solar and green adaptation strategies.

Concept	Hypothesis	Synthesis
PV mainstreaming design	Applying PV to areas with maximum solar irradiation according to shading studies and greenery to all other areas creates specific local façade layouts and an effective resolution for climate protection and adaptation conflicts.	Shading should not be a knock-out criterion for inner-city façades where solar exposure is limited in any case, and architectural criteria should have priority. →Balancing of design decisions according to individual priorities instead of the general evaluation of solar potential. →Questioning yield-oriented design.
Use of (close to) standard PV modules	Gradually transparent PV modules can be replaced by (moveable) PV shutters, thus providing flexible shading while entailing lower costs and planning efforts.	Enhanced feasibility and functionality of large-scale module design.
	Partially transparent PV modules can be replaced by a combination of transparent glazing and opaque PV areas, thus leading to lower costs and lower overheating risks.	Enhanced feasibility and functionality due to application of standard PV.
	Low investment costs of (close to) standard PV modules allow for the economically reasonable application of PV in non-ideal orientations.	Economies of scale compensate for reduced energy yield. →Questioning yield-oriented design.

Table 1. *Cont.*

Concept	Hypothesis	Synthesis
Architectural design of PV modules' backsides	The adaptability of PV modules enhances social acceptance.	Residents are sensitive to interventions in their private surroundings. →A comfortable visual ambience enhances the acceptance of PV.
Simple, robust, participative green	Simple and robust greenery systems simplify their application while entailing lower maintenance efforts and costs.	Enhanced feasibility and functionality of robust greenery systems.
	Compostable greenery systems entail lower embodied energy than sophisticated living wall systems.	Reduction of the carbon footprint of compostable vertical greenery systems.
	Individual choice of plants (and eventually its maintenance) enhances social acceptance.	The participative, voluntary, and customized integration of greenery provides identification.
Creation of accessible roof gardens	Accessible roof gardens provide semi-public open spaces and recreation areas for residents (social benefits).	Shared roof gardens strengthen the feeling of community among residents.
Enhance cooling by water running through façade greenery	Constant irrigation of vertical greenery systems increases the evapotranspiration rate.	Improved cooling performance but high water demand and constructively complex layout leads to high costs. →High effort resulting in small microclimatic effects.
Redensifying green infrastructure	Additional street trees can fill the gaps between existing ones.	Street trees provide a significantly larger amount of green volume compared to vertical greenery systems.
	Greening of glass façades improves the microclimate for street trees.	Vertical greenery systems in front of glazing reduce disturbing reflections.
Economic balancing of PV and green	High costs per m^2 (compared to PV modules) require the deliberate placing of vertical greenery systems.	The deliberate, punctual use of façade greenery generates benefits while providing affordable solutions but may be questioned in favour of design considerations.
Temporary solutions for growth period of façade greenery	Removable plant troughs can bridge the time span of 10–12 years until climbing plants reach the roof.	Intermediate greenery solutions achieve quick and efficient vegetation of façade with immediately high architectural quality.

3.3.2. Reflections on the Design Process within the Design Studio

The preceding literature research presented an unfamiliar task for the architectural students. Hence, this phase of the research by design process turned out to be time-consuming, especially when considering the short semesters. However, the intense examination of existing literature and the thorough occupation with the research topics at hand established a sound knowledge base for the design considerations. The development of research questions also revealed itself to be a challenging task for the students. While some of them effectively oriented their design process along the research questions and were able to provide coherent answers, the design concepts developed took on a different research direction in other teams, and the students failed to explicitly refine their research question to the direction of their implicitly rethought research. Hence, the research questions needed to be reformulated in an iterative way in order to provide coherent design answers (see Figure 1). During the interdisciplinary exchange of ideas with professors and external experts, diverging points of view confronted each other, and the students learned to argue for their designs when shown different perspectives. Accordingly, the earlier pre-design phase helped them defend their design ideas based on qualified scientific argumentation.

Moreover, the discourse led to the emergence of new ideas and helped to polish existing design concepts.

As the methodology represented a new didactic approach for the students, the students taking part were asked to provide oral and written feedback on the design process. They unanimously appraised the shared literature research as a beneficial stage of the design process that significantly enlarged the students' knowledge and competencies and prevented errors, thus leading to profound design decisions. The students even estimated that the time expenditure on the scientific work can be compensated by a shortened timeframe required for the design phase. The design process ran more smoothly and produced better and more well-founded results. The interdisciplinary discourse was also perceived positively, and the confrontation with diverging perspectives helped reflect their own design decisions. The definition of research questions was perceived ambivalently: Some students acknowledged the research questions as being helpful during the design process for finding a coherent design direction and thus conclusive architectural answers to the research questions. However, other students gained a negative impression from the need to subordinate their design to the research question. Moreover, the students rated the quantification of solar irradiation and solar yield, green volume, and living space as helpful—though belated—in the design process.

4. Discussion and Conclusions

The use of the research by design approach in the context of a research-based teaching course strives to bridge the gap between design, teaching, and research. From the teaching perspective, inquiry-based learning in the pre-design phase trained the students' skills in acquiring a sound knowledge base for design decisions. Applying a research process in the design phase developed their competence in conceiving meaningful questions and systematically finding solutions. Working with research questions and using design as a method for creating knowledge was a new and stimulating experience for the architecture students.

From the design perspective, despite identical assignments and project areas, the students' design proposals were diverse, and each design gave Augustenstrasse a unique appearance. The earlier literature analysis with different foci for each group, along with the development of research questions, fostered these differences and drove the designs into different focus areas. In particular, the topic of mono- versus multifunctionality of urban surfaces was controversially discussed: While the monofunctional application of each technology requires less planning effort, complexity, and cost, the scarcity of urban surfaces makes their multifunctional use reasonable. The students thus developed several design ideas for hybrid systems. However, they unanimously rejected these designs due to the high complexity and preferred the optimisation of the monofunctional use of surfaces. The controversial interdisciplinary discussion on the monofunctional versus the multifunctional use of urban surfaces, however, could not be generally synthesised. Moreover, it has become apparent that focussing on surfaces with maximum solar exposure is not a useful strategy for the design of building-integrated photovoltaics with high architectural and economic performance. Greening in existing neighbourhoods in turn offers a potential for redensification, and the growth period of façade greening can be bridged with intermediate solutions.

Overall, the students developed architecturally demanding solutions for the transformation of the existing building stock, hence answering the first research question of 'How can the transformation of urban neighbourhoods be developed and designed while negotiating the demands for climate adaptation, climate protection, and redensification?' The solutions were not only design ideas but were thought through in detail and elaborated in terms of construction and building technology. To answer the second research question, 'Which information and metrics lead to informed design decisions?', the students were asked to calculate selected metrics (greenery: green volume, also in relation to construction volume; photovoltaics: solar yield, also in relation to the buildings' energy demand; redensification: increase in floor space) for their designs. Nevertheless, the calculations for the different designs were only partially comparable due to varying calculation bases. Moreover, the metric 'green volume' needs to be transferred to the metric 'reduction in air temperature', 'reduction in mean radiant temperature', or 'improvement of universal thermal comfort index' in order to quantify the actual microclimatic impact of the designs. However, this transfer is still scientifically ambiguous and was thus excluded from this research. As a result, the deficient quantification of benefits of green interventions in the evaluation of different designs remains a shortcoming in informed design decisions.

To summarise, this publication describes the interweaving of an ongoing research project that considers the district-wide climate and energy activation of building envelopes with university master-level teaching by applying a research by design approach. Within a design studio, 12 students conceived designs for the sustainable, resilient, and liveable redevelopment of a post-war street canyon used residentially in Munich. They effectively negotiated solar and green interventions based on literature research while considering redensification measures. Hence, three designs with a different focus each were developed: One design was focused on providing financially affordable and minimally invasive solutions; the other design was meant to increase façade areas that could be energetically and climatically activated; the last design maximally enlarged the roof area used for solar energy production. Even though the research-based design challenged the students with an architectural background, their feedback on the methodology and the outcomes was mainly positive. Following the design studio, the students' designs were synthesised into design strategies, each one advancing the transformation of the urban residential structures with different strengths: The strategy of 'Modular kit for districts' conveyed the idea of developing prefabricated components for the financially affordable as well as vertical and horizontal redensification of existing buildings. The strategies of 'Enlarge active façade area' and 'Enlarge active roof area' both focused on increasing the surfaces of the building envelope while optimizing its orientation for photovoltaic applications. Due to the underlying typological approach, the strategies are transferable to other buildings of a similar typology, providing inspiration for architects and urban planners since designing for architecturally appealing redevelopment requires a certain sense and intuition for aesthetics. The selection of an appropriate strategy, however, depends on the essential objectives and visions for the district and its current status with inherent demands and potential. Hence, the design experiment was an adequate, innovative, but time-consuming solution for dealing with the wicked problems. Moreover, the literature research and the development of research questions that could be suitably answered by the design concepts call for a certain amount of practice. Thus, the research by design process can be improved and accelerated when applied several times.

The present work is mainly qualitative. However, the solar and green interventions need to be quantitatively assessed to conclusively evaluate the design strategies. The quantification of solar yield and additional floor space is straightforward and should, in terms of sustainability, be additionally indicated per person; meanwhile, quantifying the microclimatic impacts due to the integration of greenery systems and the installation of photovoltaic modules is not yet comprehensively understood and thus requires further research efforts. A sound quantitative basis for climate adaptation issues will simplify future negotiations, but some design decisions will remain subject to individual needs, priorities, and controversial interdisciplinary discussions.

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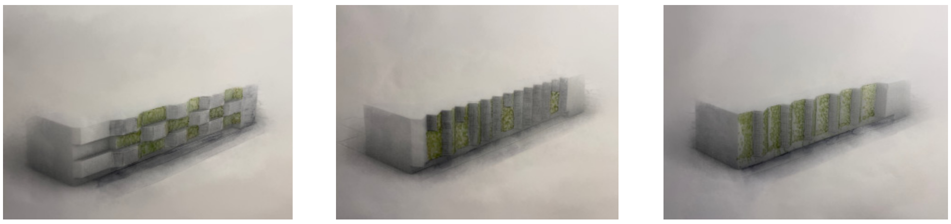
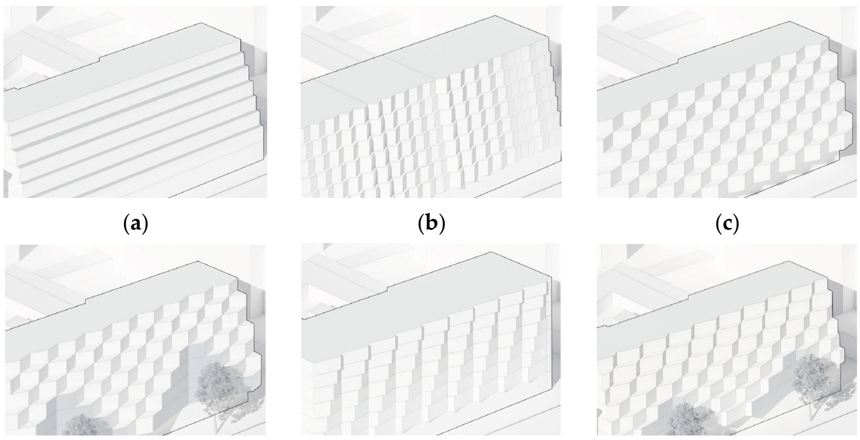
Appendix A



(**a**) (**b**) (**c**)

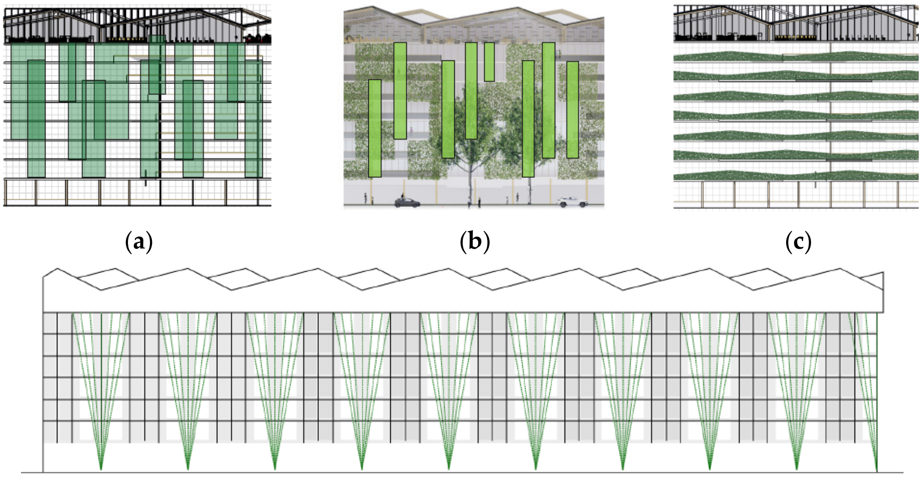
Figure A1. Development process of the final 'Modular' design: (**a**) 'Honeycomb structure' design idea; (**b**) 'Vertical folding' design idea; (**c**) 'Energy Towers' design idea.



(**a**) (**b**) (**c**)

(**d**) (**e**) (**f**)

Figure A2. Development process of the final 'Mosaic' design: (**a**) Development step 1: Terracing; (**b**) Development step 2: Folding of the façade with small folding angles; (**c**) Development step 3: Folding of the façade with enlarged folding angle; (**d**) Development step 4: Consideration of existing street trees; (**e**) Development step 5: Variation of the folding angles depending on the solar irradiation; (**f**) Development step 6: Synthesis—application of different folding angles within one façade and consideration of existing street trees.



(a) (b) (c)

(d)

Figure A3. Development process of the 'Under the city roofs' façade design: (**a**) Façade concept 1: Superposition of green elements; (**b**) Façade concept 2: Vertically oriented façade greening; (**c**) Façade concept 2: Horizontally oriented façade greening; (**d**) Final façade concept.

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