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# Implementation of a microclimate design model in the early design of new building projects – Case study Ecohof Noorderveer in the Netherlands

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A R T I C L E I N F O

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A B S T R A C T

Given the ongoing global urbanization and the rise of heat, flooding, and drought in cities, the integration of climate adaptive measures based on "ecosystem functions and services" becomes imperative in design. This study details the implementation process of a microclimate design model in the design and retrofitting of the housing project Ecohof Noorderveer in Wormerveer, the Netherlands. The model, which quantifies local urban heat and mitigating measures through ecosystem functionalities, was incorporated into the program of requirements. The design process followed a research-by-design trajectory, involving iterative creative collaboration among all stakeholders, including future residents, the municipality, the water board, and the architect. The research employed the CFIR method to compare anticipated implementation outcomes with actual results. The findings suggest that introducing the microclimate design model into the program of requirements proved beneficial for the implementation process in the early design stage. The research-by-design approach was also deemed helpful, contingent on careful involvement of all participants in the knowledge-sharing process. This implementation method demonstrates significant potential for scaling up to standard urban development projects.

## 1. Introduction

One of the problems in cities today is the extreme heat lasting for several consecutive days or weeks during summer (Wang and Yan, 2021; Serrano-Notivoli et al., 2022). By 2100, it is expected that extreme heat will affect 82% of the world's population (Yin et al., 2022). Due to the phenomenon called "urban heat island effect", cities tend to be warmer than their rural surroundings, especially during summer and at night (Hirano and Fujita, 2012). The urban heat island effect can lead to higher indoor air temperatures (Liu et al., 2017) or a higher cooling demand inside buildings (Guattari et al., 2018). This consequently leads to increased heat stress, respiratory system problems, eyes- and skin conditions and increased mortality among elderly and people with a weaker health (CBS, 2020; Ortiz et al., 2022). For example, the series of heat waves across Europe in August 2003 led to an additional 22,000–45,000 deaths that were directly linked to the prolonged high temperatures (Robine et al., 2007). As economic consequences may be noted decrease of work effectiveness by 18.5% (Pilcher et al., 2002), losing up to 33 working days per year (Shuang et al., 2019) and reducing GDP

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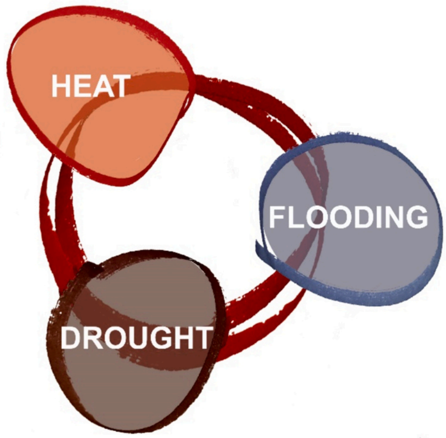


**Fig. 1.** Heat, flooding and drought are actual interrelated urban problems.

**Table 1**
Possible ecosystem services provided by green walls and green roofs (Manso et al., 2021).

| Building-scale ecosystem services | Urban-scale ecosystem services |
|---|---|
| Energy consumption reduction | Urban Heat Island (UHI) mitigation |
| Improved photovoltaic performance | Urban noise attenuation |
| Sound transmission reduction | Improved water management |
| Greywater treatment | Improved air quality |
| Increased in-service life<br>Increased property value<br>Reduced fire risk | Other (qualitative) benefits (health and well-being, biodiversity, aesthetic value, recreational use of space and urban farming) |

(*Gross Domestic Product*) by up to 2,4% (Orlov et al., *2020*). As addressed in the last IPCC report Climate Change 2023; the intensified hot extremes in urban areas compromised the whole of the urban infrastructure: transportation, sanitation, water and energy systems, resulting in economic losses and a negative effect on human well-being especially for socially and economically marginalised urban inhabitants *(*IPCC*, 2023)*.

In addition cities are growing worldwide due to the ongoing urbanization, contributing to the creation of large new surfaces of urban heat islands (Mirabi and Davies, 2022). Urban heat mitigation methods therefore needs to be improved, and new developments to be designed and built in a climate adaptive way [*UN Sustainable development goals (SDG's), source: https://sdgs.un.org/goals 2022*].

Urban heat however is part of a cohesive cyclic combination of other climate linked problems, as represented in Fig. 1, such as flooding and drought as shown by a growing number of studies (*e.g.* Zimmerman*, 2020; *Ward et al., *2020; *Shi et al., *2021; *Song et al., *2022; *Cui et al., *2022; *Yang and Yao, 2022*;* Haase and Hellwig, 2022). Due to a lack of rain fall during heat/drought periods, soil evaporates strongly resulting in its drying and finally also the drying of vegetation (Haase and Hellwig, 2022). Longer drought periods are occurring since precipitation has acquired a different frequency and intensity in recent years compared to previous years (Yang and Yao, 2022). Intensive rainfall (in the past only once every 100 years) nowadays occurs several times a year (Fathi-Taperasht et al., *2022*), but periods without precipitation are also becoming longer, especially in summer (Lv et al., *2022*).

A sustainable and effective way of reducing urban heat could be done by the use of ecosystem services in the built environment, as extensive previous research has shown (*e.g.* Costanza et al., 1997*;* MEA, 2005*;* Costanza*, 2020;* Moody et al., *2021;* Rocha et al., *2022;* Nur et al., *2022;* Fini et al., *2022;)*. Ecosystem services (ES) are the ecological characteristics, functions, or processes that directly or indirectly contribute to sustainable human wellbeing (Costanza, 2020). Ecosystem services are provided by natural elements and they can be integrated in specific design strategies, as shown in Table 1*,* in order to provide solutions for typical socio-environmental problems in urban areas (Manso et al., 2021) for example shows, urban ecosystems such as green walls and vegetated roofs can provide several ecosystem services on either a building or urban scale (Table 1).

Different properties or functions of ecosystems were analysed and partly quantified by scientific research, such as the state of existing ecosystems (Jha et al., *2022*), their cooling effect (Park et al., *2021*), crop production, air quality regulation, improved human health, pest control, socio-cultural values and increased real estate value (Paulin et al., *2020*). Quantification is necessary for the functional use of ecosystems and their services in spatial design. Through quantification, their contribution to, for example, urban cooling (or air purification, sound insulation, *etc.*) can be included in the climate adaptation strategy of buildings, can be tested and possibly standardized.

Quantifying ecosystem services presupposes establishing the indicators relevant to the functional application. These indicators must then be quantified. For example, for cooling, the gradient between the surface temperature of the material is an indicator that determines the amount of convection and long-wave radiation, but also for the transpiration of plants. The albedo of the materials and vegetation determines the amount of thermal energy absorbed (Mills and Stewart, 2021). By the implementation of quantified ecosystem services in the urban design, a new climate design strategy could be developed to solve urban problems, including urban heat (TEEB 2010, https://teebweb.org/publications/teeb-for/research-and-academia/).

Although the implementation of quantified ecosystem services into practice were the subject of a growing number of studies in recent years (*e.g.* Tamm et al., *2013;* Veretennikov and van der Veeren, 2019*,* Dagnachew et al., *2021;* Damschroder et al., *2022*) there is still a knowledge gap between theory and practice according to Qiu et al., 2022. Qiu reports in his literature review that the knowledge gap restricts the insight in how to integrate ecosystem services research, and quantifications with respect to planning (Qiu et al., *2022*).

To improve the implementation strategy of scientific research and innovation(s) into practice, Damschroder developed the Consolidated Framework For Implementation Research (CFIR). Although developed originally for the implementation of scientific innovations in the health sector, the CFIR's systematic framework can be extrapolated to other areas, including the field of urban climate adaptation. It identifies the factors that support (facilitate) or hinders the implementation process as determinants (Damschroder et al., 2009). As an example, the way of commissioning could be a hinderance for implementation and therefore a negative determining factor for the whole process (Gold et al., *2022*). Sharing knowledge with stakeholders and the involvement of all stakeholders in the decision making process on the other hand may create support and can be seen as such a.

facilitator force, a positive determinant for the implementation efforts (Damschroder et al., 2022).

The implementation of scientifically developed models in practice is a critical interdisciplinary step according to Xu and his team (Xu and Peng, 2022) to achieve sustainable cities. During this step the physical results of urban climate design methods will have to be translated into concrete decision making and urban and architectural design measures (Grunewald et al., *2021*). For the best possible 'translation' and thus implementation, the chosen architectural design method must reach the target group made up of all stakeholders involved in the construction (Mason et al., *2020*).

Lortie states that the implementation of quantified ecosystem services in the design depends on a series of actions concerning the *phase* when to introduce the model in the process and the *design method* (Lortie and Owen, 2020). Both can be defined as determinants following Damschröder's framework.

The *phase* when to introduce the model in the design process defines the integral approach. The sooner the introduction takes place, the better all participants can understand it and integrate it into the overall design (Klaic et al., *2022*). An example for an early moment in the design process is the **program of requirements**. The program of requirements is the most exact possible description of the wishes for a construction project. It is formulated at the beginning of the design process and forms the basis/frame for the design.

For a better understanding and broader support, the design method should *involve stakeholders* during the whole design process (Ehn*, 2008*). For this, the participation of all stakeholders should be stimulated through the design process itself. **Research by design** is a *design strategy* using an iterative creative process of alternating steps of knowledge input, design, feedback and correction (Zeisel, *2006*). It involves, from the start, all stakeholders in the design decisions (Nijhuis et al., *2020*). This design strategy can be applied to any project, where there is a desire to find a solution tailored for the given location (Hinterleitner et al., *2021*).

To assess whether these two strategies act as hindrances or facilitators for implementing a science-based climate design model in practice, this research scrutinized the case of a housing project in Wormerveer, The Netherlands. A climate design model was developed based on quantified ecosystem services in order to use in the early design phase of the project. The research aimed to determine whether introduction of the obtained data, calculated by the used climate design model, into the program of requirements and following a research by design process, may be a generally applicable implementation strategy for comparable projects.

The research is guided by the following questions:

1. Is the integration of the utilized climate design model's outcomes into the program requirements, along with the adoption of a research-by-design process, a valuable strategy for incorporating quantified ecosystem services into urban and architectural design?
2. Did the introduction of the model-calculated results in the program of requirements act as an impediment or a facilitator in the implementation process?
3. Was the research-by-design process a hindrance or a facilitator in the implementation process, acting as either a barrier or a facilitating factor?

## 2. Research methodology

The research investigated timelines, reports of the mutual discussions and sketches made during the design process by the architect and the participants. A comparison was made between the formulated ambitions and the in fact designed measures. The purpose of the comparison was to determine to what extent the ambitions were actually materialized in the final design. Aspects considered as influential for the design process, such as the type of commissioning (i.), knowledge sharing (ii.) and the design decisions process (iii.), were also explored and categorised as hindrances or as facilitators:

i. *Commissioning* – how the types of commissioning influenced the implementation results?
ii. *Knowledge sharing process* - to what extent the knowledge offered was actually understood and internalized by the participants according to the sketches drawn by the future residents?

**Fig. 2.** Photos of the existing school building in the original state.

**Fig. 3.** Case study "Ecohof Noorderveer"; illustration of the present situation and an edited image illustrating the future according to the ambitions of the future residents (Source Google Earth, left original, right edited image).

iii. *Design decision process* – what was the actual participation of the stakeholders to the decision moments, according to discussion reports?

## 3. Ecohof Noorderveer - Project description

### *3.1. The housing project*

Ecohof Noorderveer is a housing project in the village Wormerveer, province of North Holland, the Netherlands (*www.ecohofnoorderveer.nl*). The project area is owned by the municipality of Zaanstad and is around 3500 $m^2$. The existing buildings, built in 1954, were used as a school. As the photos in Fig. 2 show, the original school building was designed in a simple but attractive manner in a light Amsterdam School style. Its architecture was considered valuable enough by the future residents and municipality to be mostly preserved and only partially demolished. The new owner-occupied homes will be built inside the existing school building in places where the classrooms were initially located.

After retrofitting the existing buildings, the number of the new dwellings will be 11 for sale and 12 apartments for rent in the social housing category.

The project was initiated in 2013 by a private *group* of 11 families, the future residents. In addition a 'core group' was formed of different stakeholders: the housing corporation Parteon, the architect, the construction and sustainability advisors, the municipality (owner of the lot) and the water authority. All were involved in the design process from the beginning.

The motivation and initial ambition of the group of future residents was to build an urban ecological housing project. The desire of the residents was to: "not damage nature by building" without specifying the particular nature, the degree of damage, or the means to avoid harm (Fig. 3). The presented research aimed to transition from vague goals to quantifiable objectives. Through this process, the overarching goal of avoiding harm to nature was refined to include objectives such as achieving circularity (preserving existing buildings), cooling through ecosystems rather than air conditioning, and implementing water storage for irrigation during drought periods.

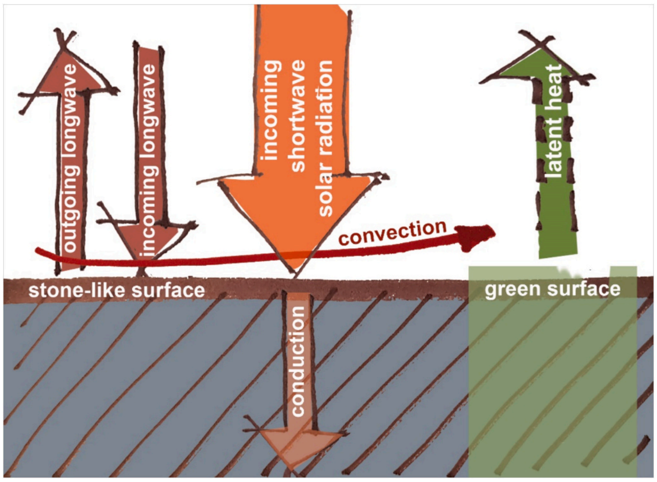


**Fig. 4.** The energy balance scheme of urban surface materials for the incoming shortwave solar radiation and incoming and outgoing long-wave radiation.

The future residents' group and the municipality jointly aimed to realize a pilot project that incorporates climate-adaptive measures to the greatest extent possible, beyond the standard sustainability requirements outlined in existing building regulations.

### *3.2. The microclimate design model*

The used model to design the urban microclimate is based on the principles of the energy balance of urban surface materials (Fig. 4) according to the research by Mills on the thermal behaviour of urban surfaces (Mills and Stewart, 2021) and on specific research on the thermal behaviour of building materials and urban vegetation (Stache et al., 2021). It calculates the *energy exchange* of the location defined by the local surface materials (including vegetation and water). Considering the incoming shortwave radiation ($kJ/m^2$) and incoming and outgoing longwave radiation ($kJ/m^2$) using local meteorological databases, the model quantified local convection, longwave radiation and latent heat production ($kJ/m^2$). The storage term was not included in the microclimate design tool because it was assumed that the accumulated heat from the mass of the surface materials returns to the surface over time as the temperature difference reverses. Because it then heats up the surface again, this energy will ultimately contribute to the convective and radiative heat.

The surfaces most sensible to heat (*Fig. 5a*), due to reflections of the solar radiation (*Fig. 5b*) were designated. Based on the results, the water amount to be evaporated ($l/m^2$ *or* $m^3$) in order to reduce surface temperatures (and consequently convection) can be determined. The necessary amount of vegetation surface to replace traditional building materials and evaporate the needed amount of water, was finally calculated.

Prior to the design process, location studies have been carried out in order to understand the local climate. Additionally, the reflective areas were identified. Due to reflections, part of the energy (depending on the albedo of the surface) is "transmitted" to the environment. Surfaces that receive this 'redirected' radiation are also heated up by the amount of reflection received. The surfaces heated by reflection were examined and identified by the architecture program Archicad 25 and resulted in a surfaces map, shown in *Fig. 5a*. To determine shadow locations and reflective surfaces, the sun angles during a summer day at the specific location were used as input parameters as shown in *Fig. 5b*.

### *3.3. Implementation process*

The calculation results of the microclimate design model were included in the program of requirements and incorporated in the design during the research by design process. Following the early introduction in the programme of requirements the ambitions were quantified. The original aim of *building sustainable houses without damaging nature* was specified and re-formulated as *the aim of a heat-neutral, water-neutral place for living, considering also biodiversity, circularity and energy-neutrality as important issues (source: https://www.ecohofnoorderveer.nl)*.

Participation, which followed the Implementation Process Scheme represented in Fig. 6, was defined as the involvement of the future residents in the research by design process. The participative research by design process started with the understanding of the calculation outcomes, which were used as a base for the design. It included several techniques as drawings, schemes, graphics, visual methods, model building, making sketches and transpositions in a 3D virtual environment. The design sketches were evaluated by all stakeholders for positive and negative aspects concerning the proposed energy system, heat production strategy, cooling strategy, water management and circularity. Also municipal experts on climate and water management were involved. Based on different feedback-loops the design was adapted several times. During all phases, design decisions were taken by the group. For each decision


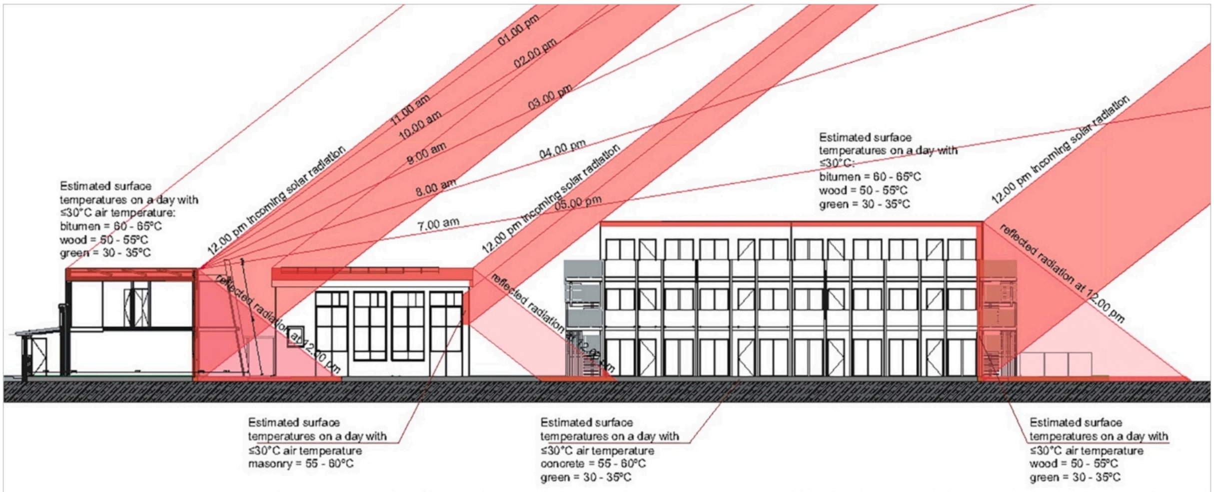


**Fig. 5.** a: Original study, used in the research by design, of the positioning of surfaces receiving shadows and reflections caused by the incoming shortwave solar radiation, for the whole building complex. The grey surfaces represent the shadowed areas, the red areas represent the surfaces with reflection. b::Original study, used in the research by design, of the surfaces receiving reflections caused by the incoming shortwave solar radiation and the estimated surface temperatures of the different building materials based on specific research (Stache et al., 2021) and built up by Archicad 25.

moment a presentation and workshop was organised, as shown in Fig. 7. During the workshops of about 3 or 4 h first the changes in the design were presented, followed by a plenary discussion about the results and design moments, with sketches and 3D models (Fig. 8). Finally decisions were taken.

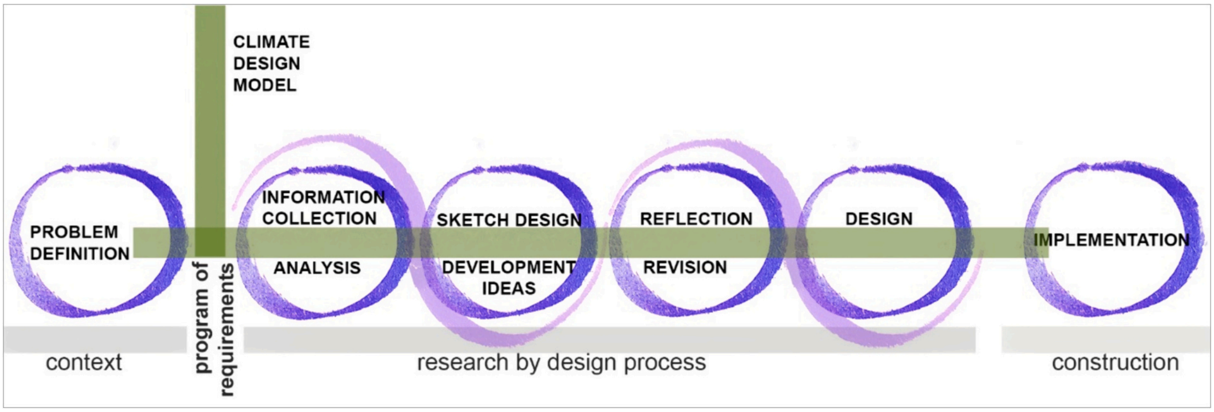


**Fig. 6.** The implementation process scheme.

**Fig. 7.** Model building workshop by the group of future residents.

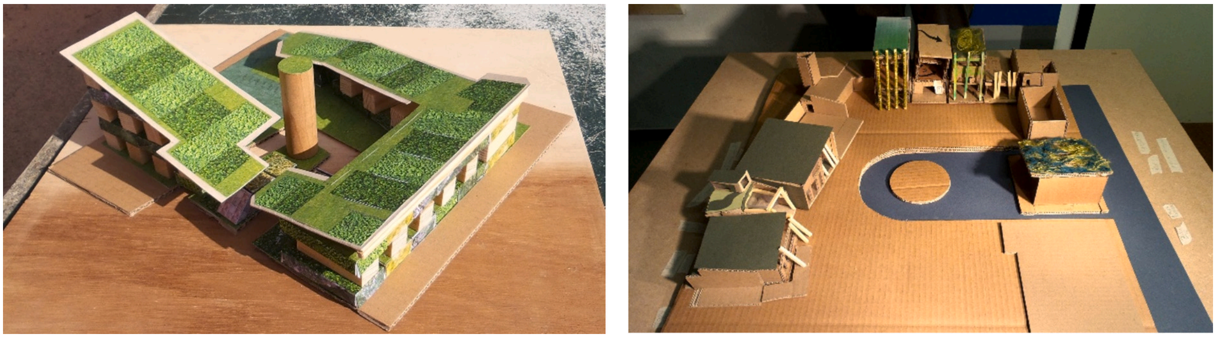

**Fig. 8.** First model built by the architect before participation sessions, and second model built together with the future residents.

## 4. Research results

The introduction of the microclimate design model in the program of requirements has resulted in the replacement of the **unquantified initial ambition** (‘*no harm to nature*’= *a general whish*) by **quantified ambitions**. The ambitions formulated based on the model calculations were related to heat - *heat neutrality* -, short term floodings - *water neutrality* - and indirectly to energy - *energy neutrality*. The first two ambitions were directly calculated by the model. The last one, energy, was calculated by the legally required method which also used as input the air temperature data of the model and as such was not a subject in this research. Relevant results are presented in Table 2. The ambitions related to circularity, social aspects and waste processing are not a subject in this research either, as they were not related to the model.

In order to validate the results the comparison (Table 2) was made between the calculated requirements/ambitions (*anticipated outcomes)* and measures eventually introduced in the design (*actual outcomes)* according to Damschröder's CFIR method (Damschroder et al., 2022). The comparison shows the results of the implementation efforts in the final design.

**Table 2**
Comparison of anticipated outcomes (calculated ambitions) and the actual outcomes (actually introduced climate adaptive measures) in the final design according to the CFIR method by Damschröder (Damschroder et al., 2022).

| *Ambition* | *Anticipated outcomes* | *Actual outcomes* | *Comparison* |
|---|---|---|---|
| *Heat neutral garden side* | incoming solar 28,951 kJ/m$^2$day = 5003 kJm$^2$day convection +25,014 kJ/m$^2$day latent heat. | 5003 kJ/m$^2$day convection and 25,014 kJ/m$^2$day latent heat production was designed. | *ambition* ***achieved*** |
| *Heat neutral street side* | received solar radiation (60% because of orientation) 12,854 kJ/m$^2$day convection heat from masonry +11,291 kJ/m$^2$day sensible heat from wood surfaces. | no green areas were designed which means that the total absorbed solar energy will be transformed into sensible heat from the facade. | *ambition* ***not achieved*** |
| *Water neutral* | incoming 870 mm/year on the lot = 870 mm/year used on the lot. | relative water neutrality has been achieved in the design, with the caveat that the water absorbed by the soil is nevertheless added to the groundwater. | *ambition* ***achieved*** |
| *Energy neutral* | total used energy/year = total produced energy/year. | this requirement is calculated considering the cooling capacity of the greenery and can be achieved according to the design. | *ambition* ***achieved*** |

**Fig. 9.** The garden side of the project, with 80% of the surfaces shadowed or replaced by greenery.

**Fig. 10.** The street side of the development, without vegetation added.

**Heat neutrality** was defined as a ratio of at least 1 between convective heat and latent heat, based on the ratio of Bowen (Bowen, 1926). According to Bowen by a ratio of 1, no warming up of the.

surrounding air will take place. The ambition to realize a Bowen ratio lower than 1, which means cooling, was succeeded in the inner courtyard of the housing project, but not realized on the street side. According to the design, in the courtyard, 80% of all facades will be shaded or covered by plants realizing a ratio of Bowen of 0,25. The anticipated outcomes at this side were achieved in the final design as shown in Fig. 9.

In contrast, as shown in Fig. 10, no walls will be covered or shaded by plants on the street sides. The reason for this was the decision of the monument conservation team of the municipality, stating that the original street view and its monumentality has to be preserved. Both aspects, monumentality and climate adaptation, were discussed and considered in the co-creation process with several specialists of the municipality, the future residents and the architect. There was consensus reached to retain the monumentality on the street side, to the detriment of climate adaptation. Because on the street side no vegetation will be added on the facades, the ratio of

**Table 3**
Comparison between 11 housing projects at primary school locations in different regions in the Netherlands.

| Project | Participation future residents | Participation information of local residents | Circularity - preservation of existing buildings | Energy neutral | Energy efficient | Heat neutral | Green environment | Water neutral |
|---|---|---|---|---|---|---|---|---|
| De Toonladder | | x | | | x | | x | |
| De Krullevaar | | x | | | x | | | |
| De Lier | | | | | x | | | |
| Schoolstraat | | x | | | x | | | |
| 3 schoollocations | | x | | | x | | x | |
| Brinkschool | | | | | x | | | |
| De Rieburg | | x | | | x | | | |
| School en Kloosterlocatie | | x | | | x | | | |
| Jubbega | | x | | | x | | x | |
| Het Veer | | x | | | x | | x | |
| Ecohof Noorderveer | x | x | x | x | x | x | x | x |

Bowen will exceed 1 on this location.

**Water neutrality** was introduced by the North Holland Water Board (*Hooghemraadschap Hollands Noorderkwartier, HHNK*) in consultation with the group. It means that all the rainwater falling on the plot shall be used on the plot. For this purpose the various possibilities for water use were mapped, and the amount of vegetation needed to achieve a ratio of Bowen lower than 1 was calculated. The results showed that all the rainwater which is not directly infiltrated in the ground, needs to be collected and stored to be used during drought periods. According to the water management design, approximately 35% of all rainwater that falls on the roofs and the paved parts of the plot could be collected, and stored in water tanks under the buildings or terrasses. A part of the stored water can be used to flush the toilets. The remaining approximately 65% of water that cannot be collected, will infiltrate into the ground or evaporate directly from the various paved (porous) surfaces, soil or plant leaves. The design created a system to use all of the available rainwater on the plot, as was the ambition formulated in the program of requirements. The anticipated outcomes were achieved in the final design.

**Energy neutrality**, defined as "no more energy is consumed than what is produced", was set as a requirement by the group. When calculating energy neutrality, the effects of quantified ecosystem services such as cooling and water retention, were also taken into account. Energy neutrality was calculated as the ratio between the energy used and produced. To reduce energy consumption, the buildings have been designed with passive house construction details, to avoid thermal bridges. The glass surfaces will have a U value of 0.7 W/($m^2$ K), (the currently used glass U value according to the legislation is 1 W/($m^2$K)). The cooling of the air by the added vegetation was taken into account in the calculation of the energy demand. In the final design ten solar panels per family were incorporated. The anticipated outcomes were achieved in the final design.

The effect of **participation** in the research by design process was investigated by a comparison with 10 other projects redeveloping old primary school locations which did not involve participation of future residents in the design process (*see* Table 3). The comparison investigated the achievements on circularity through the preservation of existing buildings, energy, heat and water neutrality, with and without participation of future residents in the design process.

It is important to mention that biodiversity was not part of the project or of this research. The greenery used was deemed to meet the requirements calculated by the microclimate design tool, but it was not specified which species meet these requirements. Nor was it a requirement to increase biodiversity. The residents have had complete freedom to choose plant species that meet the calculated requirements without also having to take biodiversity into account.

## 5. Discussion

Analysing the implementation process according to the CFIR by Damschröder there were found two important determinants: knowledge sharing and participation.

Knowledge sharing was first introduced at a very early moment and continued during the whole design process. The understanding of the climatological processes, the calculation methods developed by the TU Delft and their recommendations, created a supporting base by the participants. Due to this supporting base that was continuously maintained during the design process, the high climate adaptive ambitions could be formulated.

This kind of knowledge sharing was possible due to the early introduction of academic knowledge in the process. It also created an environment where knowledge became attractive and necessary. According to the discussion reports, the participants showed a kind of knowledge hunger, looking for more in each consecutive phase of the design process. The early introduction of the scientific microclimate design model in the program of requirement was therefore found a facilitator force for the implementation process.

The process of acquiring and using knowledge for the design was also supported by the participative design process. All future residents were encouraged to share the knowledge found and in each phase the design was adapted to the new insights. Also specialists from the municipality and the water board participated in the knowledge sharing and design process. Due to the participation of all stakeholders and the knowledge sharing and participative design method, the final project shows a significant amount of knowledge applied in the design.

Knowledge sharing was found to be a defining factor of the design process. We can state that about a third of the future residents fully interiorised the information provided - according to the analyses of the sketches made by them (based on the outcomes of interviews, logbooks and the sketches). Although the remaining two third not all fully understood the complex data, they were sufficiently involved to be able to participate in the decisions. The research by design process offered an appropriate frame for the participative and intensive knowledge acquiring and sharing.

Both the knowledge sharing and the collective design process were found to have had a facilitator effect on the implementation of the microclimate design model in the project. This results are congruent with those reported in literature (*e.g.* Portman, *2013*; Qiu et al., *2022*).

The comparison between the 11 housing projects at primary school locations in various regions in the Netherlands shows that, with the exception of the Ecohof project, none have considered retaining the existing building in connection with circularity. Also, none of the other 10 projects has achieved the ambition level of heat and water neutrality.

The early introduction of the microclimate design tool in the program of requirements created the time for all participants to familiarize themselves not only with the content and use of the calculation model but also the water management, circularity, and energy transition principles and to understand the results properly. As a consequence all stakeholders, including the municipality and water board, adhered to the requirements and, during the research by design process, jointly investigated the possibilities for realizing these requirements.

It is a shortcoming of the project that biodiversity was not a subject for the project. Further pilot projects should also include this important aspect in the design process.

While the expected sustainability goals were met on the garden side, achieving the same on the street side proved unattainable, primarily due to the building's monument status conferred by the municipality. The preservation of the culturally and historically significant street view of the building precluded the implementation of climate adaptive measures. Simultaneously, it is anticipated that the densely vegetated garden side will contribute to a broader environmental cooling effect, although this aspect was not investigated in this study.

Addressing the application of climate adaptive measures in areas with high culturally and historically valuable street views or buildings poses a compelling question in sustainability processes within existing urban areas: How far should we go in redesigning these buildings/areas in term of climate adaptation or to create resilient cities? Although this critical question related to urban climate adaptation and sustainability was only indirectly addressed in this study, it represents crucial considerations for future projects, especially in the dense and older parts of (historical) cities. Consequently, further research is recommended to explore these aspects in more depth.

The influx of knowledge is intrinsic to research by design, and co-creation is also an increasingly used ingredient. Research by design works well in complex issues where many different stakeholders are involved. It can be a key to bringing together knowledge, people and an executable plan (Hinterleitner et al., *2023*). In the Ecohof project, the research by design process has opened the way for discussions about possible solutions. All stakeholders invested time and effort in finding the best possible solution for the formulated ambitions. Triggered by these high ambitions, people started to search for technical innovations that could make the ambitions come true. Analysis showed that the design process using visual methods, model building and sketching contributed to a better understanding. The active knowledge-sharing method (*e.g.* drawing sketches by participants), has been able to remove barriers linked to lacks of understanding (*e.g.* the climatological processes), by at least a third of the group.

The *project organisation* was defining the decision making process. As there was no regular developer or investor involved, the group of future residents could make different and less profit oriented decisions than a developer would make. The participation of the future users/residents in the project may therefore be also considered as 'facilitator factor' for the implementation process, a result congruent with results reported by Damschröder (Damschroder et al., 2022). However the research did not investigate the social composition of the participants group which may be a determinant factor (Damschroder et al., 2009). This aspect should be investigated further in a following research.

Although this research found that both, knowledge sharing and research by design, are facilitator factors for the implementation of scientific innovation in building projects, the question however remains whether the method applied at the Ecohof, can be scaled up to be applied in other projects and become part of standard design trajectories. How can scientific models and data be introduced in cases where there is no scientist in the design team? How can the iterative process of research by design, the knowledge sharing and the participative design decisions be implemented in cases where future residents might not be on board yet?

The architect plays a crucial role in promoting climate adaptation measures within construction projects, provided they possess the necessary knowledge and can effectively communicate it. The Ecohof project stood out due to the unique aspect of having a PHD candidate as an architect, a circumstance uncommon in conventional design and construction procedures. To enhance architects' understanding of recent scientific research, additional research is warranted. Potential strategies to tackle this issue may include:

- Make an innovative low-threshold climate adaptation toolbox easily available to designers and initiators of construction projects;
- Involve municipal advisors on climate adaptation in scientific knowledge sharing processes;
- Involve universities better in practice;
- Collaborations between universities and sectors or professional organisations;
- Specializations within the architectural profession towards climate-adaptive innovations.

The role of the municipality in advancing new science based climate adaptation measures in construction projects appears to be limited. Municipalities are bound by the legal requirements for climate adaptation. In the case of Ecohof, the ambitions set by the initiators went beyond the legal requirements. The municipality has welcomed this initiative but has had no resources to test or help the innovations.

The role of the future residents, defined by the participation in the research by design methodology, turned out to be decisive for the decisions taken. It was of great importance that future residents could determine their own future living environment and sustainability standards. Although the design process was longer and more complex, the results represent the real wishes of the end users. This differs from construction projects realized by developers where the end users (future owners) have no say in the future living environment. Further research could clarify how future residents/end-users can be better involved in design processes where they are not the developing party.

## 6. Conclusions

This research delved into the integration of a microclimate design model in the Ecohof Noorderveer design (case study), utilizing the CFIR method proposed by Damschröder (Damschroder et al., 2022). The investigation primarily focused on assessing the impact of two key determinants: firstly the degree to which incorporating the microclimate design model into the program of requirements acted as either a hindrance or a facilitator, and secondly the extent to which the research-by-design process contributed to streamlining the implementation process.

The approach implemented at Ecohof Noorderveer project resulted in the successful incorporation of a substantial number of climate adaptive measures. Both introducing the microclimate design model at an early project stage (within the program of requirements) and engaging in an iterative creative process through research by design were identified as facilitating factors in the implementation process.

The municipality's role was deemed insignificant, given the absence of legal mechanisms to regulate innovative climate adaptive measures not covered by existing legislation. Conversely, the architect/scientific researcher's role was identified as pivotal in the knowledge-sharing process. Given that not all architects possess the requisite academic knowledge, alternative methods of disseminating this knowledge are essential. This could involve creating an easily accessible innovative climate adaptation toolbox for designers and project initiators or establishing municipal advisors focused on climate adaptation. In the former scenario, developers could contribute to implementing climate adaptive strategies in their projects, while in the latter, municipalities should take the lead in integrating new knowledge into the design process. In both cases, universities should play a central role in providing accessible knowledge for all stakeholders involved in building projects.

The implementation strategy employed in this project holds the status of a pilot project, but its core values exhibit significant potential for integration into standard procedures for urban development projects.

## CRediT authorship contribution statement

**E. Stache:** Validation, Resources, Project administration, Methodology, Formal analysis, Data curation, Conceptualization, Writing – review & editing, Writing – original draft. **J. Hinterleitner:** Conceptualization. **M. Ottelé:** Supervision, Methodology. **H.M. Jonkers:** Supervision.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Appendix A. Appendix

Short description of the model used to design the local microclimate in the Ecohof Noorderveer project.

### *A.1. Purpose of the model*

The aim of the model was to identify the energy flows generated by the incoming solar radiation at the surface of various building materials and vegetation in the project and calculate their quantities.

### *A.2. Methodology*

The model used existing physical equations (*Incropera* 2017) to calculate the amount of absorbed energy $Q_a$ and identify and quantify the convective heat flux $Q_H$, radiative heat flux $Q_R$ and latent heat flux $Q_E$ produced by the urban surfaces and vegetation under a specific incoming short wave solar radiation during a heat period. The calculations were based, according to the results by Mills (Mills and Stewart, 2021) on the premise:

$$Q^* = Q_H + Q_R + Q_E + Q_G \tag{1}$$

Parameters for the calculation were found in literature or were calculated based on specific research described in the article 'Comparative analysis in thermal behaviour of common urban building materials and vegetation and consequences for urban heat island effect' by Stache (Stache et al., *2021*). In Table A there is an overview presented of the parameters and equations used for the model.

**Table A**
of used parameters and the way they were obtained.

| *Parameter* | *Symbol* | *Derived from:* | *Source:* |
|---|---|---|---|
| Albedo | r | Estimated based on literature | Incropera (2017)<br>Stache et al., 2021 |
| Incoming shortwave radiation | $S\downarrow$ | KNMI data | KNMI |
| Emissivity (broad spectrum) | $\varepsilon$ | literature | Incroper (2017) |
| Absorbed energy by the surface | $Q^*$ | $(1 - r)\, S\downarrow$ | Incropera (2017) |

(*continued on next page*)

**Table B**
of the maximum surface temperatures used in the model.

| *Materials* | *albedo* | *Max. Ts from literature* | *Max. Ts from measurements* |
|---|---|---|---|
| | | °C | °C |
| masonry | 0.26 | 57.4 | 58.2 |
| concrete | 0.13 | 57.3 | 57.5 |
| wood | 0.35 | 50.1 | 51.1 |
| vegetation | 0.09 | 37.3 | 38.1 |

**Table A** (*continued*)

| *Parameter* | *Symbol* | *Derived from:* | *Source:* |
|---|---|---|---|
| Convectional heat flux | $Q_H$ | $h\ (A)(T_s - T_{air})$ | Incropera (2017) |
| Convection coefficient | $h$ | calculated by Nusselt number | Incropera (2017) |
| Radiative heat flux | $Q_R$ | $\varepsilon \cdot \sigma \cdot (A)(T_s - T_{air})^4$ | Incropera (2017) |
| Conductive heat flux | $Q_G$ | $k(T_s - T_{sub})$ | Incropera (2017) |
| Materials conductivity | $k$ | literature | Incropera (2017) |
| Latent heat flux | $Q_E$ | $\phi \Delta h_{fg}$ | eq. (9) |
| Latent heat of evapotranspiration | $hfg$ | $(Q^*\text{-}Q_H\text{-}Q_R)/\ \Delta h_{fg}$ | Mills (20121) |
| Surface temperature | $T_s$ | measurements *in situ* | Testo 810 2 |
| Rate of evapotranspiration | $\phi$ | Calculated based on literature | Stache et al., 2021 |
| Air temperature | $T_{air}$ | KNMI data | KNMI |
| Involved area surface | A | measurements *in situ* | |
| Stefan-Boltzman constant ($5.67 \cdot 10^{-8}$ $Wm^{-2}$ $K^{-4}$) | σ | literature | Incropera (2017) |

The stored energy $Q_G$ was not included in the microclimate design tool because it was assumed that the accumulated heat from the mass of the surface materials returns to the surface over time as the temperature difference reverses. Because it then heats up the surface again, this energy will ultimately contribute to the convective and radiative heat.

The maximum surface temperatures (used to calculate the gradients with the air temperature) of the existing building components were measured *in situ* on three consecutive hot days in august 2018. The results were congruent with data from our own laboratory measurements and literature as shown in Table B:

### *A.3. Results*

A total of 28,951 kJ/m2·day of incoming thermal energy was considered in the calculation of climate adaptive measures. Based on preliminary research by Stache, wood, masonry, and concrete were expected to absorb 65%, 74%, and 87%, respectively, resulting in absorbed solar energy of 18,818 kJ/m2·day, 21,424 kJ/m2·day, and 25,187 kJ/m2·day (Stache et al., 2022*)*. To offset this energy, 8 l/m2·day, 9 l/m2·day, and 10 l/m2·day of water are required, respectively. Plants convert their absorbed energy into transpiration and latent heat production, providing a cooling effect. To minimize convectional and radiative heat production, it was recommended to strategically place vegetation covering at least 80% of the surface (both vertical and horizontal) to reduce heat production by 80%.

### *A.4. References*


Incropera, Incropera's Principles of heat and Mass Transfer. Wiley 2017, Global Edition, 8th edition.

Mills G., Stewart T.D., The urban heat island – A guide book, Elsevier, 2021.

Stache E., Schilperoort B., Ottelé M., Jonkers H.M., Comparative analysis in thermal behaviour of common urban building materials and vegetation and consequences for urban heat island effect, *Building and Environment* (2022), doi: https://doi.org/https://doi.org/10.1016/j.buildenv.2021.108489.


## References


Bowen, I.S., 1926. The ratio of heat losses by conduction and by evaporation from any water surface. Phys. Rev. 27 (6), 779–787. Bibcode:1926PhRv...27..779B. https://doi.org/10.1103/PhysRev.27.779.

CBS, 2020. Tijdens hittegolf vooral meer sterfte in langdurige zorg [online], accessed 1 September 2021,. https://www.cbs.nl/nl-nl/nieuws/2020/35/tijdens-hittegolf-vooral-meer-sterfte-in-langdurige-zorg.

Costanza, R., 2020. Valuing natural capital and ecosystem services toward the goals of efficiency, fairness, and sustainability. J. Ecosyst. Serv. 43, 101096 https://doi.org/10.1016/j.ecoser.2020.101096.

Costanza, R., Ralph, d'Arge R., de Groot, R., Farberk, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Suttonkk, P., van den Belt, M., 15 May 1997. The value of the world's ecosystem services and natural capital. Nature 387.

Cui, H., Jiang, S., Ren, L., Xiao, W., Yuan, F., Wang, M., Wei, L., 2022. Dynamics and potential synchronization of regional precipitation concentration and drought-flood abrupt alternation under the influence of reservoir climate. J. Hydrol. Reg. Stud. 42, 101147 https://doi.org/10.1016/j.ejrh.2022.101147.

Dagnachew, A., Hof, A., van Soest, H., van Vuuren, D., Climate Change Measures And Sustainable Development Goals, 2021. Mapping synergies and trade-offs to guide multi-level decision-making, Climate change measures and sustainable development goals © PBL Netherlands Environmental Assessment Agency. In: The Hague. PBL publication number: 4639.

Damschroder, L.J., Aron, D.C., Keith, R.E., Kirsh, R., Alexander, J.A., Lowery, J.C., 2009. Fostering implementation of health services research findings into practice: a consolidated framework for advancing implementation science. Implement. Sci. 4, 50. https://doi.org/10.1186/1748-5908-4-50.
Damschroder, L.J., Reardon, C.M., Marilla, A., Widerquist, O., Lowery, J., 2022. Conceptualizing outcomes for use with the consolidated framework for implementation research (CFIR). Implement. Sci. 17, 7. https://doi.org/10.1186/s13012-021-01181-5.
Ehn, P., January 2008. Participation in Design Things, Conference Paper. https://doi.org/10.1145/1795234.1795248. Source: DBLP.
Fathi-Taperasht, A., Shafizadeh-Moghadam, H., Minaei, M., Xu, T., 2022. Influence of drought duration and severity on drought recovery period for different land cover types: evaluation using MODIS-based indices. Ecol. Indic. 141, 109146 https://doi.org/10.1016/j.ecolind.2022.109146.
Fini, A., Frangi, P., Comin, S., Vigevani, I., Rettori, A.A., Cecilia Brunetti, C., Moura, B.B., Ferrini, F., 2022. Effects of pavements on established urban trees: growth, physiology, ecosystem services and disservices. Landsc. Urban Plan. 226, 104501. https://doi.org/10.1016/j.landurbplan.2022.104501.
Gold, H.T., McDermott, C., Hoomans, T., Todd, H., Wagner, T.H., 2022. Cost data in implementation science: categories and approaches to costing. Implement. Sci. 17, 11. https://doi.org/10.1186/s13012-021-01172-6.
Grunewald, K., Bastian, O., Louda, J., Arcidiacono, A., Brzoska, P., Bue, M., Cetin, N.I., Dworczyk, C., Dubova, L., Fitch, A., Jones, L., La Rosa, D., Mascarenhas, A., Ronchi, S., Schlaepfer, M.A., Sikorska, D., Tezer, A., 2021. Lessons learned from implementing the ecosystem services concept in urban planning. Ecosyst. Serv. 49, 101273 https://doi.org/10.1016/j.ecoser.2021.101273.
Guattari, C., Evangelistia, L., Balaras, C.A., 2018. On the assessment of urban heat island phenomenon and its effects on building energy performance: a case study of Rome (Italy). Energ. Build. 158, 605–615. https://doi.org/10.1016/j.enbuild.2017.10.050.
Haase, D., Hellwig, R., 2022. Effects of heat and drought stress on the health status of six urban street tree species in Leipzig, Germany. Trees Forests People 8, 100252. https://doi.org/10.1016/j.tfp.2022.100252.
Hinterleitner, J., Daamen, T., Nijhuis, S., 2021. Design studio performance in complex spatial projects: lessons from the Netherlands. J. Urban Des. https://doi.org/10.1080/13574809.2021.1917986.
Hinterleitner, J., Van der Linden, H., Daamen, T., 2023. Ontwerpen in gebiedsontwikkeling. Chair of Urban Area Development, Delft University of Technology, Ontwerpend onderzoek als strategisch instrument voor visievorming en versnelling.
Hirano, Y., Fujita, T., 2012. Evaluation of the impact of the urban heat island on residential and commercial energy consumption in Tokyo. Energy 37, 371–383. https://doi.org/10.1016/j.energy.2011.11.018.
IPCC, 2023. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, p. 184. https://doi.org/10.59327/IPCC/AR6-9789291691647.
Jha, S.K., Negi, A.K., Alatalo, J.M., 2022. Quantification of ecosystem services providing socio-economic benefits to customary owners of natural resources in Pauri, western Himalaya. Curr. Res. Environ. Sustain. 4, 100121 https://doi.org/10.1016/j.crsust.2021.100121.
Klaic, M., Kapp, S., Hudson, P., Chapman, W., Denehy, L., Story, D., Francis, J.J., 2022. Implementability of healthcare interventions: an overview of reviews and development of a conceptual framework. Implement. Sci. 17, 10. https://doi.org/10.1186/s13012-021-01171-7.
Liu, Y., Stouffs, R., Tablada, A., Wong, N.H., Zhang, J., 2017. Comparing micro-scale weather data to building energy consumption in Singapore. Energ. Build. 152, 776–791.
Lortie, C.J., Owen, M., 2020. Ten simple rules to facilitate evidence implementation in the environmental sciences. FACETS 5, 642–650. https://doi.org/10.1139/facets-2020-0021.
Lv, P., Rademacher, T., Huang, X., Zhang, B., Zhang, X., 2022. Prolonged drought duration, not intensity, reduces growth recovery and prevents compensatory growth of oak trees. Agric. For. Meteorol. 326, 109183 https://doi.org/10.1016/j.agrformet.2022.109183.
Manso, M., Teot'onio, I., Silva, C.M., Cruz, C.O., 2021. Green roof and green wall benefits and costs: A review of the quantitative evidence. Renew. Sust. Energ. Rev. 135 https://doi.org/10.1016/j.rser.2020.110111, 110111.
Mason, S.A., Olander, L.P., Grala, R.K., Galik, C.S., Gordon, J.S., 2020. A practice-oriented approach to foster private landowner participation in ecosystem service conservation and restoration at a landscape scale. Ecosyst. Serv. 46, 101203 https://doi.org/10.1016/j.ecoser.2020.101203.
MEA, Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC. ISBN 1-59726-040-1.
Mills, G., Stewart, I., 2021. The Urban Heat Island. Elsevier. https://doi.org/10.1016/B978-0-12-815017-7.00001-1.
Mirabi, E., Davies, P.J., 2022. A systematic review investigating linear infrastructure effects on urban Heat Island (UHIULI) and its interaction with UHI typologies. Urban Clim. 45, 101261 https://doi.org/10.1016/j.uclim.2022.101261.
Moody, R., Geron, N., Healy, M., Rogan, J., Martin, D., 2021. Modeling the spatial distribution of the current and future ecosystem services of urban tree planting in Chicopee and Fall River, Massachusetts, Urban Forest. Urban Green. 66, 127403 https://doi.org/10.1016/j.ufug.2021.127403 (https://www.milieucentraal.nl/energie-besparen/duurzaam-warm-water/close-in-boiler-of-kokendwaterkraan/).
Nijhuis, S., Xiong, L., Cannatella, D., 2020. Towards a landscape-based regional design approach for adaptive transformation in urbanizing deltas. Res. Urban. Ser. 6, 55–80. https://doi.org/10.7480/rius.6.94.
Nur, I.J., Sarker, M.H., Hossain, T., Ferdous, T., Rahman, S., Iqbal, B., Helal, G.J., Hossain, F., 2022. Evaluation of ecosystem services of rooftop gardens in Dhaka, Bangladesh. Curr. Res. Environ. Sustain. 4, 100166 https://doi.org/10.1016/j.crsust.2022.100166.
Orlov, A., Sillmann, J., Aunan, K., Kjellstrom, T., Aaheim, A., 2020. Economic costs of heat-induced reductions in worker productivity due to global warming. Glob. Environ. Chang. 63, 102087 https://doi.org/10.1016/j.gloenvcha.2020.102087.
Ortiz, L., Mustafa, A., Herreros, Cantis P., McPhearson, T., 2022. Overlapping heat and COVID-19 risk in new York City. Urban Clim. 41, 101081 https://doi.org/10.1016/j.uclim.2021.101081.
Park, C.Y., Park, Y.S., Kim, H.G., Yun, S.H., Kim, C., 2021. Quantifying and mapping cooling services of multiple ecosystems. Sustain. Cities Soc. 73, 103123 https://doi.org/10.1016/j.scs.2021.103123.
Paulin, M.J., Rutgers, M., de Nijs, T., Hendriks, A.J., Koopman, K.R., Van Buul, T., Frambach, M., Sardano, G., Breure, A.M., 2020. Integration of local knowledge and data for spatially quantifying ecosystem services in the Hoeksche Waard, the Netherlands. Ecol. Model. 438, 109331 https://doi.org/10.1016/j.ecolmodel.2020.109331.
Pilcher, J.J., Nadler, E., Busch, C., 2002. Effects of hot and cold temperature exposure on performance: a meta-analytic review. Ergonomics 45 (10), 682–698. https://doi.org/10.1080/00140130210158419.
Portman, M.E., 2013. Ecosystem services in practice: challenges to real world implementation of ecosystem services across multiple landscapes - a critical review. Appl. Geogr. 45 https://doi.org/10.1016/j.apgeog.2013.09.011, 185e192.
Qiu, L., Dong, Y., Liu, H., 2022. Integrating ecosystem services into planning practice: situation, challenges and inspirations. Land 11, 545. https://doi.org/10.3390/land11040545.
Robine, J.-M., Cheung, S., Le Roy, S., Van Oyen, H., Herrmann, F.R., 2007. Report on Excess Mortality in Europe during Summer 2003. EU Community Action Programme for Public Health, p. 28.
Rocha, A.D., Vulova, S., Meier, F., Förster, M., Kleinschmit, B., 2022. Mapping evapotranspirative and radiative cooling services in an urban environment. Sustain. Cities Soc. 85, 104051 https://doi.org/10.1016/j.scs.2022.104051.
Serrano-Notivoli, R., Canovas, M.L., Barrao, S., Pablo Sarricolea, P., Ruiz, O.M., Tejedor, E., 2022. Heat and cold waves in mainland Spain: Origins, characteristics, and trends. Weather Clim. Extrem. 37 https://doi.org/10.1016/j.wace.2022.100471, 100471.
Shi, W., Huang, S., Liu, D., Huang, Q., Han, Z., Leng, G., Wang, H., Liang, H., Li, P., Wei, X., 2021. Drought-flood abrupt alternation dynamics and their potential driving forces in a changing environment. J. Hydrol. 597, 126179 https://doi.org/10.1016/j.jhydrol.2021.126179.
Shuang, Y., Jiangjiang, X., Zhongwei, Y., Anzhi, Z., Yang, X., Dabo, G., Jiarui, H., Jun, W., Liang, C., Liu, YakuN L., 2019. Loss of work productivity in a warming world: differences between developed and developing countries. J. Clean. Prod. 208 https://doi.org/10.1016/j.jclepro.2018.10.067, 1219e1225.
Song, N., Wu, D., Xu, H., Jiang, H., 2022. Integrated evaluation of the reactive oxygen species (ROS) production characteristics in one large lake under alternating flood and drought conditions. Water Res. 225, 119136 https://doi.org/10.1016/j.watres.2022.119136.

Stache, E., Schilperoort, B., Ottelé, M., Jonkers, H.M., 2021. Comparative analysis in thermal behaviour of common urban building materials and vegetation and consequences for urban heat island effect. Build. Environ. https://doi.org/10.1016/j.buildenv.2021.108489.

Tamm, et al., 2013. ValuES: Methods for integrating ecosystem services into policy, planning, and practice. In: German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) as part of the International Climate Initiative (IKI). https://www.giz.de/en/worldwide/41607.html.

Veretennikov, P., van der Veeren, R., 2019. Report on Possibilities of Application of Ecosystem Services and Natural Capital approaches in OSPAR Activities. Report of the Ministry of Infrastructure and Water Management.

Wang, J., Yan, Z., 2021. Rapid rises in the magnitude and risk of extreme regional heat wave events in China. Weather Clim. Extrem. 34, 100379 https://doi.org/10.1016/j.wace.2021.100379.

Ward, P.J., de Ruiter, M.C., Mård, J., Schröter, K., Van Loon, A., Veldkamp, T., von Uexkull Wanders, N., AghaKouchak, A., Arnbjerg-Nielsen, K., Capewell, L., Llasat, M.C., Day, R., Dewals, B., Di Baldassarre, G., Huning, L.S., Kreibich, H., Mazzoleni, M., Savelli, E., Teutschbein, C., van den Berg, H., van der Heijden, A., Vincken, J.M.R., Waterloo, M.J., Wens, M., 2020. The need to integrate flood and drought disaster risk reduction strategies. Water Sec. 11, 100070. https://doi.org/10.1016/j.wasec.2020.100070.

Xu, Z., Peng, J., 2022. Ecosystem services-based decision-making: a bridge from science to practice. Environ. Sci. Pol. 135, 6–15. https://doi.org/10.1016/j.envsci.2022.04.010.

Yang, X., Yao, L., 2022. Reexamining the relationship between surface urban heat island intensity and annual precipitation: effects of reference rural land cover. Urban Clim. 41, 101074 https://doi.org/10.1016/j.uclim.2021.101074.

Yin, C., Yang, Y., Chen, X., Yue, X., Liu, Y., Xin, Y., 2022. Changes in global heat waves and its socioeconomic exposure in a warmer future. Clim. Risk Manag. 38, 100459 https://doi.org/10.1016/j.crm.2022.100459.

Zeisel, J., 2006. Inquiry by Design: Environment / Behavior / Neuroscience in Architecture, Interiors, Landscape, and Planning. W.W. Norton & Company, London and New York.

Zimmerman, R., 2020. Heat measures for climate and infrastructure services. Urban Clim. 34, 100658 https://doi.org/10.1016/j.uclim.2020.100658.