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Comparing PV-green and PV-cool roofs to diverse rooftop options using decision analysis

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ABSTRACT

Flat roofs can employ a range of technologies to improve sustainability, such as photovoltaic (PV) panels, green roofs, cool roofs, or a combination of these options. Yet, weighing the benefits, costs, and performance of different roofing technologies is complex, especially when different stakeholders are involved. Decision analysis techniques, such as multi-criteria decision analysis (MCDA), can be used to systematically evaluate a diverse range of rooftop options to assess trade-offs in a quantitative way and avoid decision biases. This study offers a holistic comparison of different roof types, considering stakeholder preferences and uncertainty using MCDA. Ten flat roof options are compared, including black, gravel, cool, extensive green and semi-intensive green roofs, each with or without a rooftop PV installation, for nine objectives and three hypothetical stakeholder profiles. Performance is evaluated using building energy simulation, hydrologic modeling, and literature research. Uncertainty analyses are used to evaluate the effects of model assumptions on the MCDA results. For assumed preferences of an urban planner and environmentalist, semi-intensive green roofs with integrated PV installation are the best performing option; however, for a hypothetical building owner more concerned with costs, a gravel roof with PV ranks best. Uncertainty plays a role in the results, in particular, the uncertainty of the predicted outcome of options for the building owner, which can change the top-ranking options considerably. The uncertainty analyses are useful to identify consensus options over all three stakeholder types. Despite considerable uncertainty, extensive and semi-intensive green roofs with PV are recommended as relatively robust best-performing options.

1. Introduction

As cities continue to densify in the face of the global climate, energy, and biodiversity crises, many are looking to rooftops to fill the demand for space needed by humans and the environment. Flat roofs, which are cost-effective, optimize space, and are often adopted in dense urban areas, can employ a range of technologies to improve urban sustainability [1,2]. These technologies include photovoltaic (PV) panels to supply renewable energy, vegetated "green" roofs to protect biodiversity and capture runoff [3], and reflective or "cool" roofs (covered in a light-colored coating [4]) to reduce surface temperatures [1]. Legislation mandating the use of these technologies is increasing across the world (e.g., in Toronto [5], Zurich [6], France [7], and Tokyo [8]). However, the decision to adopt such a system may be approached from a narrow perspective – with little to no consideration of a range of technologies and sustainability objectives [9]. Stakeholders may choose to implement a solar PV system, for example, due to its renewable energy potential, without considering a number of additional advantages that can be provided by green roofs [3], such as stormwater attenuation [10,11], increased biodiversity [12,13], noise mitigation [14,15], air pollution abatement [16,17], and cooling [18]. In fact, since green roofs can be up to 25 °C cooler than conventional roofs [19,20], they can be combined with PV panels to increase their efficiency [21,22] since PV cells are temperature dependent [23,24]. The same is true for reflective, "cool" roofs, which due to their low albedo, have also been shown to be up to 25 °C cooler than conventional roofs, and thus also increase PV efficiency [1,19,25,26] at a lower cost than green roofs.

There is a body of literature dedicated to optimizing the design [27,28] and planning [29] of PV systems for buildings [30]. However, this work does not typically incorporate green or cool roofs into the optimization process. Instead, to account for the unseen or "public" benefits [31] of green roofs in particular, many have turned to multicriteria

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decision analysis (MCDA). MCDA is a set of methods to structure and analyze complex decision problems, which accounts for different objectives (i.e., criteria) in a transparent and holistic manner [32]. Based on a systematic literature review (see Supplementary Information), it is clear that these studies often focus on structuring the decision-problem, the first step in MCDA, to include a plethora of objectives (sometimes 15 or more [33–35]). These many objectives, such as stormwater management (as in Refs. [33,35,36]), biodiversity (in Refs. [37,38]), and cooling (in Refs. [37,39]) can level the playing field for green roofs when compared to traditional flat roof types (e.g., black membrane or gravel), which are typically cheaper with lower maintenance. They also help to choose between different green roof decision options [40], such as intensive (depth ≥20 cm) or extensive green roofs (≤15 cm) (as in Refs. [33,36,41,42]). Intensive roofs have higher costs due to increased structural requirements [43], but also higher environmental benefits (e.g., more rainwater storage and suitable habitat), which may outweigh the costs for some stakeholders.

While comparisons with green roofs are manifold, few decision-making studies have included cool roofs [44], solar roofs [45], or both [9], as individual decision options and to date, none of these studies have analyzed integrated options that combine PV panels with green or cool roofs. This is unfortunate, as these integrated technologies would likely be a competitive choice for many stakeholders if they were able to quantitatively assess their synergies and benefits using MCDA. Though this gap may be a result of a narrowed perspective of decision objectives and options, it could also be due to a lack of performance data of these integrated systems.

To be able to come to a “rational” decision, the second step of MCDA is to estimate the predicted performance of the decision options and many MCDA studies rely on literature values for these estimates. Yet advanced simulation models are needed to capture differences in performance of PV output over different rooftop types and climate, and studies providing these values are in their infancy [1]. MCDA studies also often rely on proxy indicators for energy and stormwater-related performance objectives. However, due to variations in regional climate and roof characteristics, green and cool roof performance is sensitive to modelling parameters (as shown in e.g., Refs. [1,46,47]), and these proxies in MCDA may lead to an oversimplification and inaccurate performance predictions. Only a handful of rooftop MCDA studies use mathematical models to estimate the performance of climate and building dependent objectives (e.g., Refs. [48–52]), such as energy savings and stormwater runoff. Simplified modelling approaches are often used when numerous objectives are evaluated (as in Refs. [41,50]), while studies that use more complex models (e.g., Ref. [44]) typically only assess objectives that can be evaluated with a single performance model, failing to capture a holistic set of benefits. The performance quantification methods for green roofs (e.g., for stormwater runoff [10], heat fluxes [53], and multiple benefits [22]) are vast, as are those for cool roofs [54] and PV panels (e.g., Refs. [55,56]). The potential to increase the complexity and type of models used for estimating the predicted performance in MCDA is large, yet underemployed.

As mathematical modeling for predicted performance is often missing from MCDA of sustainable rooftop choices, so are the assessments of uncertainties that are associated with predicted (e.g., modelled) performance. A few studies tangentially related to decision analysis of sustainable rooftops (e.g., suitability for air pollution reduction [41], placement of green roofs in a city [51,52], and PV project portfolio selection [57]) have elegantly assessed these uncertainties. However, consideration of performance modeling uncertainty has not yet made its way into MCDA for flat roofs on individual buildings. The sensitivity of the decision outcome to stakeholder preferences – steps 3 and 4 in the MCDA process – has, however, been evaluated (although gaps still remain, including systematic sensitivity analysis to subjective preferences). In fact, the outcome of which roof type is preferred often depends largely on stakeholder preferences (e.g., weights assigned to objectives) [9]. Yet it still remains unclear how sensitivity to stakeholder preferences compares to sensitivity and uncertainty related to performance estimation of different objectives.

In summary, MCDA studies of rooftop choices are in their infancy. These analyses still need to incorporate integrated decision options such as PV-green and cool roofs, more complex and additional mathematical models for the predicted performance of these and other rooftop options, as well as, uncertainty analysis of performance predictions and comparisons to sensitivity of stakeholder preferences. To fill this gap, MCDA is used in this study to evaluate a range of integrated decision options, including sustainable and traditional flat roof types with and without a photovoltaic installation, across relevant objectives using state-of-the-art performance models that incorporate uncertainty. Detailed thermal and runoff simulation models are combined with literature review to evaluate the holistic performance of these options. The MCDA is carried out with respect to three upper-level objectives, including low energy and carbon footprint, low environmental impact, and low cost, while accounting for and comparing the effects of stakeholder preferences and uncertainty on the decision outcome.

2. Approach

In this study, MCDA, specifically multi-attribute value theory (MAVT), commonly used due to its transparency, easily justifiable results, and ability to account for uncertainty [58,59], was used to evaluate the relative performance and associated trade-offs between achieving objectives of 10 different flat roof types. This section first presents the study location and rooftop options (2.1), followed by the decision objectives and attributes (2.2), estimating the predicted performance of options and simulation models (2.3), and finally the MCDA modelling, including assumed stakeholder preferences and uncertainty evaluation (2.4).

2.1. Study location and rooftop characteristics

The considered case study is a commercial building located in Dübendorf, Switzerland. Commercial buildings tend to have a large flat roof area, bearing a high potential for sustainable roofs and PV generation, as well as a high roof to floor area ratio, which makes them relatively sensitive to roof type. Since sustainable roofs are an interesting option for the retrofit of existing buildings, the building was chosen to reflect an average construction in terms of insulation levels and HVAC systems (dimensions of 100 m × 50 m, window-to-wall ratio of 18 % [60]).

Five main flat roof options were evaluated in this study, including: three types of impervious roofs, a black bitumen roof, a gravel ballasted roof, and a cool roof, as well as, two types of pervious, green roofs. Each of these options was considered both on its own and in combination with a rooftop photovoltaic (PV) installation. The different roof technologies were selected due to their popularity or their potential to reduce the negative environmental impacts of urban areas.

While there are several types of "black" flat roofs, for this study, a bituminous flat roof was selected, which is built on top of three layers, an MDF (medium-density fiber) board, a vapor barrier, and a 120 mm PUR (polyurethane) insulation layer [61]. The *black roof* served as base case, both in terms of performance and construction. Shown in Fig. 1, the other roof types build up on this popular roof type.

The *gravel*, or rock-ballasted, roof is another popular roof construction due to its ease of construction and low maintenance requirements. For this case study, a 5-cm layer of gravel was added on top of the black roof construction. *Cool,* i.e., reflective, or white roofs are coated in a high-albedo material or paint, altering their radiation balance to reflect as much energy as possible [4]. The cool roof was considered as identical to the black roof except for the albedo value for thermal modelling.

Due to their high heterogeneity, *green roofs* are often classified into three categories: extensive, semi-intensive and intensive green roofs

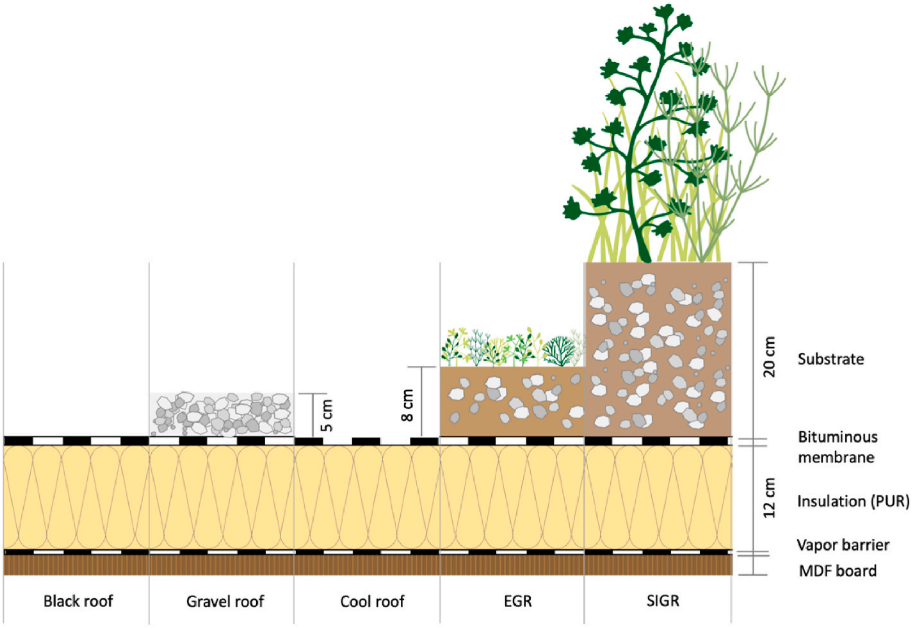

Fig. 1. The construction of the different roof types evaluated in this study.

[62]. In this study, an extensive and a semi-intensive roof were compared, given that both would likely not require structural reinforcement. Following common extensive green roof design properties [22,63], this roof option consisted of Sedum-type plants [64] and a 8-cm soil depth [63]. Since extensive green roofs are known to underperform in many of the benefits typically attributed to green roofs [22,65], a semi-intensive green roof with 20-cm soil depth consisting of grasses, herbaceous plants, and small shrubs was also considered.

The PV installation in this study was based on a setup from Cavadini and Cook (2021) [21], who evaluated integrated PV-green roofs in a similar location. Their setup was replicated as closely as possible in terms of orientation, inclination, and PV area to roof area ratio [66]. This resulted in a total PV area of 2′400 m^2 at an inclination of 13° and facing South-East and North-West alternately as shown in the Supplementary Information (SI).

2.2. *MCDA objectives and attributes*

MCDA consists of several stages, including: (1) *structuring the decision problem*, where decision options (alternatives), objectives (criteria), and attributes (performance indicators) to quantify these objectives are selected; (2) *predicting the performance of each option,* where each option is evaluated with respect to each objective; (3) *eliciting stakeholder preferences,* as example the relative importance of each objective (i.e., weights); (4) *solving the selected MCDA model* using the objectives, predicted performance outcomes of each option, and stakeholder preferences as model parameters; (5) *analyzing results* and *uncertainty;* and (6) *discussion* with the stakeholders to reach consensus or develop an action plan [59]. In a real-world case, MCDA can be an iterative process, where the discussion with stakeholders can lead to changes in decision problem structure and stakeholder preferences (see SI Fig. 3). In some decision cases, after conducting a first MCDA, results are discussed with stakeholders, and new compromise alternatives could be constructed and

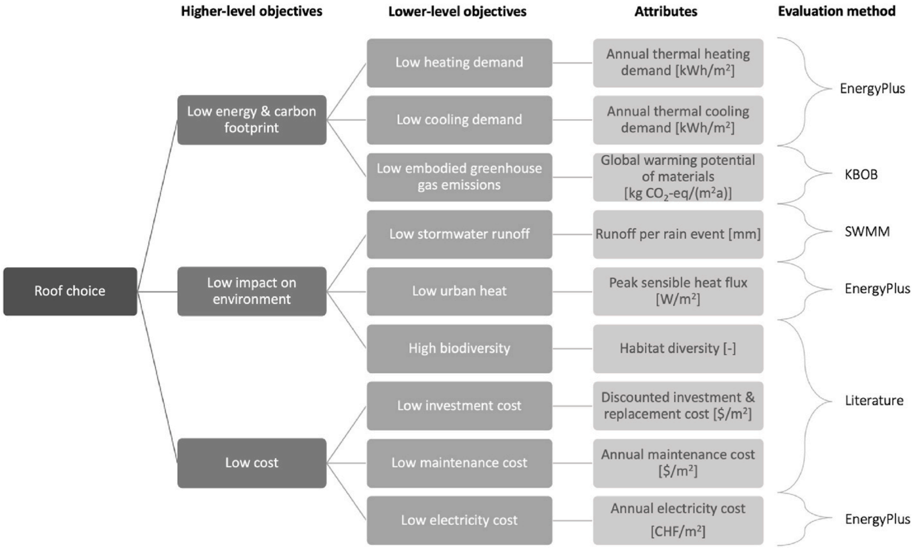

Fig. 2. Objectives hierarchy showing the selected higher-level objectives (left side) and lower-level objectives (middle) for the MCDA with their attributes (right side) and their predicted performance evaluation methods (far right).

evaluated in the same MCDA model (e.g., Hostmann et al., 2005 [67]). The decision criteria ideally remain the same, since the decision context is unchanged, and the stakeholder preferences do not need to be re-elicited. Since the decision case used in this study is hypothetical, these discussions did not take place.

The following sub-sections present the objectives and attributes used in the MCDA model. Shown in Fig. 2, three top-level objectives were selected to evaluate the rooftop decision options, including: low energy and carbon footprint, low environmental impact, and low cost. Although this list is not exhaustive, these objectives were deemed most important since they capture the main advantages and drawbacks of each roof type. These top-level objectives each comprised several lower-level objectives, forming the problem's objectives hierarchy (see Fig. 2). The lower-level objectives need to have a sufficient level of detail to be measurable; to this end, attributes (performance indicators) are selected. Discussed subsequently, the predicted attribute levels of six of nine lower-level objectives were evaluated using simulation or estimation models, while the predictions for the remaining objectives were based on literature values. Fig. 3 gives an overview of how EnergyPlus [68] and SWMM [69] were used to predict the roof options' performance with respect to the different objectives. The following sections present how the predicted attribute levels were estimated for each option.

2.2.1. Low heating, cooling, and greenhouse gas emissions

Minimizing the energy needed for heating and cooling a building is important for several reasons. Typically, heating and cooling rely on fossil fuels as a primary energy source, which contribute to climate change. Thus, reducing heating, cooling, and GHG emissions will ultimately help mitigate climate change. In addition, heating and cooling come with an operational (fuel) cost, while recently, the security of energy supply and energy availability have also become noteworthy aspects. The predicted performance levels for *heating* and *cooling demand* were taken from the building energy simulation output (see Section 2.3.2), as the annual thermal energy demand for heating and cooling and normalized by the heated floor area.

To account for the building's carbon impact during construction, the *embodied emissions* (global warming potential) of the respective roof technology were calculated using the life cycle impact database KBOB [70]. For more details, see Section 2.3.1 as well as SI 4.4.2.

2.2.2. Low stormwater runoff

During rain events, runoff from impervious surfaces flows to the sewer system. When this flow exceeds the sewer capacity, flooding or discharge of sewage to surface waters can occur, with negative consequences for humans and the environment [71,72]. Delaying or reducing the stormwater runoff entering the sewer can thus help to avoid these consequences. Due to their pervious nature, the capability of green roofs to temporarily detain rainwater on an event basis [73,74] is one of the most important aspects to delay peak stormwater. Thus, the *runoff per rain event* was considered as the attribute to estimate the achievement of the objective of low stormwater runoff.

Discussed in Section 2.3, the time series needed to quantify *runoff per rainfall event* was generated using SWMM [69]. The extensive and semi-intensive green roof types were compared to an impervious roof (see Section 2.3.3). A rain event was defined in this study after a dry period of 6 hours or more. The metric used for this attribute was the 90th percentile of the total runoff during a rain event. Runoff during the following dry period was excluded since the initial delay in runoff is more relevant to limit the surcharge of sewer systems [75].

2.2.3. Low urban heat

Due to a high prevalence of dark, impervious surfaces, urban areas tend to experience significantly higher air temperatures than nearby rural areas [76], which negatively affects comfort outside (and inside) of buildings [77,78]. The sensible heat flux (i.e., the flow of heat energy) from a roof to the surrounding air was used to approximate the roof's impact on outdoor urban heat [75,79,80]. This flux is known to decrease (reducing heat) with higher albedo (as on a reflective roof) and increased evapotranspiration (as on a green roof) [81]. As suggested by Scherba et al. (2011) [19], peak sensible heat flux was used as an indicator of the maximum daytime temperature. The sensible heat flux was calculated according to Eqn. (1), where h_c is the outside convection heat transfer coefficient of the roof surface, $T_{surface}$ the roof surface temperature and $T_{ambient}$ the ambient air temperature. In dry conditions, the dry bulb air temperature was used, but during rain events, the wet bulb air temperature was used instead.

$$q_{sens} = h_c * \left(T_{surface} - T_{ambient}\right) \qquad \text{Eqn. 1}$$

Since urban heat is mostly an issue during hot periods, only days with a peak air temperature of 25 °C or more were considered for this attribute. After calculating the hourly sensible heat flux, the average *daily peak heat flux* for these days was computed.

2.2.4. High biodiversity

Biodiversity is fundamental to all aspects of life, yet species are currently being lost at an alarming rate [82]. Cities are particularly harsh environments for many flora and fauna and provision of suitable habitats for these species can help to counteract biodiversity loss. Green roofs can act as habitats, as well as, stepping stones that connect between other habitats [83]. To evaluate biodiversity of a habitat, there are a range of metrics available that are typically applied to a specific taxon or to several species, such as species richness or the Shannon Weaver diversity index, among others [84]. However, without sampling data, these metrics cannot be quantified. Habitat diversity – or the number of habitats in a particular unit – can be used as proxy for species richness, as different species will be drawn to different characteristics of

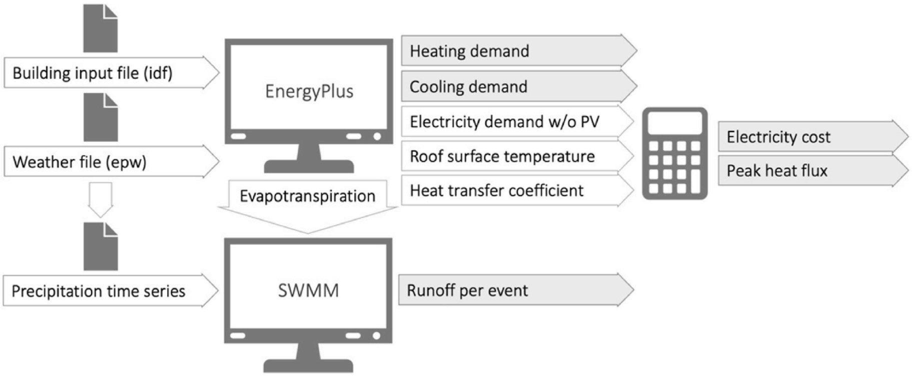

Fig. 3. The simulation workflow including both simulation tools used in this study. Outlined arrows are input variables or intermediate results, and filled arrows are the predicted level of attributes (for each option).

a unit (in this case, a green roof habitat) [85]. Following Langemeyer et al. (2020), biodiversity was evaluated as habitat diversity in this study [86]. In Langemeyer et al. (2020) [86], five types of green roofs were rated on a scale of 0–1 by a group of experts. A score of 1 corresponds to a naturalized roof, emulating natural habitats with high diversity. The extensive roof, with typically low substrate depth and vegetation diversity, received a score of 0.42, while the semi-intensive roof, with deeper substrate and more plant variety, scored 0.50.

There is also evidence in literature that photovoltaic installations increase the growth and coverage of plants on green roofs [87,88] and may increase the vegetation and habitat diversity [89–91], which in turn has the potential to increase arthropod diversity [92]. Consequently, the PV-green roof combinations scored slightly higher than the respective non-PV options with respect to this attribute.

2.2.5. *Low investment and maintenance cost*

Costs, which ideally would be low, were measured by the roof's investment and replacement cost, as well as by its annual maintenance and electricity cost (see 2.2.6).

Cost distributions for construction and maintenance costs for the different roof types as well as for rooftop PV installations were based on literature [9,86,93–103]. The literature data were converted to $/m^2 and adjusted for inflation. Cost data on semi-intensive green roofs is rare in literature, thus data for intensive green roofs was used instead, at the risk of overestimating the actual investment and maintenance costs of this roof option.

The *investment cost* was then computed as the discounted cost of construction and replacement after 50 years, using the replacement periods in Table 1 and according to Eqn. 2, and a discount rate of 3.2 % [104].

$$NPC = \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t} \qquad \text{Eqn. 2}$$

Maintenance cost was expressed as an annual cost per square meter of roof surface.

2.2.6. *Low electricity cost*

The annual *electricity cost* was calculated as the net annual electricity consumption multiplied by the price of electricity of 0.212 CHF/kWh [105]. While the electricity price is subject to many uncertainties and fluctuations, any such uncertainties would affect all options in the same way, and thus would not impact the comparison of options in the MCDA results. As a result, the electricity price was assumed constant in this calculation.

The net annual electricity consumption was approximated by the annual electricity consumption from the building energy simulation minus the annual PV generation. This is a simplification as in reality, only a part of the generated electricity can be utilized by the building with the rest being fed into the grid. Yet, this methodology allowed to account for the temperature-dependency of PV module efficiency [106] as described by Cavadini and Cook (2021) [21]. In their work evaluating a polycrystalline silicone installation to determine the temperature-dependency of annual PV output using different sustainable roofing technologies, they found a linear correlation between the 95th percentile of roof surface temperature and the annual PV generation. Since their study was also based in Dübendorf, Switzerland, their linear relationship could be used in this work under certain assumptions. In order to eliminate other influencing factors, their albedo values and PV setup were replicated (see Section 2.3.2). The final equation for the annual PV generation Y as a function of the 95th percentile of roof surface temperature $T_{surface\_95}$ is shown in Eqn. (3).

$$Y = -0.06858\frac{kWh}{m^2\,{}^\circ C} * T_{surface_{95}} + 42.6626\;kWh\Big/m^2 \qquad \text{Eqn. 3}$$

2.3. *Modeling the predicted performance*

Several models were used to estimate the predicted performance of the options for six of the attributes, including: an LCA model (KBOB [70]) used to estimate greenhouse gas emissions; a building energy balance model, EnergyPlus [68], used to simulate temperature- and energy-related objectives; and the EPA Stormwater Management Model (EPA SWMM) [69] used to evaluate the runoff per rain event. Fig. 3 presents the workflow of the simulation tools, including input data, output variables, and how these outputs correspond to their respective attributes.

2.3.1. *KBOB modeling*

The embodied greenhouse gas emissions were based on the KBOB database [70], which provides life-cycle impact data for a large range of materials, as well as for energy carriers and building systems. Each of the roof technology's layers was quantified and multiplied by its life-cycle impact value. The expected life span of each roof type, as shown in Table 1, was accounted for in the calculation. For the embodied impact of PV modules, data from Frischknecht et al. (2022) [107] was used instead of the KBOB data due to the rapid improvements in PV technology, leading to continuously decreasing embodied greenhouse gas emissions of PV modules [108]. The life-cycle impact of PV in KBOB is based on research from 2012 to 2015 [108,109], and is thus likely to

Table 1
Construction and roof parameters, including the ranges used for the sensitivity analysis of the EnergyPlus model (Section 2.3.4).

Parameter	Black roof	Gravel roof	Cool roof	Extensive green roof	Semi-intensive green roof
Roof properties					
Albedo [−] [21]	0.06 (0.03–0.15)	0.22 (0.2–0.3)	0.7 (0.5–0.85)	0.3 (0.2–0.35)	
U-value [W/m2K]	0.20 (0.13–0.24)	0.20 (0.13–0.24)	0.20 (0.13–0.24)	0.19 (0.13–0.23)	0.17 (0.12–0.21)
Roof thermal mass [kJ/m2K]	10.8 (10.6–10.8)	12.1 (11.1–12.4)	10.8 (10.6–10.8)	14.2 (12.5–20.0)	26 (20–107)
Replacement period [a]	15	25	15	40	40
Green roof properties					
Vegetation type				Sedum	Herbaceous
Vegetation height [m]				0.05 (0.05–0.15)	0.3 (0.2–0.5)
Substrate depth [m]				0.08 (0.05–0.15)	0.2 (0.15–0.6)
LAI [−] [79]				1.88 (1–3)	5 (1–5)
Stomatal resistance [s/m]				300 (180–300)	55 (55–180)
Annual precipitation [m] [115]				1.048 (0.80–1.436)	
Top layer of roof					
Thermal conductivity [W/mK] [116]	0.5 (0.2–0.6)	0.96 (0.4–1.6)	0.5 (0.2–0.6)	0.3 (0.25–1.5)	
Heat capacity [J/kgK] [116]	1000 (800–1100)	1000 (200–1000)	1000 (800–1100)	1000 (800–1000)	
Density [kg/m3] [116]	1700 (700–2200)	1800 (1000–2200)	1700 (700–2200)	1000 (800–2000)	
General building					
U-value of external walls [W/m^{2}K]	0.38 (0.17–0.65)				
Building thermal mass [kJ/m^{2}K]	12.3 (12.3–182)				

overestimate the PV panels' embodied emissions. In order to capture the impact of different building life spans on the number of roof replacements, building life spans of 40, 50, and 60 years were evaluated and the results normalized by the building life span. For details on the materials and quantities, refer to SI 4.4.2.

2.3.2. EnergyPlus modeling

EnergyPlus [68] is a whole building energy simulation program used to model energy consumption from heating, cooling, and ventilation, as well as electrical loads. Due to its user-interface, DesignBuilder [110] was used to set up the building construction, while EnergyPlus was used directly to run the simulations. Both DesignBuilder and EnergyPlus have been used in numerous studies concerning green roofs and building energy consumption, (e.g., Refs. [79,111–113]).

The EnergyPlus EcoRoof module, developed by Sailor in 2008 [79], was used to evaluate the energy and moisture balance of the green roof soil and the vegetation layer. The model accounts for all relevant processes, including: long wave and short wave radiation balance of the plant canopy, plant canopy effects on convective heat transfer, evapotranspiration from the soil and plants, as well as heat conduction and storage in the soil layer [114].

The building was modelled with dimensions of 100 m × 50 m with a window-to-wall ratio of 18 % [60]), comprising two identical open plan floors of 4 m height. PV modules were modelled as building blocks in DesignBuilder in order to capture not only the effect of shading, but also the long-wave radiation of the hot panels on the roof surface. This approach is limited by the minimum height of a building block being 10 cm. However, this modelling approach was deemed more accurate than approximating the panels by a two-dimensional plane and only taking into account short-wave radiation shading. For more details, see SI 2.1.

Table 1 presents the building construction and rooftop parameters used in EnergyPlus. Several parameters of the vegetated roof were customized, including the soil depth, vegetation height, leaf reflectivity and leaf area index, minimum stomatal resistance, soil characteristics, and initial soil moisture content.

An existing EnergyPlus weather (epw) file for Dübendorf, Switzerland [117] was used as input to the EnergyPlus model. Aggregated data from 2006 to 2019 represents a typical meteorological year (TMY). The binary "rain status" information from this file was used to create a precipitation schedule that provides intensity values for each rain period [118]. Details about this method are provided in SI 2.2.

2.3.3. SWMM modelling

EPA SWMM is a dynamic rainfall-runoff model [69] used to simulate water flows in urban drainage systems [69] and the hydrologic response of green infrastructure, such as green roofs. In this study, the black, gravel, and cool roofs were all considered equivalent and simulated as an impervious roof (nearly all water runs off) without evapotranspiration (ET). The two types of green roofs (extensive and semi-intensive), which can store water within the soil or release it via ET, were simulated separately depending on the soil and vegetation characteristics (Table 2). The main input data of SWMM includes precipitation and evapotranspiration (ET) time series. The precipitation used as input to EnergyPlus was also used as input for each roof model in SWMM. ET timeseries from the extensive and semi-intensive green roofs simulated in EnergyPlus were used as input for the extensive and semi-intensive roofs in SWMM, respectively.

Relevant roof characteristics from EnergyPlus, described in Table 1, were translated into associated SWMM parameters, as shown in Table 2, for both extensive and semi-intensive green roofs. Parameters not listed in Table 2, which include surface slope, field capacity, hydraulic conductivity, suction head, and drainage mat characteristics, were equivalent for the two types of green roofs (see SI). These parameters were estimated based on values recommended in the SWMM manual [119]. All parameters were tested for sensitivity in several modelling simulations. Additional details related to the SWWM model, including parameter ranges for each run, are listed in SI 3.1–3.2.

2.3.4. Sensitivity analysis of modeling of the predicted performance

Due to the hypothetical nature of the case-study, model validation is not possible. To account for a range of potential real-world building setups, a detailed sensitivity analysis was performed both for the EnergyPlus and SWMM models. Each of the parameters listed in Tables 1 and 2 were varied to the lower and upper bound of the specified ranges. For each varied parameter, the model was run with all other parameters kept at their original value.

Since the ET is linked to the EnergyPlus parameters, the associated sensitivity analysis in EnergyPlus was used for the input data to the SWMM sensitivity run when applicable. For instance, the ET timeseries from the simulations in EnergyPlus when depth is maximized were used as input to SWMM when depth was maximized. To estimate green roof performance with a lower porosity in SWMM, the ET output file from the EnergyPlus run with a high soil density was used. As field capacity is associated to vegetation type, ET from the simulation with minimum and maximum vegetation depth was used, respectively, to evaluate the minimum and maximum field capacity. In simulations that evaluated runoff with a low vegetation volume fraction, ET from EnergyPlus simulations with a high leaf area index were used. Additional details about the ET timeseries used in the sensitivity analysis can be found in SI 3.3.

2.4. Stakeholder preferences and decision uncertainty

2.4.1. MAVT model

This study used Multi-Attribute Value Theory (MAVT) to calculate an overall value for each decision option and create a ranking based on that value [58,59]. One of the main advantages of MCDA is that it can consider the stakeholders' subjective preferences such as the relative importance of the objectives for each stakeholder, who may weigh each objective differently. These weights (also called scaling constants) thus capture the trade-offs a stakeholder is willing to make if not all objectives can be fully achieved. The ValueDecisions app, developed by Haag

Table 2
Parameters of SWMM model translated from EnergyPlus.

SWMM green roof parameter	Associated Energy Plus parameter	Source	Range Extensive	Intensive
Berm height [mm]	Estimated using EnergyPlus vegetation depth and LAI	SWMM Manual	50 (30–60)	55 (40–70)
Vegetation volume fraction [%]	Estimated using EnergyPlus vegetation depth and LAI	SWMM Manual	0.05 (0–0.20) %	0.1 (0–0.20) %
Surface roughness	Associated to the type and height of vegetation	McCuen (2005) [72]	0.15 (0.05–0.24)	0.24 (0.15–0.8)
Soil thickness	Substrate depth (from EnergyPlus)	Roof options (see Section X)	80 (50–150) mm	200 (150–600) mm
Porosity	Converted from EnergyPlus soil density using assumed particle density of 2.6 g/cm3	Cook and Larsen (2020) [22]	0.69 (0.42–0.77) %	0.62 (0.23–0.69) %
Precipitation timeseries	Typical meteorological year (from EnergyPlus)	epw file for Dübendorf, Switzerland [117]		
Evaporation timeseries	Output from EnergyPlus			

et al. (2022), was used to implement the MAVT method [120]. This app was chosen due to its ease of use, its ability to incorporate uncertainty into the predicted outcomes of options (propagating the input uncertainty to MCDA results with Monte Carlo simulation), and its ability to carry out extensive sensitivity analyses of preference parameters, including weights, value functions, and the MCDA aggregation model. Details of the MAVT method and ValueDecisions app are included in Haag et al. (2022) [120], and references therein.

In addition to the weights, other preference parameters also enter the decision model and may be elicited from stakeholders. These include the conversion of each attribute (with its specific unit) to a neutral value from 0 (worst level of this attribute) to 1 (best level of this attribute; over all options considered in this decision). Moreover, the type of MCDA aggregation model used may also depend on the stakeholders' preferences. For the baseline of this analysis, linear single-attribute value functions and an additive MCDA aggregation model were assumed. Single-attribute value functions measure the relative degree of achievement of an objective [120] and their shape depends on the stakeholders' preferences. The assumption of linear value functions implies that, for example, a decrease in investment cost of 50 $/m^2 has the same importance to a stakeholder whether the reduction is from 100 $/m^2 to 50 $/m^2 or from 450 $/m^2 to 400 $/m^2. In reality, this assumption is often not valid [121–123].

Another assumption was that an additive aggregation function [58] could be applied (Eqn. (4) [59]). The additive MAVT model determines the overall value $v(a)$ of an option a as:

$$v(a) = \sum_{r=1}^{m} w_r v_r \ (a_r) \qquad \text{Eqn. 4-1}$$

where a_r is the level of attribute X_r for option a; $v_r(a_r)$ the respective value of the attribute value function v_r; w_r the weight (scaling constant) assigned to each objective/attribute; and $w_r > 0$; and where:

$$\sum_{r=1}^{m} w_r = 1 \qquad \text{Eqn. 4-2}$$

While this is a highly popular aggregation method [120,124], it comes with certain limitations [59]. Additivity implies that a) a low value in one objective (= low achievement) can be fully compensated by a high value in another objective and b) that there is no distinction between two options with the same average value where one has a more balanced achievement of objectives and one a more extreme one. For more information regarding value functions and aggregation methods, refer to Haag et al. (2022) [120]. Sensitivity to these preference assumptions was tested and results are briefly discussed in Section 3.7 with more details in SI 5.4.2.

2.4.2. *Stakeholder preferences*

In this study, preferences from stakeholders were not elicited, but extreme assumptions about possible preferences to test the sensitivity of MCDA results were evaluated. The stakeholder preferences were thus entirely hypothetical and inspired by Collier et al. [9]. Three different hypothetical stakeholders were explored: a building owner, an urban planner, and an environmentalist. Each of these stakeholders most valued objectives closest to their respective field, while the remaining objectives received lower weights. The assigned weights are shown in Fig. 4.

The building owner cared mostly about building-related objectives, such as low energy use and low costs, while the urban planner valued urban-scale issues such as low stormwater runoff and low urban heat. Finally, the environmentalist valued global objectives like low energy and carbon footprint and high biodiversity, while giving less importance to low costs.

2.4.3. *MCDA model sensitivity and uncertainty*

To account for uncertainty in MCDA, the sensitivity of the MCDA result was evaluated with respect to the stakeholders' preferences as well as to the uncertainty in the predicted performance of options (for each objective). *Stakeholder preference* uncertainty was assessed by increasing and decreasing each weight by 20 %. The remaining weights were renormalized to keep the same proportions [59]. The sensitivity of results to the shape of the value function was also evaluated (from linear to non-linear single-attribute value functions), and to changing from an additive to a slightly non-additive MCDA aggregation model. The results of these analyses are summarized in Section 3.7 with the full analyses presented in supplementary information (SI 4.6).

The uncertainty in the *predicted performance* of options was accounted for through Monte Carlo simulation based on a specified uncertainty distribution for each attribute. The attributes that were derived from the EnergyPlus or SWMM models were fitted with a normal uncertainty distribution based on the results from the performance models' sensitivity analysis (see Section 2.3).

The embodied GHG emissions, which are time-sensitive and depend on the evaluation time horizon, were assigned a triangular distribution according to the range of time-normalized emission data for a time horizon of 40, 50 and 60 years. Investment and maintenance costs were assigned triangular distributions based on the range of literature data. Habitat diversity was also assigned a triangular uncertainty distribution.

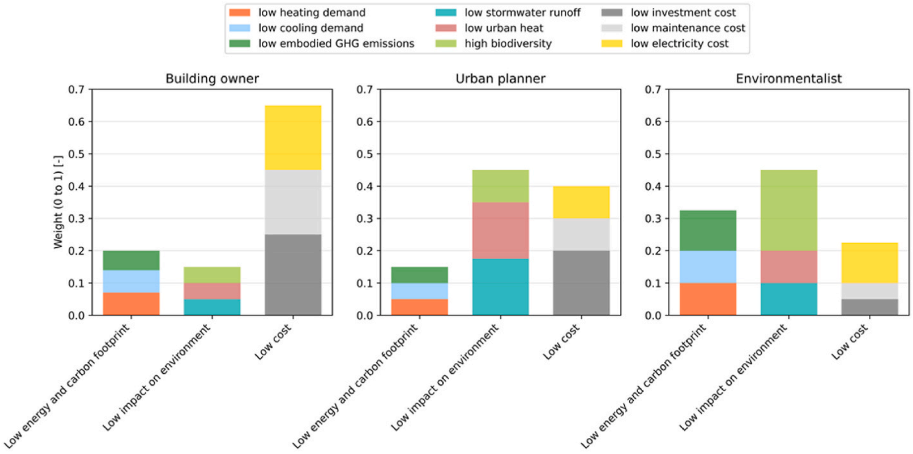

Fig. 4. The hypothetical weights assigned to each lower-level objective (colored bars) by the hypothetical stakeholders, and the according higher-level objectives (length of each stacked bar). For each stakeholder, the global weights (= weights of all lower-level objectives together) sum up to 1.

3. Results & discussion

3.1. Estimated thermal performance of rooftop decision options

Clear trends emerged when comparing the peak sensible heat flux of each roof option with the roof surface temperature (Fig. 5). Low peak sensible heat flux (i.e., "sensed" or perceived heat) is desirable to achieve the lowest-level objective low urban heat. Green roofs without PV that have the same 95th percentile surface temperature as those with PV tended to have a lower sensible heat flux. This could be due to the panels themselves releasing more sensible heat, which has shown to be true in large PV installations [125]. Gravel and black roofs without PV, on the other hand, tended to be hotter than those with PV, but emitted a similar amount of sensible heat as roofs with panels. In this case, shading from the PV likely outweighed any negative effects from panels emitting more sensible heat than roofs without panels.

Cooling demand, for which a low prediction is beneficial, was strongly correlated with roof temperature. On average, for every degree that the 95th percentile surface temperature increased, cooling demand per unit area increased by about 33 Wh. However, for green roof types, there was more variability around the same surface temperature. Cooling demand of green roofs did not seem to be affected by the presence of PV panels, but depended instead on the substrate depth and plant height (i.e., whether the roof was extensive or semi-intensive). On the other hand, cooling demand of black and gravel roofs depended highly on the presence of panels, as PV roofs had up to 0.54 KWh/m^{2}a lower cooling demands than their non-PV equivalents. High PV yield contributed to lower electricity demand and thus low electricity costs. In this analysis, PV yield was estimated as a function of surface temperature, following Cavadini and Cook (2021), thus this variability in performance for the same surface temperature was lost. A coupled modeling approach to simulate PV in conjunction with EnergyPlus would improve uncertainty quantification; however, as the MCDA approach also accounts for uncertainty, the authors chose to rely on the Monte Carlo simulation already incorporated into the MCDA in ValueDecisions.

3.2. Stormwater and evapotranspiration relationship

Unsurprisingly, the green roofs discharged considerably less runoff per rain event than the impervious roofs (to the far left, Fig. 6), thus better achieving the objective "Low stormwater runoff". The semi-intensive green roof released about half as much runoff as the extensive green roof. A portion of this reduction may be attributed to considerable increases in evapotranspiration (ET) by the semi-intensive green roof compared to the extensive green roof (due to different plant properties). However, a large portion can also be attributed to the difference in soil depth of the two roofs (8 cm vs 20 cm), where the semi-intensive roof can store considerably more water. If a semi-intensive green roof is not possible, even increasing the extensive roof's depth from 12 cm to 15 cm led to a decrease of nearly 50% in runoff.

Rainfall had the largest influence on runoff, as ET and runoff are both largely dictated by the rainfall (scenarios with high rainfall led to higher ET and higher runoff). Increasing annual rainfall by 37% also increased average event runoff of the impervious roof by 37%. However, for the green roofs, a 37% increase in rainfall led to an increase in runoff of 70% and 114%, respectively, for the extensive and semi-intensive green roofs. This variability highlights the importance of testing for sensitivity across a range of roof types, in particular to rainfall, which varies interannually.

For extensive roofs, the slope of the hydraulic conductivity function also affected runoff, indicating that runoff is sensitive to how fast water can travel through the soil, in particular in shallower soils. Semi-intensive roofs were particularly sensitive to decreases in the soil porosity, i.e., a denser soil that allows for lower infiltration. In this case, decreasing the porosity of the semi-intensive green roof by about half (from 62 to 35%) led to more than triple the amount of runoff per event. Attribute numbers such as hydraulic conductivity slope and porosity can be difficult to estimate and predict. Therefore, it is important to consider a range (rather than a single number) for these attributes when estimating the hydrologic performance of green roofs.

3.3. MCDA input: predicted performance estimates

The predicted performance outcome of the different attributes is summarized in Fig. 7 with the numerical data given in SI Table 10. While cool and green roofs performed positively for many of the attributes, such as heating and cooling demand, event runoff, and habitat diversity, their predicted performance estimations for investment and maintenance costs were significantly less good than for gravel and black roofs. The performance predictions for electricity cost mostly differentiated between options with and without PV, but barely between the different roof types. This is due to the fact that the electricity demand and cost captured in this attribute excluded electricity required for heating and cooling to avoid double counting of these aspects. Overall, the nine attributes captured different trends in the predicted performance outcomes of the options, suggesting that the objectives were well selected to avoid double counting and high correlations between attributes [59] (see SI 5.2).

It is also clear that for certain attributes, the uncertainty was high, which reduced the significance of differences in the (average) predicted performance estimates between the different options. Whereas the level of uncertainty was similar for all options in heating demand, uncertainty was significantly higher for the green roof types in investment and maintenance cost. This may be due to the high heterogeneity of green

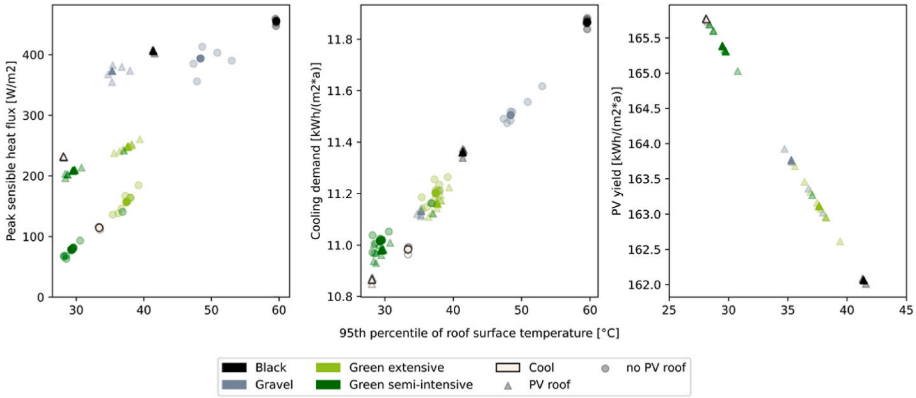

Fig. 5. Simulated 95th percentile roof surface temperature (x-axis) compared to peak sensible heat flux (left panel), cooling demand (middle), and PV panel yield (right panel) for each of the roof options across all sensitivity runs in EnergyPlus.

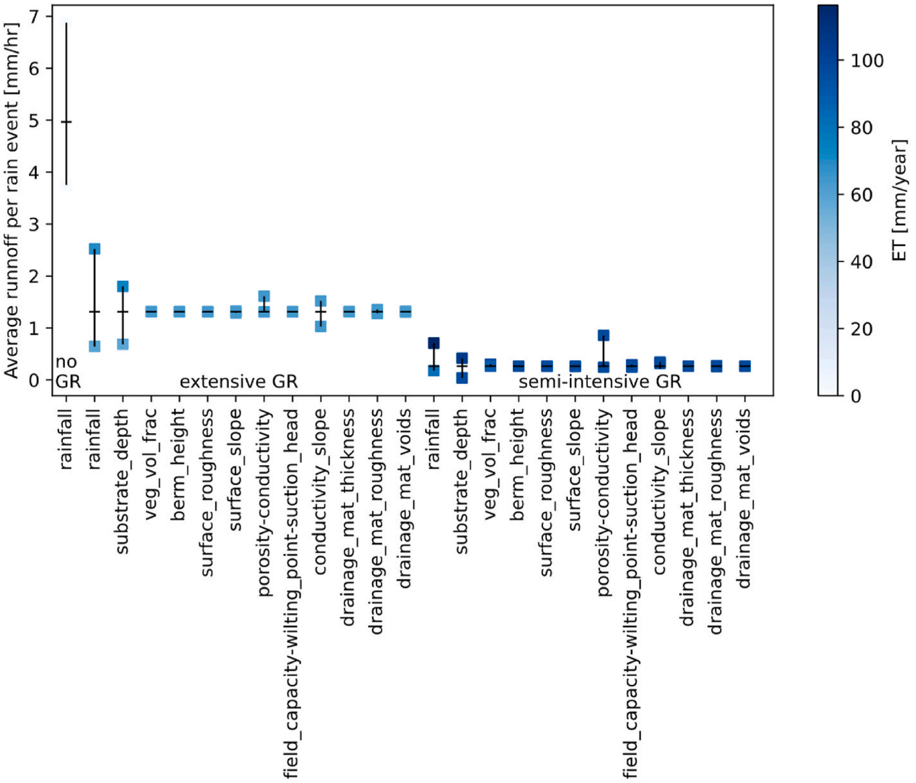

Fig. 6. Relationship between mean annual evapotranspiration and mean runoff per rain event for all roof types and runoff simulations. Upper and lower bounds: sensitivity analysis for each parameter in the SWMM green roof module; dash: baseline; marker color: total evapotranspiration for the simulation year. GR: green roofs. no GR: impervious roofs (assuming gravel, black and white roofs have the same runoff properties); ET: evapotranspiration. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

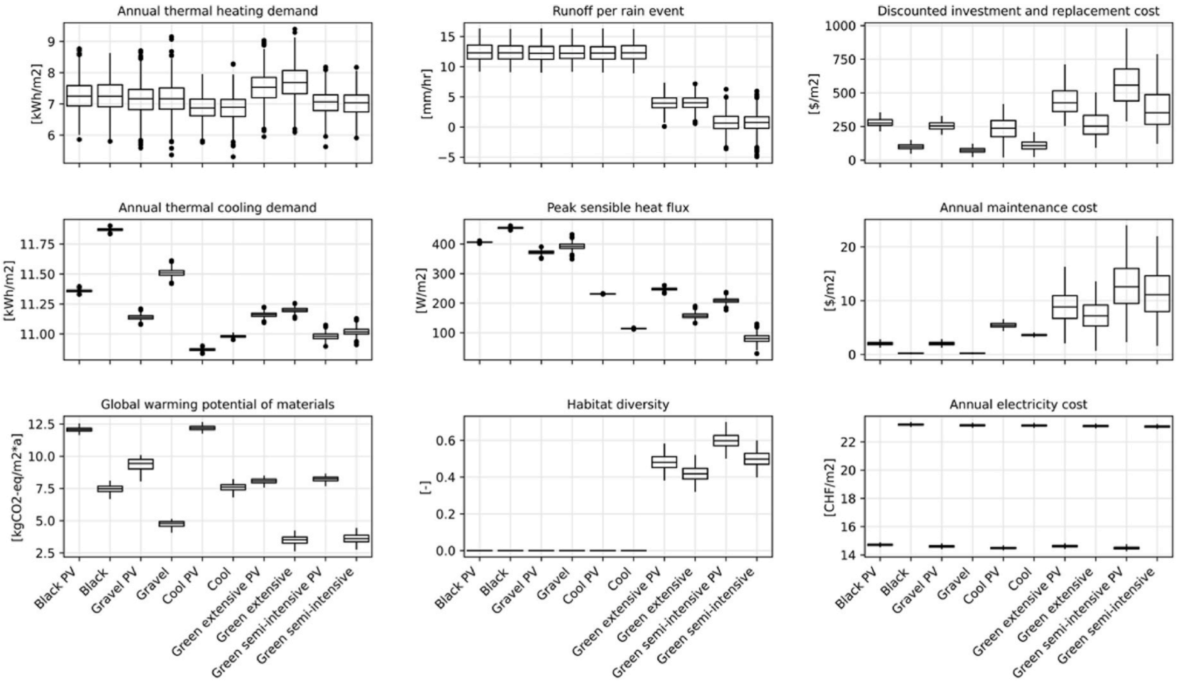

Fig. 7. Predicted outcome (y-axis) of each roof option (x-axis) for each attribute (boxes) with uncertainty of predictions. Boxplots show the 0.25 (lower), 0.5 (median), and 0.75 (upper) quartiles of the uncertain predictions. The whiskers extend to the minimum and maximum levels within 1.5 times the interquartile range. Points (i.e., predictions) outside the whiskers are outliers. For the numerical data, refer to SI Table 10.

roofs, making it difficult to find sources that accurately represent the specific green roof types evaluated in this analysis. The importance of proper problem structuring has shown itself repeatedly during this analysis. The MCDA model, including the choice of options and objectives, and elicitation of stakeholder preferences such as value functions and weights, requires equal attention and diligence as the performance models.

3.4. MCDA results: performance of decision options

Interestingly, both the extensive and semi-intensive roof types with photovoltaic (PV) achieved the highest values (v = 0.67 to 0.76) and ranked in the top three places for all hypothetical stakeholders for the analyses without uncertainty (Fig. 8). While the gravel roof with PV achieved the first rank for the hypothetical building owner, the overall value (v = 0.72) was very similar to the green PV roofs (v = 0.71 and 0.70). However, to find consensus options over all three stakeholder types, a gravel roof with PV would not be a wise choice, as it achieved considerably lower overall values for the other two stakeholders (v = 0.44 and 0.52). Green roofs with solar panels ranked consistently higher than cool roofs with solar panels, contrary to findings from Cavadini and Cook (2021) [1], who found PV-cool roofs to outperform PV-green roofs in terms of thermal benefits. This highlights the importance of using decision analysis to holistically evaluate the multiple benefits of green roofs.

The analysis also showcased that PV roof options performed better than non-PV roofs for all three stakeholder types and all ten rooftop options. To give one example: the overall values after calculating the MCDA were higher for black roofs with PV (far left on x-axis; Fig. 8) than black roofs without PV (next option on x-axis). The exception to this was the urban planner, for whom the cool and green roof types, PV and non-PV roofs achieved a very similar overall value. This can be explained by the fact that it was assumed that this stakeholder places more weight on environmental objectives (e.g., heat mitigation; Fig. 4) and that for the cool and green roof types, PV panels appear to increase the overall surface temperature and heat flux (Fig. 5). The black and gravel roofs without PV ranked last (ranks 9 and 10) for all three stakeholder profiles and had considerably lower values than the best-performing options. Therefore, they are clearly not recommendable. SI Fig. 6 explores the costs and benefits of the different roof types for each stakeholder and showcases that the black and gravel roofs without PV are inefficient options for all three stakeholders.

3.5. Uncertainty analysis of predicted performance

In addition to the analysis without uncertainty (Section 3.4), 2′000 Monte Carlo simulation runs were used, drawing from the uncertainty distributions of the predicted performance estimations to analyze MCDA results. More detailed results are shown in SI Fig. 5 and SI Table 11. For the environmentalist and urban planner profiles, the green roof types ranked consistently in the top two, especially the semi-intensive type (Fig. 9). For these stakeholders, semi-intensive green roofs (with or without PV) should be encouraged, as the benefits such as heat mitigation, energy savings, stormwater runoff, and biodiversity were all assumed to be valued and received high weights (Fig. 4). For the building owner, the results were less straightforward. The overall values without uncertainty of the different roof options were relatively close for this stakeholder (Fig. 8); thus, the effect of uncertainty in the predicted performance on the MCDA results was much larger than for the other hypothetical stakeholder profiles. Each of the non-PV roof types ranked in the bottom two ranks at times, and each of the PV roof options in the top two.

Given the uncertainty range of predictions for certain attributes, the green PV roofs could rank in both the top (rank 1, 2) and bottom position (rank 9, 10) for a given run for the hypothetical building owner. A reason for this may be the high uncertainty assigned to the investment and maintenance cost for these roof types (Fig. 7). This can also be seen by the fact that even though the cool roof with PV only ranked 4th in the analysis without uncertainty for the building owner (Fig. 8), it ranked in the top two ranks much more consistently than either of the green PV roof types for this stakeholder (Fig. 9). This may also be due to the uncertainty distribution of the maintenance costs, which was smaller for cool roofs than green roofs (Fig. 7). Thus, given the assumed preferences of a potential building owner, cool roofs more consistently outperformed green roofs in Monte Carlo simulation, as maintenance costs were lower. This showcases the importance of accounting for uncertainty in the performance predictions, and of reducing uncertainty ranges by obtaining realistic cost estimates of different roof top choices. It also highlights the sensitivity of MCDA to stakeholder preferences; as these considerations do not apply to the other two hypothetical stakeholders,

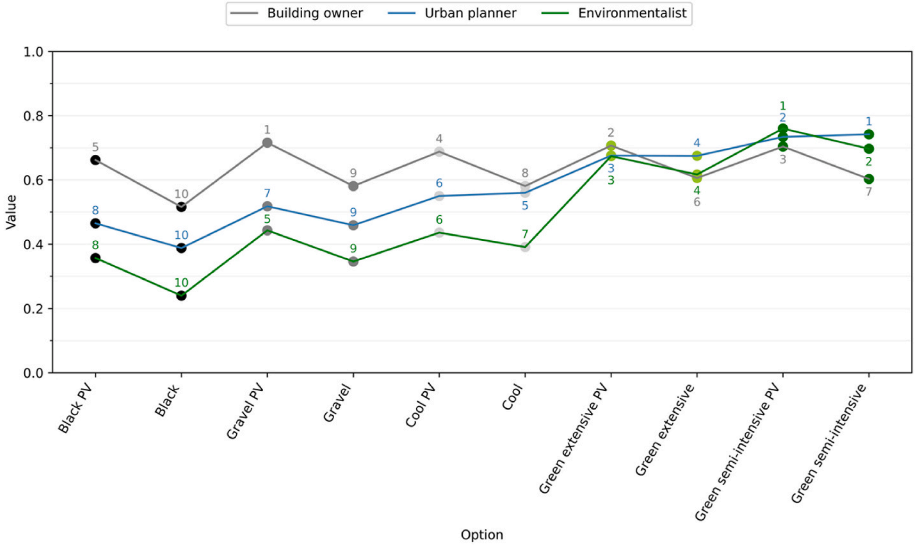

Fig. 8. Overall value v(a) after aggregation using MCDA (y-axis) and ranking (annotations) of the roof options (x-axis) according to each hypothetical stakeholder (colored lines), when excluding the uncertainty of predictions. An overall value of 0 indicates that none of the objectives are achieved at all, while 1 indicates that all objectives are fully achieved. A rank of 1 indicates that this option performed best for the respective stakeholder, and a rank of 10 that it performed worst. PV: photovoltaic. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

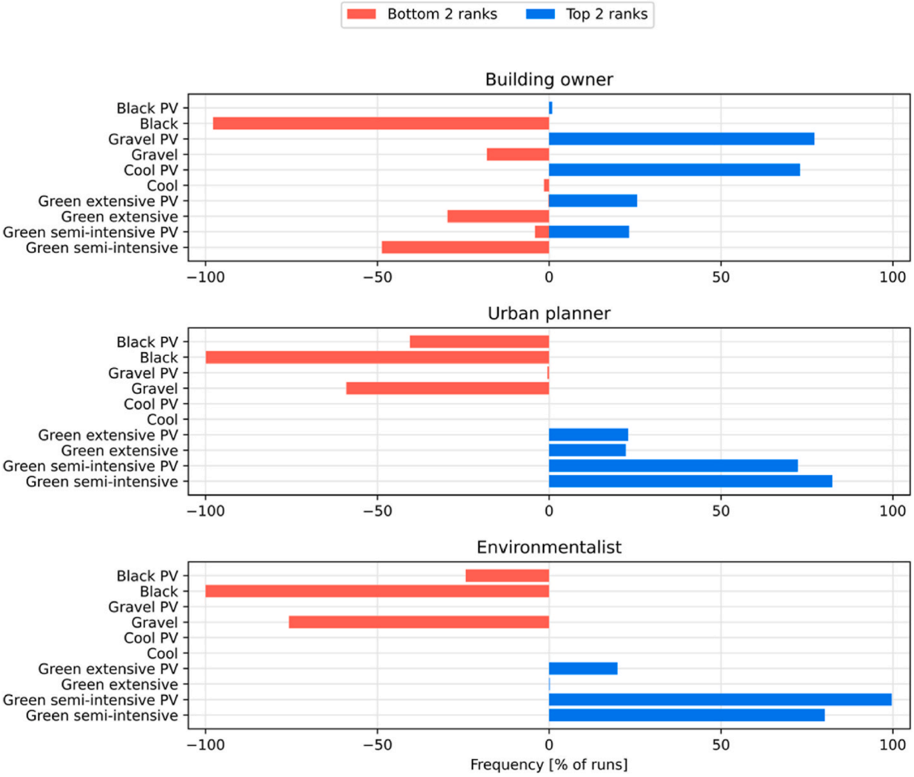

Fig. 9. MCDA ranking of 10 roof options (y-axis) for three hypothetical stakeholders (boxes) including the uncertainty of predictions: Frequency of each roof option appearing in the top 2 (blue) or bottom 2 ranks (red), resulting from 2′000 Monte Carlo simulation runs. Abbreviations see Fig. 8. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

for whom costs were assumed to be of much lower importance (see weights in Fig. 4).

Overall, given the results of the uncertainty analyses of predictions, presumably acceptable consensus options over all three hypothetical stakeholders, were the extensive and semi-intensive green roofs, both including PV. Both of these two options achieved the first or second rank in around 25% of the simulation runs for the building owner. For the other two stakeholders, the semi-intensive green roof with PV would be recommended as first choice, as it achieved the top two ranks in 75–100% of the simulation runs.

3.6. *Sensitivity analysis of stakeholder preferences: weights*

The predicted performance estimation is not the only source of uncertainty. The stakeholder preferences, and in this example the weights assigned to objectives, are often subject to considerable uncertainty. A local sensitivity analysis was carried out to understand whether changing the weights assigned to objectives would change the MCDA results, and specifically, the ranking of options [120,123,126]. To do so, the weights of each lower-level objective were increased and decreased by 20 % (and the remaining weights renormalized; [59]). For each new weight set, a standard MCDA was calculated (excluding the uncertainty of predictions; Fig. 10). For a more detailed analysis of how changing weights impacted the overall value of options, refer to SI Fig. 7.

Similar to the results including the uncertainty of predictions (Fig. 9), the ranks seemed relatively stable overall for the urban planner and environmentalist profiles. Especially important is the observation that all four green roof options (extensive and semi-intensive green roofs without or with PV) always achieved the best four ranks. This corresponds well to the previous results: when including the uncertainty of predictions, the green roof options performed consistently best for these two stakeholders (Fig. 9). For the urban planner, however, the green roof options showed frequent rank reversals among the respective PV and non-PV roof options. Again, this likely stems from the very similar overall value these roof types achieve in the MCDA as shown in Fig. 8.

The results for the building owner showed more frequent and more pronounced rank reversals than for the other two stakeholder profiles, but only in the lower ranks 6 to 10. The top three options remained the same in all weight scenarios, which are: gravel PV, and extensive or semi-intensive green roofs, both with PV. The only time the semi-intensive green roof with PV ranked first was if the weight for maintenance cost decreased by 20%. This of course makes sense when comparing with the other two hypothetical stakeholders: both the urban planner and environmentalist scenarios put less weight on low cost, and the extensive green roof with PV always achieved the top 2 ranks for these stakeholder profiles.

In the analysis including the uncertainty of predictions, the gravel and cool roofs, both with PV, ranked first or second in around 75% of the simulation runs for the hypothetical building owner (Fig. 9). This corresponds to the results of the sensitivity analyses of weights, where gravel PV also consistently ranked first for the building owner, except when the weight of maintenance was decreased by 20% (Fig. 10). The cool roof PV option consistently achieved rank 4 across all weight sensitivity scenarios, but never reached the top two ranks. This option also never reached a top rank for the other two stakeholders. It is important to again note that the ranks do not have much discriminating power if the according values are very similar; which is the case in the baseline weight scenario for the top four options for the building owner (see Fig. 8).

Overall, given the results of the sensitivity analyses of weights, good consensus options over all three hypothetical stakeholders, are the extensive and semi-intensive green roofs, both including PV.

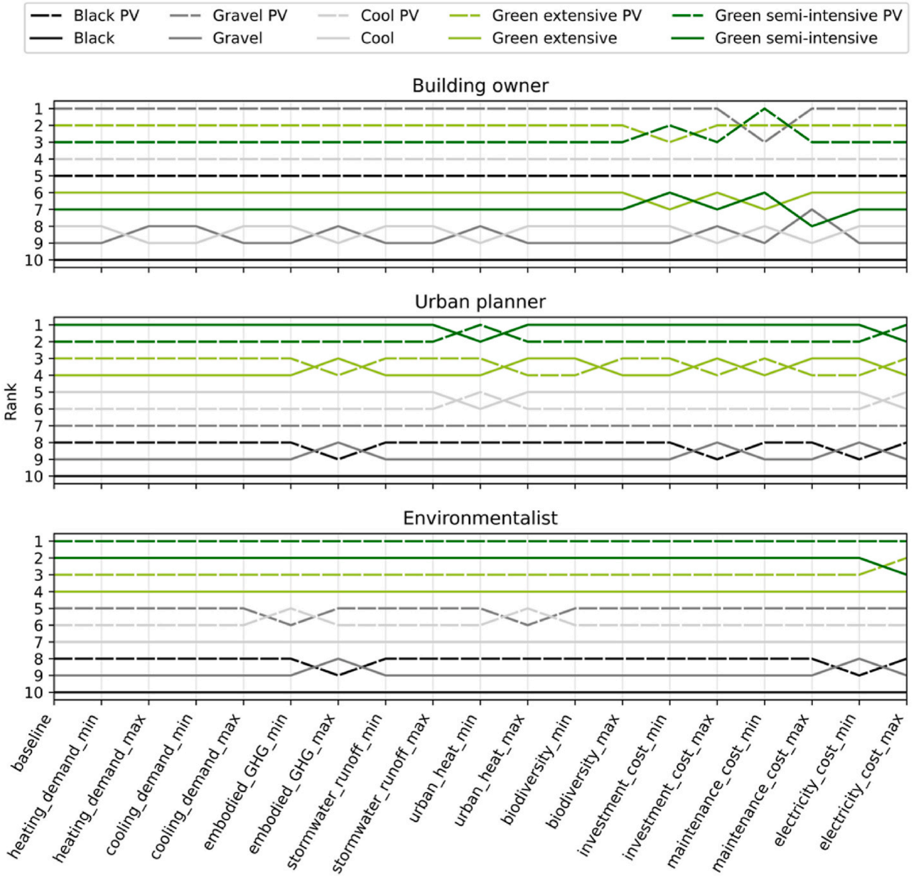

Fig. 10. Sensitivity analysis of weights of lower-level objectives (x-axis) for three hypothetical stakeholders (boxes). The baseline (x-axis to the far left) corresponds to the weights given in Fig. 4. MCDA results were calculated after decreasing the weight of each lower-level objective by 20% (xxx_min) and increasing it by 20% (xxx_max). The results are given as ranks (y-axis) for each of 10 roof options (colored lines; abbreviations see Fig. 8); where 1 is the best rank, and 10 the worst.

3.7. Sensitivity analysis of stakeholder preferences: value functions and MCDA aggregation model

In general, within the MCDA literature, the performance of options can also be sensitive to assumptions concerning the shape of single-attribute value functions and the aggregation model. Whether results are sensitive to these standard assumptions of the preference model strongly depends on the specific case (see e.g., Refs. [120,123,126]). In this analysis, the good consensus options extensive and semi-intensive green roofs with PV were often corroborated by the results of the sensitivity analysis of changing value-function curvatures and aggregation model. The extensive and semi-intensive green roofs with PV often achieved high values, even with these changes (see SI Fig. 8). However, because the overall values were usually very similar, these top 2 consensus options did not necessarily achieve the top 2 ranks (SI Fig. 9). As in previous analyses, the sensitivity of results was highest for the building owner. For this stakeholder, cool and gravel roofs with PV often achieved higher ranks than the two green PV roofs (SI Fig. 9); however, their mean value was rarely much lower than the value of the top options (SI Fig. 8). For more details refer to SI 5.4.2.

Thus, in our case, the simplifying assumption of using linear single-attribute value functions and the additive aggregation model produced relatively stable (or: robust) results; but not in all cases for the building owner. As results did strongly depend on the weights, it is recommended to elicit these from real stakeholders in a next step. Additionally, it might be beneficial to check assumptions concerning shapes of value functions and the additive aggregation model with at least some stakeholders.

3.8. Further discussion about method generalization

The results presented in this paper concern a specific, exemplary case about the choice of a “best” sustainable flat rooftop option. To analyze different flat roof types, a combination of literature data, building energy simulation, hydrologic modeling, and MCDA was used. To overcome the limitations of a single case, wherever possible, generic data were used, e.g., from literature or widely used models. However, even the best real-world data includes variability and uncertainty. The idea of this paper is to demonstrate the importance of carrying out careful modeling that can deal with the uncertainty of the predicted performance. The data are thus case-specific, but the integrated methods are generalizable, as are the results, which would be indicative of results in similar cases. Actually, any meaningful comparison in a real-world decision needs to use case-specific data that reflect the local conditions, as well as, the stakeholder preferences that are involved in the actual decision.

To include stakeholder preferences in the MCDA, typical hypothetical stakeholders were chosen that represent broadly contrasting and relatively extreme preferences concerning the importance of objectives. This paper thus additionally demonstrates methods for dealing with the uncertainty or variability of stakeholder preferences. Various sensitivity analyses to challenge assumptions about the preference parameters of the MCDA model were carried out, including changed weights, value functions, and aggregation functions. These analyses allowed to test for the stability of results and reach relatively robust conclusions. The proposed approach and the specific methods used are thus appropriate to address other cases of rooftop choices. They can also be implemented to address other types of technical decision problems, for instance concerning the choice of blue-green infrastructure [127,128] which can be planned to address a range of objectives [129]. The MCDA itself, including uncertainty and sensitivity analyzed, is an excellent method that can be applied to any type of decision case.

4. Conclusions and future work

Due to costs and often overlooked advantages, sustainable roofing solutions like green roofs, cool roofs, and solar panels may remain under implemented. To comprehensively evaluate these technologies and make informed choices, multi-criteria decision analysis (MCDA) has been used by others to systematically assess a wide range of rooftop options across various objectives. However, these studies typically overlook hybrid options like combining PV panels with green or cool roofs, despite the potential for improved panel cooling and efficiency. Furthermore, MCDA studies often omit engineering modeling and its associated uncertainties, potentially leading to inaccurate assessments of decision options. This study used MCDA to holistically compare ten different flat roof options on a commercial building, including black, gravel, cool (white), extensive green and semi-intensive green roofs, each with or without a rooftop photovoltaic installation, for nine objectives and three hypothetical stakeholder preference profiles.

The predicted performance for each option, which relied on simulation modeling and literature review, varied across objectives. Green roofs had the best performance across the most objectives, while cool roofs performed respectively poor. Semi-intensive green roofs had the lowest stormwater runoff per rain event (90% lower than black, gravel and white roofs), lowest heat flux (82% lower than black roofs), and highest habitat diversity. Cool roofs, on the other hand, performed best in only one objective when combined with PV (median cooling demand was 8% lower than black roofs), but performed worst for median heating demand and global warming potential. Extensive green roofs had the best (lowest) median heating demand and global warming potential (11 and 71% lower than cool roofs, respectively). Gravel roofs held the lowest investment costs (74 $\$/m^2$ compared to 416 $\$/m^2$ for semi-intensive PV green roofs), while maintenance costs were lowest for black and gravel roofs (0.23 $\$/m^2$) and electricity costs lowest for the PV options (~14.5 CHF/m^2 compared to ~23 CHF/m^2 for non-PV roofs).

Combining these performance estimates with three stakeholder preference profiles, green roofs, especially the semi-intensive ones with PV panels, appear to be the best options for two stakeholders in this analysis (semi-intensive green roofs reach the top 2 ranks in 72 – 99% of runs), and a good one for the third (reaching the top 2 ranks in up to 23% of runs for the building owner), due to their multifunctional benefits. Roofs with a PV solar installation outrank the other roofs for all three stakeholders. Given their respectively poor performance, cool roofs rank consistently lower than green roofs for all stakeholder profiles (mean value difference of 0.10). These results are generally robust to predicted performance uncertainty (from a Monte Carlo analysis) and sensitivity of stakeholder preference features (e.g., weights, value functions, and aggregation models). These findings highlight the importance of evaluating PV-roofs and in particular, integrated PV-green roof options, in rooftop decision analyses.

Overall, this analysis has shown the importance of integrating performance modeling into the MCDA analysis. This integration not only allows for the inclusion of hybrid and PV decision options – which ended up being the best performing options – but is also crucial to keep the uncertainty small and have an accurate portrayal of the considered options. Testing for uncertainty and sensitivity of predicted performance of options and stakeholder preferences also ensured the results and conclusions were robust. While the method used in this study is universal, specific results are limited to commercial buildings in a current Swiss climate with flat roofs and the distinct technologies tested (e.g., polycrystalline silicone PV panels, extensive green roofs with *Sedums* and semi-intensive green roofs with grasses and shrubs). The results for these technologies are generally robust to changes in performance predictions and stakeholder preferences; however, given the deep uncertainty due to climate change, it is worth reevaluating these predictions in a future, more variable climate, as well as, comparing whether the uncertainty of climate change or stakeholder preferences matters more.

Future work could confirm or broaden these findings through the exploration of additional case studies, decision options, and objectives, as well as, by eliciting real stakeholder preferences and validating engineering performance models, when applicable. Additional case studies could include residential buildings, which would likely alter building operation patterns and building height, and thus energy savings. Particularly for residential buildings, it may also be interesting to consider the importance of recreational space as an objective, which, if important, may reduce the value of PV options. Numerous additional rooftop decision options could also be evaluated, including various green roof designs, blue roofs, and rooftop wind generators.

CRediT authorship contribution statement

Bettina Maurer: Writing – review & editing, Writing – original draft, Visualization, Software, Formal analysis, Conceptualization. **Judit Lienert:** Writing – review & editing, Writing – original draft, Validation, Resources, Methodology. **Lauren M. Cook:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Methodology, Formal analysis, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

The authors declare that Generative AI and AI-assisted technologies have not been used in the writing process of this manuscript.

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

The data and code used to conduct the analyses reported herein is available open-access at the Eawag repository, ERIC: https://doi.org/10.25678/0009C4.

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Appendix A. Supplementary data

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