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Towards probabilistic performance metrics for climate change impact studies

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ABSTRACT

This paper explores the current state-of-the-art in performance indicators and use of probabilistic approaches used in climate change impact studies. It presents a critical review of recent publications in this field, focussing on (1) metrics for energy use for heating and cooling, emissions, overheating and high-level performance aspects, and (2) uptake of uncertainty and risk analysis. This is followed by a case study, which is used to explore some of the contextual issues around the broader uptake of climate change impact studies in practice. The work concludes that probabilistic predictions of the impact of climate change are feasible, but only based on strict and explicitly stated assumptions.

1. Introduction

The relationship between climate change and building performance is complex [1]. Climate change impacts both the mean and variability of key weather parameters like temperature, precipitation, humidity, solar irradiation and wind speed and direction [2]. These bear on the building behaviour and, within the thermal field, may lead to increased energy use and associated greenhouse gas emissions [3,4], which contribute to further anthropogenic climate change. While the contribution of individual buildings towards overall greenhouse gas emissions is negligible, the built environment as a whole is responsible for about one third of all emissions [5].

Within the human endeavour to tackle climate change, building science has started to explore this complex interrelation of climate change and building behaviour. The predominant work in the field concentrates on climate change mitigation, which deals with making buildings more energy efficient in order to curb greenhouse gas emissions and thereby prevent or even reverse climate change. However, since the turn of the century another area is emerging that focuses on the reverse relation, being the prediction of likely consequences of expected ('locked-in') climate change for buildings. Generally work in this field is labelled as dealing with climate change adaptation; it deals with the robustness and resilience of building performance towards changing conditions as well as needed interventions. Individual projects in this area are often named climate change impact studies. Seminal publications in this area are the work by Hacker et al. [6] and Crawley [3].

Energy use for heating and cooling provides a clear starting point to assess the behaviour of buildings under climate change. Yet other performance indicators like peak heating and cooling load, direct measures of greenhouse gas emissions and overheating hours also have a role to play. Furthermore, given the fact that climate change impact studies by their very nature are based on long-term predictions of how buildings will behave in the future, one would expect that these performance indicators would be assessed in a probabilistic manner, and subject to a propagation of uncertainties and risk analysis. However, it appears that most studies reported thus far are of a predominantly deterministic nature.

Predicting the future behaviour of buildings is a complex matter. Just focussing on the climate conditions only one has to deal with complex datasets. Arguably as of 2011 the state-of-the-art in climate change predictions are the UK climate change projections 2009 (UKCP09). These were released in June 2009 and are the first to provide probabilistic projection for a number of weather variables [7]. UKCP09 takes into account three types of uncertainty: natural internal climate variability, uncertainty in climate models, and uncertainty in future emissions. These projections can be used for building performance analysis, but their use is not straightforward. By way of example, Fig. 1 shows the cumulative distribution functions of annual mean temperature in Birmingham (UK) from UKCP09 for four future time periods. Every curve in this figure represents 3000 hourly weather files and hence requires significant computational power when applied in a building simulation context.

This paper explores the current state-of-the-art in performance indicators and use of probabilistic approaches used in climate

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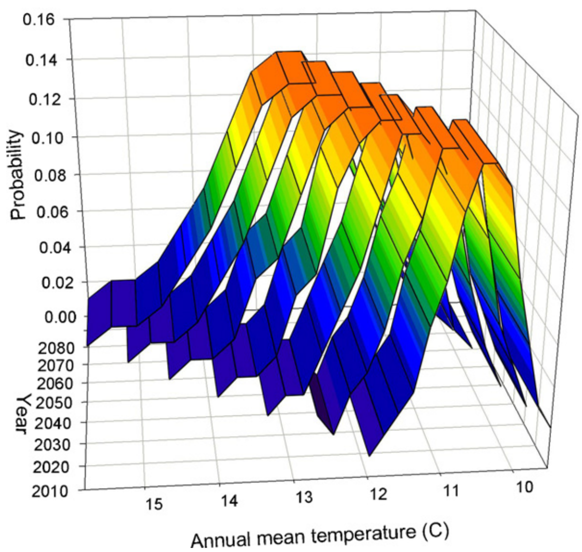

Fig. 1. Histogram of annual mean temperature for seven future overlapping time periods under medium emission scenario in Birmingham (UK) from UKCP09.

change impact studies. It presents a critical review of recent publications in this field, followed by the presentation of a case study conducted by the authors which is used to highlight some of the issues that need to be addressed.

2. Metrics and probabilistic approaches as used in recent climate change impact studies

Climate change generally implies an increase in average annual temperatures. On a global scale, this is beneficial to buildings operating in a cold climate, as higher outdoor temperatures reduce the (dominant) heating energy use. The effect has a detrimental impact on buildings in a warm climate, as it further increases their cooling energy use. For buildings in a mild, temperate climate heating energy use will be swapped for cooling energy [3]. Generally speaking small buildings are more sensitive to climate change than large buildings [8] which usually have higher internal heat gains and a more favourable volume to façade ratio, making them less susceptible to changes of the outdoor temperature. Buildings that employ natural ventilation systems for cooling will only show a decrease of annual energy use and associated carbon emissions, since heating energy use decreases when the climate warms. However, in this case overheating risk may well increase, resulting in a need to study an additional performance indicator. In buildings that have both heating and cooling, like mixed-mode and mechanically ventilated buildings, effects might be amplified by a changeover between different system drivers, for instance from a gas-driven heating system to an electricity-based cooling system [3,6]. Different coefficients of performance (COP) of similar systems can also cause unexpected results.

At the same time climate change also has an impact on extreme weather events, which can have a severe impact on the thermal conditions in buildings, especially in the form of health impacts of heat waves [9,10].

2.1. Metrics/performance indicators

An initial way of studying the impact of climate change on buildings focuses on the outdoor climate conditions, measuring heating degree days (HDD) and cooling degree days (CDD); see for instance [11,12]. Heating degree days are defined as the product of the number of days that the average daily outside temperature falls below a given threshold value, times the number of degrees below that threshold; cooling degree days are similar, but now as number of days that the average temperature raises above a set limit. HDD and CCD give an indication of heating and cooling needed, without having to study the building itself in any detail other than via the threshold values.

The basic performance metrics for measuring energy use for heating and cooling are reasonably well-understood and are directly applicable to climate change impact studies. Generally heating and cooling energy use are expressed in terms of kWh or MJ per annum; see for instance [13,14] as well as many others. For purposes of cross-comparison with other buildings, some authors translate these values to energy use per unit area (kWh/m^2 year [15] or MJ/m^2 year [16]). Depending on the context of specific climate change impact studies, they are often broken down into energy use by zone, component, system or plant, allowing analysis at various levels, as in [17]. Some studies calculate percentage in change relative to a baseline energy use. The seminal work by Hacker et al. uses this approach with reference to energy use under the 1989 climate conditions [6], motivating this by stating that '*rather than use fixed thresholds, percentage changes in energy use have been considered to be indicative of changes in future performance*'. Note however that figures presented this way still are based on energy use data, and now include the setting of the reference/baseline case and underlying argumentation.

Apart from average effects on annual energy use, climate change is also likely to change the peak loads for heating and cooling systems. This can lead to unmet loads; however, it also impacts the sizing of systems. According to Watkins and Levermore [18], the peak cooling load for an office room in the UK will increase by about 10% due to an increase of 1 °C ambient air temperature. The work by Thevenard into the influence of expected climate conditions on the sizing of heating and cooling systems [19] indicates that design temperatures, used to predict loads which then motivate the capacity of selected systems, have already changed. Thevenard reports that design temperatures have increased by an average of 0.76 °C per decade for a 99.6% annual cumulative frequency of occurrence of the heating system design temperature, 0.38 °C per decade for 0.4% annual cumulative frequency of occurrence of the cooling design temperature, and 0.28 °C per decade for a 0.4% annual cumulative frequency of occurrence of dehumidification dew point temperature. Based on these results Thevenard recommends that 0.13 °C should be added to the cooling design temperature for every 10 years of cooling system life expectancy to tentatively cope with climate change effects. Thevenard recommends no changes to the heating design temperature. However, it should be mentioned that cooling load calculations are highly dependent on both the availability of design information and designer judgment [20].

Annual energy use figures are often converted into greenhouse gas emissions; typically these are reported as relative or equivalent carbon emissions in metric tonnes (tCO_2eq/year [21]). Carbon emissions are a product of the combustion of fossil fuels and are directly linked to climate change, with cutting carbon emissions now being the target of many incentives and regulations like the UKs Code for Sustainable Homes, or the European Energy Performance of Buildings Directive (EPBD). The use of carbon emissions as metrics has the advantage of offering a universal method for comparing the efficiency of different systems, since it allows taking into account that different systems might use different fuel mixes. This is a non-trivial issue; for instance [22,23] report cases where net carbon emissions increase even when overall energy use is reduced. For climate change impact studies, which by their very nature cover time spans of several decades, it is important to note that fuel mix is likely to change over time [24]. For example, the carbon intensity for purchased electricity in the UK has decreased from 0.821 to 0.571 $kgCO_2/kWh$ between 1990 and 2008, due to an increased contribution of renewable sources to the national electricity production [25]. Equivalent carbon emissions have an additional complexity, accounting for the emission of methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur, and hexafluoride as well as for carbon dioxide itself. These other greenhouse gas emissions are translated into equivalent carbon emissions on the basis of an assumed contribution to climate change; this conversion (and its impact on policy making) is not without issues [26]. Carbon emissions can also be extended to cover both operational emissions (for heating and cooling purposes) as well as embodied carbon emissions (ECO_2) that are attributed to fabrication and construction activities). This then allows to calculate cumulative CO_2 emissions, ECO_2 payback time, and CO_2 savings over a 100 year lifetime [21]. Finally, like for energy use, some authors choose to calculate percentage in change relative to baseline carbon emissions [6,27].

Overheating risk is a different concern for buildings subject to climate change. This is especially true for buildings that have systems that rely on the temperature of outside air, like natural ventilation or summer night cooling. Buildings that include mechanical cooling might also be impacted by climate change due to a reduction of cooling capacity in a warmer climate. The simplest method to measure overheating is by a direct assessment of the indoor temperature in °C or K, and analyze maximum average and peak values, see for instance [28]. A more advanced metric for measuring overheating is the use of a weighted sum of hours exceeding a threshold value, similar to cooling degree days, but now for the indoor temperature [29]. Hacker et al. then apply a cut-off value of 1% of the total number of hours that the building is occupied to discern between comfortable conditions and a situation with overheating [6]. This way of measuring can be made even more detailed by specifying different threshold values for daytime and nigh time (sleeping) hours [30]. An alternative is to use the well-known PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied) indicators as defined by Fanger, and set thresholds for required number of satisfied occupants. However, these approaches have one key problem: it is likely that, with a change in environmental conditions, occupants change their acceptance of thermal conditions. To this end overheating would actually need to be measured via an adaptive thermal comfort method as advocated by de Dear [31]; an initial application has been demonstrated [32]. A good probabilistic handling of overheating is demonstrated by Kershaw et al. who have created histograms and probability density functions for mean annual internal temperatures and maximum occupied temperature. They use a high-level overheating criterion which is defined by the probability that the maximum daily temperature is over 30 °C and that the minimum daily temperature is over 15 °C for a minimum of three consecutive days [33]. Note that in computational studies of overheating the assumptions on the zonal resolution of the model are crucial [32].

It is interesting to note that Crawley, back in 2008 [3], points out the capability of building performance simulation tools like EnergyPlus to report on additional performance metrics like HVAC equipment runtime fraction and part-load ratios; however, few if any studies actually use these metrics in the context of climate change impact studies.

Apart from the metrics that are directly related to thermal behaviour of the building and the emissions of the systems, there are also are related performance indicators. Examples are hard medical indicators like the number of admissions to hospital or even daily deaths in an urban environment [10] during heat waves. Another indicator that seems to be gaining interest is the predicted relative work performance, or decrease thereof. Efforts to directly relate work performance to indoor temperature have been presented by Seppanen et al. [34] and this has been applied in the context of climate change [35]. Other researchers use aggregate indicators that weight and combine various aspects; a good example is the climate change sustainability index (CCSI) for New Zealand, which takes into account both climate change adaptation and mitigation, and not only covers thermal aspects but flood risk and wind damage as well [36].

2.2. Uncertainty and risk analysis

Various authors have pointed towards the uncertainties that are inherent in climate change predictions. As highlighted by Guan, one issue with climate change projections is that they cannot be validated since they cannot be mapped to an experiment or 'replicable event' [37]. However, due to the uncertainties in the area of climate change, it seems reasonable to expect that any predictions that underpin climate change impact studies are of a probabilistic nature.

The key problem in probabilistic studies is the definition of the distributions of input variables, in line with the research purpose. Uncertainties in input parameters are an inherent part of climate change impact research, since all long term predictions involve a degree of uncertainty in most aspects of the building, its use and operation, and context. The uncertainties in building performance simulation can be categorized into four types: modelling uncertainty, numerical uncertainty, specification uncertainty (system definition, building geometry, material properties), and scenario uncertainty (occupant behaviour, facility management and renovation scenarios, and climate conditions) [38]. Previous research indicates that there is only very limited data available for the process of building performance uncertainty analysis [39]; Macdonald and Strachan provide a relatively detailed discussion on assignment of probabilities for input parameters in building energy simulation [40]. Modelling and numerical uncertainties play a role in any simulation effort and therefore are not specific for climate change studies.

The uncertainties in climate change itself are already studied by climatologists [41]. Complexity is introduced by the fact that many climate predictions reflect a specific set of assumptions and are only valid for specific timeframes. For instance it is usual in climate change research to distinguish between a number of emission scenarios, which each having its own climate prediction. But even then, meteorological predictions are normally not presented in a format that is directly applicable for building simulation, which typically requires hourly weather data. The usual approach followed in many projects is to combine the climate change predictions with historical trends via 'morphing' [42]. However, this morphing process is based on some additional assumptions that are not undisputed; for instance de Dear questions the idea that some of today's climate characteristics will be preserved in a future climate [31], and a similar opinion is voiced by Kershaw et al. [33]. An additional complication is the need to translate global climate change predictions to the regional and local scale [43], which introduces additional uncertainties. Furthermore, at the local level climate change impacts can be amplified by the Urban Heat Island (UHI) effect [44].

Of the other scenario uncertainties, occupant behaviour is known to have a significant impact on the thermal behaviour and energy use of buildings and thus play a key role in the predictions obtained from simulation models [45]. Facility management and renovation scenarios introduce further unknowns. Deterioration of building elements during the building life will lead to further reduction in building thermal performance over time [46], with facility management playing a role in the pace of this deterioration [47].

Specification uncertainties also play a significant role in climate change impact studies Holmes and Hacker warn that '*it has to be recognized that the HVAC plant will be replaced several times during the life of the building*. . . *A building and associated systems may take a number of different forms throughout the life of that building.*

It is probably impossible to predict the changes that will be made to the HVAC systems' [29]. While their lifetimes are different, similar observations can be made for the building envelope and plug-and-play appliances that are used within the building. Changes to these systems are to be expected, but it is extremely difficult to predict the moment of intervention and the replacement system that will be selected. For instance, Chow and Levermore discuss the retrofitting (upgrading) of offices, but do not tackle the issues of when these upgrades take place within the office lifetime [12].

Given this broad range of sources of uncertainty, it is surprising to see that most climate change impact studies are still deterministic in nature. The seminal work by Hacker et al. [6] emphasizes the impact of changes in climate conditions; while noting the dependence on greenhouse gas scenarios they focus on one key scenario, the 'medium–high' scenario for the 2080s time slice, and provide climate scaling factors (CSFs) to relate other scenarios to this specific one. The data they present for the impact of climate change on the case study buildings in their report is valid only for the medium–high scenario and deterministic. Crawley [3] still provides a range of predicted energy performance values, but again only as a function of variation in climate conditions. Various authors have followed these leads, focussing on the climate change prediction for a medium–high emission scenario, but without taking the climate scaling factors forward and thus de facto limiting themselves to one prediction for each future time slice only [13,15,29].

In this context it is worth noting that Coley and Kershaw have defined a climate amplification coefficient C_T, and have used this to demonstrate that there is a linear relationship between increases in external temperatures due to climate change and increases in internal temperatures [48]. However, these amplification coefficients are unique for each building, and Coley and Kershaw do not give generic values for building categories, let alone the generic building stock. It must therefore be questioned how applicable the generic climate scaling factors are.

For the research that actually presents results in terms of a bandwidth for likely values, most of the propagation of uncertainties is limited to uncertainty in climate conditions and a limited set of interventions in the building only [12,30,33]. This is surprising since it should not be assumed that the uncertainty due to future climate change is necessarily more dominant than other factors that lead to uncertainties in prediction of future performance [49].

Moving from uncertainties to risk, it is interesting to note that risk and the related concepts of risk abatement and resilience are often mentioned in the context of the impact of climate change of buildings [36,50]. However, within the thermal domain, to date no reports actually quantify these risks in great depth. Yet any predictions of the future thermal behaviour of buildings are always going to include uncertainties, and risks that need to be managed [36]. Initial efforts to quantify thermal risk in buildings due to climate change are under way by the authors of this paper.

Beyond probabilistic analysis, stochastic modelling also has interesting prospects. It is worthwhile to consider a suggestion by Crawley, who points out that building performance simulation can be used in a novel way when coupled with models that represent a part of (or even an entire) building stock [3]. This idea has not yet been taken forward. Gaterell and McEvoy give a deep discussion of the building stock in the United Kingdom but do not follow that up with a representative stock model, opting for the study of one single case study building instead [14]. However, this seems a sound approach to conduct large-scale climate change impact studies on an urban, regional or even national level.

3. Case study: the Roland Levinsky Building

An attempt to apply probabilistic performance metrics in a computational climate change impact study of a real university building has been undertaken by the authors of this paper. The case study for this work is the Roland Levinsky Building, a new flagship facility at Plymouth University in the UK. A detailed description of this work can be found in Tian and de Wilde [51]. It includes the propagation of uncertainties in the climate change predictions, using UKCP09 data, as well as propagation of the uncertainties in interventions in the fabric and systems of the building. This second category includes changes to *U*-values of the building shell, infiltration rates, plug-and-play equipment heat gains, lighting heat gains, boiler efficiencies and chiller COPs. The key metrics used in this study are annual energy use for heating and cooling [kWh/m^2] and equivalent carbon emissions [kgCO$_2$eq/m^2]. Thermal simulation was carried out using the simulation program EnergyPlus. Uncertainties where propagated using a Monte Carlo approach, yielding results that give a probable distribution of performance rather than a single deterministic value. Outcomes have been presented by means of box-and-whisker diagrams, which are a convenient way to convey findings for a large dataset, highlighting the lowest observed outcome, lower quartile, median, upper quartile, largest observed outcome, and outliers. Results have also been subjected to sensitivity analysis using SRC (Standard Regression Coefficients) and ACOSSO (Adaptive Component Selection and Smoothing Operator) to determine which parameters are most influential in driving the outcomes. It must be noted that this case study required significant computational power; for this specific project grid computing has been employed to manage a total of 2400 simulation runs in EnergyPlus. For further details and discussion, see [51].

Apart from demonstrating the feasibility of the use of building performance simulation to conduct a probabilistic climate change impact study, the assessment of the Roland Levinsky Building has also been selected to investigate the context in which this type of assessment must be placed, and the constraints and limitations that apply to this type of analysis. To this end, a range of associated research activities was carried out. This included a detailed analysis of the design and construction process of the building via a series of interviews with key actors (client, architects, engineers, contractor) followed by formal, structured process modelling [52] as well as open interviews with key personnel from the local Estates department. The following salient insights have been obtained, which are useful in the context for positioning climate change impact studies in actual building engineering, construction and facility management practice:

- While climate change adaptation and resilience now feature strongly in the UK public debate [53], this recent flagship development did not have any specific mention of this aspect in the design brief. This finding is perhaps less surprising for those who work in practice, but in academia there appears to be an over expectation of briefs in terms of thermal performance criteria. According to practising engineers, specific criteria for issues like overheating and energy use are mostly introduced by themselves while working on building designs, rather than provided beforehand by the clients. Adherence to building regulations sets a basic target, sometimes augmented with voluntary rating schemes like BREEAM or LEED. In this context, it is interesting to note a comment by Sanders and Phillipson who believe that '*the whole culture of standardization, which is based on well-established data over the last 30 years, makes it difficult for British and European Standards, which underpin regulations, to react to the changing climate*' [54]. This might very well be one reason why climate change adaptation and resilience do not feature in the design and engineering process. Given the large computational effort to conduct probabilistic climate change impact studies, there is an issue with the feasibility in today's engineering offices that needs further investigation. Note that the event of cloud computing might

Fig. 2. Boilers in the plant room of the Roland Levinsky Building.

provide a solution, bypassing the need to invest in in-house grid computing facilities.

- A study of a real facility like the Roland Levinsky Building, and how it was designed, reveals that there is no need to be overly concerned about climate change leading to unmet design heating or cooling loads. While academia might expect buildings services to be optimized to just meet maximum peak loads, real systems are designed using a pragmatic approach that provides back-up facilities. This is useful for breakdown as well as maintenance situations. As such, the Roland Levinsky Buildings has several chillers and boilers, see Fig. 2. The total capacity of the combined systems provides a large safety factor that can easily cope with slight increases in peak loads. However, this also means that systems will often operate on part-load only. This can be linked back to the remark by Crawley [3] that simulation tools have the capability to report on metrics like HVAC equipment runtime fraction and part-load ratios, and the observation that this is seldom reported in the context of climate change impact studies.
- Another finding from the actual building is that it deviates from the thermal systems design provided by the building services engineers. This is mainly due to 'value engineering' efforts which led to omission of some of the air handling systems. This leads to local overheating problems within the current climate conditions, whereas overall cooling capacity ought to be sufficient. It is likely that climate change will only enhance this issue. Such interventions between engineering design and construction put a strong limitation on the benefit that computational climate change impact studies might provide during the design stage.
- Facility management by the local Estates department prioritizes the efficient operation of the building under current climate conditions, as evidenced by their Carbon Management Plan. For the long term, there are provisions to renew building services at the end of their (15–20 years) lifetime. This change of systems is seen as a good opportunity to deal with any slight changes in climate conditions if needed.

These findings lead to a need to carefully consider the benefits from deep climate change impact studies. While they clearly can provide useful insights, it is clear that the additional information that they provide will face some difficulty in permeating the whole design, construction and facility management chain.

4. Conclusions and remarks

The review of the state of the art of metrics and probabilistic approaches and the discussion of a case study on an actual university building in the UK lead to the following conclusions and remarks:

1. Typical performance metrics for the thermal behaviour of buildings like annual energy use for heating and cooling [kWh/year or MJ/year], greenhouse gas emissions [tCO_2eq/year] and overheating hours [h] are fully applicable to climate change impact studies. However, in many cases the potential of a shift from heating to cooling and increased overheating risk requires a solid review of which metrics are appropriate. There also is a need to critically review underlying assumptions, like the fuel mix used in calculating equivalent carbon emissions or the application of static versus adaptive comfort models for overheating assessment, as these assumptions might not be constant over the long time spans that are implicit in this type of analysis.
2. Climate change predictions have an inherent uncertainty. One would therefore expect climate change impact studies to all be of a probabilistic nature. Interestingly most recent work is lacking in this respect. A potential reason for this might be that the seminal work by Hacker et al. [6] focussed on one (medium–high emission) climate scenario and used climate scaling factors to relate outcomes to other scenarios; many later studies maintain the focus on the medium–high emission climate change scenario but fail to take the climate scaling factors forward. An additional issue is the lack of consideration of other uncertainties that ought to be taken into account at the long timescales used for climate change impact studies. It is highly unlikely that a building and its operational regime will stay exactly the same for 50–100 years.
3. A probabilistic approach to climate change impact studies has been demonstrated and found to be viable [51]. However, this requires the availability of solid data on other uncertainties, especially where this relates to predicting future interventions in the building envelope, building services/HVAC systems, future occupant behaviour, and future control settings. There is an urgent need to expand the knowledge base on these issues if climate change impact studies are to be taken to the next level.
4. There is a need to explore the limits to climate change adaptation studies. While some prediction of the future is useful and can guide today's decisions, a full probabilistic approach to all potential futures is likely to yield an uninformative spread of outcomes and leads to the proverbial 'garbage in, garbage out' situation. One solution might be to refocus on the lifetime expectancy of initial building configurations as a key indicator, without making too many assumptions about the potential replacement options (which requires predictions of the technology and efficiency of systems 15, 20 years down the line). Another useful approach would be to focus on passive aspects that are inherent to the overall building, like orientation, thermal mass etcetera, and which are unlikely to be affected by future interventions. Getting these aspects right would climate-proof the building, and reduce the impact of the other uncertainties.
5. Climate change impact studies are proliferating in building science; however, uptake in building design practice is slower. Some practical barriers, like the role of existing regulations and the current organisation of the industry, have been identified. At the same time, it seems that existing safety margins for system dimensioning make many buildings more resilient towards climate change than often is assumed. Additionally, the relatively short lifetime of building services/HVAC systems creates an opportunity to repeatedly adapt a building to changing climate conditions, provided the overall building design is reasonably sound.

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