# Robust Optimisation of Building Retrofits for Present versus Future Climate Scenarios in Humid Continental Climates (*Dfb* subtype) to Reduce Heating Demand and Mitigate Future Overheating Risk

Nicholas Swedberg<sup>1\*</sup> <sup>1</sup>Arup, Boston, USA \*corresponding author: nick.swedberg@arup.com

## Abstract

The outdoor environment is a major driver of building performance; a changing climate poses a significant challenge to the effective deployment of building retrofits. The Dfb Köppen climate zone, a humid continental climate with warm summer subtype, is poised to confront significant annual and seasonal temperature changes within the next thirty years. This study examined the relationship between retrofits' ability to reduce heating demand and simultaneously mitigate future overheating risk. A low-rise apartment was used as the basis of a multi-objective design optimisation (MODO) that modelled building heating demand and overheating risk across a series of input variables, considered either optimisable (i.e.: building envelope upgrades) or nonoptimisable (i.e.: occupancy profiles) in the context of this study. The metric overheating-degree-hours (OHDH) was utilised to assess overheating risk. The results of this study reinforced previous findings indicating envelope upgrades can significantly reduce heating demand, but also underscored the importance of implementing solar heat gain mitigation strategies for overheating risk reduction. Additionally, the study highlighted the appropriateness of amalgamated weather data for performance analysis.

# Introduction

As the outdoor environment is a major driver of building performance, regarding both energy use and occupant comfort (de Wilde and Coley, 2012), a changing climate poses a seminal challenge to effective building design. Additionally, as the built environment represents a major source of energy consumption (IEA, 2016), contributing significantly to global greenhouse gas (GHG) emissions (de Wilde and Coley, 2012), building stock energy efficiency improvements are required to reduce emissions and mitigate the extremity of climate change (Nik and Sasic Kalagasidis, 2013; van Hooff, et al., 2016).

Though the impacts of climate change will be felt globally (Wang and Chen, 2014), the *humid continental climate with warm summer subtype*, the *Dfb* Köppen climate zone (Beck, et al., 2018), is poised to confront more extreme temperature changes within the next thirty years (Bastin, et al., 2019).

### Background

A comprehensive study by Bastin, et al. (2019) examined the likely climate shifts for 520 major global cities between the years 2020 and 2050. Under the Representative Concentration Pathway 4.5 (RCP 4.5) used in the Bastin, et al. (2019) study, 77% of the 520 cities examined were found to experience a climate in 2050 ('future climate') that differs from their climate in 2020 ('current climate'), with future climates generally becoming warmer, winters in northern latitudes becoming wetter, and summers globally becoming drier (Bastin, et al., 2019). Northern latitudes cities in the Dfb climate zone were found to experience dramatic shifts in extreme temperature conditions in terms of absolute temperature change (Bastin, et al., 2019). Whereas the global mean increase in minimum winter temperature and maximum summer temperature by 2050 is projected to be 2.1°C and 3.3°C, these changes in the Dfb region were shown to be 4.1°C and 5.8°C, respectively (Bastin, et al., 2019).

In major *Dfb* population centres, a significant burden of climate change adaptation falls on the residential sector, specifically apartments. In Canada, apartments represent 68% of the Montréal housing stock and 51% of the Ouébec City housing stock (Statistics Canada, 2022); in the Swedish cities of Stockholm and Örebro, apartments respectively represent 69% and 52% of the housing stock (Statistikmyndigheten, 2021). In such Dfb locations, large segments of the population not only find themselves in multi-family dwellings, but in dwellings that are more aged. In Montréal, 76% of all residential apartments are at least 40 years old, and 36% of all apartments require some form of renovation (Ville de Montréal, 2020a, 2020b). In Sweden, 70% of all apartments in both Stockholm and Örebro were built before 1980 (Statistikmyndigheten, 2021). Similarly in Norway, 59% of apartments are at least 30 years old (Statistisk sentralbyrå, 2022). It is essential that apartments in the *Dfb* climate zone adequately prepare for a warming world so as to ensure that large portions of residents are not exposed to increased risk, overheating or otherwise.

Retrofits are an effective and necessary means of updating existing buildings to meet energy and emissions performance targets and provide climate change adaptations (van Hooff, et al., 2016). In *Dfb* countries like Sweden, most energy efficient building measures will

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occur in the form of retrofits, rather than as new projects (Liu, et al., 2014). A study by Liu, Rohdin and Moshfegh (2015) found that retrofitted buildings had the potential to reduce annual space heating demand by roughly 39%. Further, a recent study by Schwartz, Raslan, and Mumovic (2022) noted residential refurbishments (albeit in a UK context) generally had 20% lower lifecycle carbon emissions and were 27% cheaper to build and operate than the best-optimised new construction solutions. This underscores the environmental and cost imperative of optimising retrofit solutions and attests to the reality of aging multi-family apartments.

Overheating represents a major climate change-induced risk to building occupants. As global temperatures rise, overheating prevalence will increase (de Wilde and Coley, 2012). Overheating causes adverse health impacts for building occupants, the most severe being mortality (Liu, et al., 2015). However, many existing buildings in the Dfb climate region are unequipped with active cooling systems, instead using passive means to combat mild summer conditions (Wang and Chen, 2014; Nik and Sasic Kalagasidis, 2013). While the current approach has the benefit of producing fewer operational carbon emissions, as Dfb summer temperatures rise, the continued use of passive approaches without further adaptation may prove insufficient to meet future cooling and overheating risk mitigation needs, thus facilitating a shift towards more carbon-intensive cooling applications or increasing building occupants' overheating risk exposure.

Despite the importance of addressing overheating risk, a single definition of overheating is non-existent. Defining an overheating metric requires identifying a threshold temperature above which overheating occurs, as well as considerations for duration and severity. Per the Charted Institution of Building Services Engineers ((CIBSE), 2017) Guide A, the overheating threshold is 25°C in all spaces, except for bedrooms, where the threshold is 23°C; overheating occurs when 1% of occupied hours exhibit a temperature above this threshold. The Swedish Board of Health (SNBHW, 2005) recommends that the overheating threshold is 24°C in the winter, and 26°C in the summer. The limit for overheating is 25°C as relates to the concept of thermal autonomy (Kesik, 2019). Beyond the overheating threshold temperature, frequency and severity must also be quantified. In CIBSE (2017) Guide A, overheating frequency, but not severity, is described: one hour at 26°C would report the same percentage of overheating as one hour at a temperature of 32°C. Porritt, et al. (2011) and Jenkins, et al. (2011) have therefore recommended the use of a composite metric, the overheating-degree-hour (OHDH) to better describe the severity and frequency of overheating events.

Overheating is a concern in current climate conditions, becoming increasingly important for the resilient assessment of *Dfb* retrofit measures. As noted in the *Thermal Resilience Design Guide* (Kesik, 2019), overheating is a central climate change-driven health and well-being risk for building occupants. This risk is, however, additionally driven by the increasing prevalence of extreme weather events. Amongst climate changeinduced risks, rising temperatures pose one risk factor, but power outages or other energy scarcity events pose a secondary risk in that active building systems may be taken offline when they are most needed (Kesik, 2019).

### Methods

This study assessed the performance of a range of retrofit measures applied to a low-rise apartment building. The basis for energy modelling was a US Department of Energy (DOE) reference energy model (DOE, 2020). As noted in the 'background' section, a multi-family apartment typology represents a large portion of housing in Dfb cities. This DOE archetype was modified based on a survey of research conducted in various Dfb countries and cities to ensure that the baseline energy model properties aligned with the constructed realities in this climate zone. The effectiveness of building envelope retrofit measures were subsequently analysed across two metrics, area normalised heating demand measured in kilowatt hours per square metre (kWh/m<sup>2</sup>), and overheating risk measured in overheating-degree-hours (OHDH). This multi-objective design optimisation (MODO) identified the optimal building envelope retrofits as those simultaneously minimising heating demand and overheating risk. Fig. 1 summarises the study design.



Figure 1: Study design

#### **Climate and Weather Data**

A climate analogue mapping study by Bastin, et al. (2019) formed the basis of development of future climate weather files used in building performance simulation (BPS). As the work by Bastin, et al. (2019) provided data for fewer North American cities, the work of Fitzpatrick and Dunn (2019) was used as a companion to determine analogues for North American cities, under the same RCP 4.5 pathway. The cities examined in this study included *Dfb* cities identified in the work of Bastin, et al. (2019) and Fitzpatrick and Dunn (2019); *Table 1* summarises and *Figs. 2-3* visualise the analysed cities and their analogues.

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City	ID	Analogue <sup>1</sup>	ID	
Berlin, DE	BER	San Marino, SM <sup>3</sup>	SM	
Burlington (VT) US	BVT	Lafayette (IN) US <sup>2</sup>	LAF	
Helsinki, FI	HEL	Vienna, AT	VIE	
Kyiv, UA	KYI	Belgrade, RS	BEG	
Minsk, BY	MSQ	Sofia, BG	SOF	
Montréal, CA	MTL	Cincinnati, US	CIN	
Moscow, RU	MOW	Sofia, BG	SOF	
Oslo, NO	OSL	Bratislava, SK	BTS	
Ottawa, CA	OTT	Pittsburgh, US	PIT	
Portland (ME) US	POR	Newark US <sup>2</sup>	EWR	
Riga, LV <sup>3</sup>	RIX	Vienna, AT	VIE	
St. Petersburg, RU	SPB	Sofia, BG	SOF	
Stockholm, SE	STO	Budapest, HU <sup>3</sup>	BUD	
Tallinn, EE <sup>3</sup>	TLL	Bratislava, SK	BTS	
Toronto, CA	TOR	Washington, US	DC	
Vilnius, LT <sup>3</sup>	VNO	Pristina, XK <sup>3</sup>	PRN	
Warsaw, PL	WAW	Novi Sad, RS <sup>3</sup>	NS	
Winnipeg, CA	WPG	Minneapolis, US <sup>2</sup>	MSP	

Table 1: Dfb cities analysed and associated analogues

1. Bastin, et al. (2019), unless otherwise noted.

2. Fitzpatrick and Dunn (2019).

3. A secondary or tertiary analogue (Bastin, et al, 2019) was used based on .epw file availability.



Figure 2: Analysed European Dfb cities and correlating 2050 climate analogues (see Table 1).



Figure 3: Analysed North American Dfb cities and correlating 2050 climate analogues (see Table 1).

Weather files for cities included in this study, and their corresponding climate analogues, were sourced from the *EnergyPlus* weather file database (EnergyPlus, 2020). A weather file dataset was created that amalgamated the extreme data from both 2020 and 2050 analogue data into a single .epw file. Temperature and precipitation data from 1 October to 31 March for a given analysis city (extreme heating demand scenario) was combined with temperature and precipitation data from 1 April to 30 September (extreme overheating scenario) for a listed climate analogue, i.e.: the creation of an amalgamated weather file (AWF) for Berlin mapped the weather data from San Marino (see *Table 1*) from 1 April to 30 September into the 2020 Berlin weather file.

The minimum, median, and maximum weather profiles were identified from the set of cities analysed in *Table 1*. 'Minimum, median,' and 'maximum' were qualified in terms of the mildest and most extreme absolute seasonal low and high dry bulb temperatures. The minimum, median, and maximum conditions are represented by Berlin, Vilnius, and Winnipeg, respectively; Berlin represented the mildest conditions, Vilnius the median, and Winnipeg the most extreme summer and winter conditions. The median weather data set, Vilnius, was used for principal optimisation modelling.

#### **Energy Model Creation**

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the US DOE have a series of archetypical building energy models based on a survey of the US building stock (DOE, 2020). As this study sought to analyse multi-family residential projects, the ASHRAE mid-rise apartment archetype model (DOE, 2020) was utilised as the basis energy model geometry for this study.

Except as noted, the assumptions included with this ASHRAE mid-rise archetype were imported into this study. The height of the building was modified from four to two stories to better reflect the size of multi-family apartment typologies found in the *Dfb* region (EIA, 2015). The resultant geometry is shown in *Fig. 4*.



Figure 4: Visualisation of low-rise apartment used in study, based on ASHRAE archetype (DOE, 2020)

#### **Occupancy Profiles**

Occupancy data was based on previously published studies utilising two occupancy profiles: a family with two working adults and two children, and a pensioner/retiree couple (Mavrogianni, et al., 2014; Porritt, et al., 2012). These studies provided the basis for occupancy profiles and the internal gains utilised in BPS. Simplified summaries of these occupancy profiles are summarised in *Table 2*. Each occupancy profile was applied to half of all the units in the building, with the profiles distributed equally by floor and façade exposure.

Table 2: Occup	oancy profiles	utilised in	study
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Time	Person(s)	Activity	Heat		
			Gain		
			(W)		
Family (child)	ren): all days				
01:00-08:00	Child (x2)	Sleep (x2)	140		
08:00-09:00	Child (x2)	Shower (x2)	200		
09:00-18:00	-	-	-		
18:00-20:00	Child (x2)	Play/TV (x2)	200		
20:00-21:00	Child (x2)	Shower (x2)	200		
21:00-00:00	Child (x2)	Sleep (x2)	140		
Family (adult	s): weekdays v	. weekend			
01:00-06:00	Adult (x2)	Sleep (x2)	140		
06:00-07:00	Adult (x2)	Eat (x1)/sleep (x1)	170		
07:00-08:00	Adult (x2)	Shower (x1)/eat (x1)	200		
08:00-09:00	Adult (x1)	Read (x1)/-	100		
09:00-10:00	Adult $(x1)^1$	Read $(x1)/-1$	100 <sup>1</sup>		
10:00-17:00	-	-	-		
17:00-18:00	Adult $(x1)^1$	TV (x1)/-1	1001		
18:00-19:00	Adult (x1)	-/Eat (x1)	100		
19:00-21:00	Adult (x2)	Watch TV (x2)	200		
21:00-22:00	Adult (x2)	Toilet (x2)	200		
22:00-23:00	Adult (x2)	Read (x1)/sleep (x1)	170		
23:00-00:00	Adults (x2)	Sleep (x2)	140		
Pensioner/retiree: all days					
01:00-07:00	Retiree (x2)	Sleep (x2)	140		
07:00-08:00	Retiree (x2)	Toilet (x2)	200		
08:00-22:00	Retiree (x2)	Eat/Read/TV (x2)	200		
22:00-00:00	Retiree (x2)	Sleep (x2)	140		

1. Weekend only activity.

### **Building Envelope Properties**

The envelope properties of the DOE reference model were modified to reflect the as-built condition of apartments in the *Dfb* climate zone; the result of this survey is summarised in *Table 3*. The surveyed studies examined multi-family residential housing in Estonia (Arumägi & Kalamees, 2014), Sweden (Bonakdar, Sasic Kalagasidis, & Mahapatra, 2017), the 'Nordic' region, defined as Denmark, Finland, Norway, and Sweden (Berggren & Wall, 2013); and the United States (US DOE, 2022). Data surveyed included building envelope thermal transmittance, air infiltration rates, and glazing performance. The subsequent *Table 4* summarises the input data used for BPS in this study. The input values generally selected the median or mode performance value from amongst the surveyed buildings.

### **Definition of Building Envelope Optimisations**

This study considered all aspects of the building envelope to be optimisable, including external wall, slab, and roof thermal transmittance; air tightness as represented by infiltration, and glazing performance, including both thermal transmittance of glazing units and the solar heat gain coefficient (SHGC). Rather than analyse envelope build-ups, performance values for whole assemblies were utilised to permit performance-based analysis.

Table 3:	<i>Typical</i> Dfb	building	performance	data survey
	21		r - J	

	Region of data survey							
	Estonia <sup>1</sup>	Nordic <sup>2</sup>	Sweden <sup>3</sup>	USA <sup>4</sup>				
Building envelo	Building envelope							
Thermal transm	ittance (W/(	m <sup>2</sup> K))						
Exterior wall	0.51	0.35	0.29	1.13				
	0.57		0.34					
	0.65							
Slab	0.46	0.31	0.63	-				
	0.50							
	0.52							
	0.53							
Roof	0.42	0.20	-	-				
	0.50							
	0.59							
	0.66							
Air tightness (A	CH)		-	-				
Infiltration	2.67	-	-	-				
	3.57							
	4.91							
	5.29							
Fenestration & shading								
Glazing	2.9	2.3	2.9	2.9				
(thermal								
transmittance								
$(W/(m^2K)))$								
Glazing	-	-	-	$0.70^{5}$				
(SHGC)								

1. Arumägi and Kalamees (2014).

- 2. Denmark, Finland, Norway, & Sweden (Berggren & Wall, 2013).
- 3. Bonakdar, Sasic Kalagasidis, and Mahapatra (2017).

4. US DOE (2022).

- 5. Survey indicated a 44% prevalence of double-glazing; 35% for single-glazing; 21% 'unknown' (DOE, 2022). Double-glazed value used in alignment with surveyed thermal transmittance.
- 6. Entries showing '-' indicate no data for the listed study. *Table 4: Summary of baseline modelling assumptions*

	Surveyed data analysis					
	Mean	Mode	Median	Input		
Building envelope						
Thermal transmittane	$ce (W/(m^2))$	K))				
Exterior wall	0.48	-	0.51	0.51		
Slab	0.49	-	0.51	0.51		
Roof	0.44	-	0.46	0.46		
Air tightness (ACH)						
Infiltration	4.11	-	-	4.11		
Fenestration & sha	Fenestration & shading					
Glazing (thermal	2.8	2.9	2.9	2.9		
transmittance						
$(W/(m^2K)))$						
Glazing (SHGC)	-	0.70	-	0.70		

*Table 5* shows the parameters optimised in this study, and the range of input values accepted. In all cases, the input value as defined in *Table 4*, was used as the baseline ('base') threshold for each parameter, while the upper ('high') performance limit was determined per the *Passivhaus Primer: Designer's Guide* (BRE, 2015) recommendations for a southern European climate.

Consequently, shading elements were added to all glazing units on the south façade of the building used in BPS optimisations. This addition of shading to the building geometry is visualised in *Fig. 5*.

	Base <sup>1</sup>	High <sup>2</sup>	Step	No. of inputs
Building envelope				
Thermal transmittance (	$W/(m^2K)$	)		
Exterior wall	0.51	0.15	0.02	19
Slab	0.51	0.15	0.02	19
Roof	0.46	0.15	0.01	32
Air tightness (ACH)				
Infiltration	4.11	0.6	0.3	12
Fenestration & shading				
Glazing (thermal transmittance (W/(m <sup>2</sup> K)))	2.9	0.85	0.05	42
Glazing (SHGC)	0.70	0.20	0.02	26
Shading overhang (m)	0.0	0.9	0.15	7

Table 5: Envelope optimisation matrix

1. Baseline value.

2. Per Passive House guidelines for a Southern European climate (BRE, 2015); upper ('high') performance study limit.



Figure 5: Building geometry shown with shading (red)

# Multi-Objective Design Optimisation (MODO)

The input variables, including weather file data, building envelope properties and occupancy data, and the proposed envelope optimisation parameters, were utilised to conduct building energy simulations using *EnergyPlus*, *jEPlus*, and *jEPlus+EA*. Baseline models were tested utilising EnergyPlus, while jEPlus was used to add the optimisation parameters to the modelling file as defined in Table 5. jEPlus+EA was utilised to conduct the MODO; the generation and evaluation of models utilised the NSGA-2 (Non-dominated Sorting Genetic Algorithm) optimisation application. The digital models were evaluated using two metrics (described in 'output metrics' subsection): heating demand and overheating risk. The MODO sought the simultaneous prioritisation of the reduction of annual heating demand and overheating risk.

### **Output Metrics**

The primary output variables utilised for the MODO of the retrofit measures were kWh/m<sup>2</sup> and OHDH. Area normalised heating demand was measured in kWh/m<sup>2</sup>. In order to better assess the well-being risk that non-climate resilient retrofits pose to building occupants with regards to overheating, this study chose to deploy a compound overheating risk metric, OHDH, in order to quantify both the frequency and the severity of overheating events (de Wilde and Coley, 2012; Porritt, et al., 2011). OHDH is measured in °C-hours above an overheating threshold temperature. The threshold used to define overheating was 25°C, in accordance with the upper temperature limit for thermal autonomy as defined for a southern Canadian climate (Kesik, 2019). When calculating OHDH, the number of degrees above the 25°C threshold was multiplied by the duration of the overheating event (the number of hours for which the overheating event (the number of hours for which the overheating event occurred), i.e.: a temperature of 27°C occurring for a period of two hours would result in 4 OHDH. Where noted subsequently in this study, 'OHDH' is indicated as the unit for measuring overheating risk, which correlated to '°C-hours above the 25°C overheating threshold.'

#### Results

The optimisation results of retrofit measures for heating demand reduction and overheating risk mitigation are presented below. Additionally, the impact of the different weather files on simulation outputs is presented.

#### **Benchmarking of Baseline Energy Performance**

A baseline model was run to ensure that the baseline BPS inputs were correctly calibrated to match historical building performance consistent with the *Dfb* region. Using a Stockholm 2020 weather file, the baseline model returned a heating demand of 122 kWh/m<sup>2</sup>. This value was consistent with the Bonakdar and Sasic Kalagidis (2017) heating demand survey of Swedish multifamily housing; housing from the 1970s and 1980s exhibited a spatial heating demand of 143.8 and 124.3 kWh/m<sup>2</sup>, respectively (Bonakdar and Sasic Kalagidis, 2017). Baseline models were also run with the 2020 weather files for Berlin and Winnipeg (the upper and lower limits of the *Dfb* climate extremes), and with both the Vilnius 2020 weather file and the Vilnius AWF. The results are summarised in *Table 6*.

Heating Demand (kWh/m <sup>2</sup> )	Overheating Risk (OHDH)	Weather File Used
122	504	Stockholm 2020
118	790	Berlin 2020
132	662	Vilnius 2020
109	1,744	Vilnius AWF
166	1,538	Winnipeg 2020

Table 6: Summary of baseline model performance

#### **Optimisation of Building Envelope Retrofits**

The results of the optimisation modelling are summarised in *Fig. 6*, in which the Pareto Front of best performing variable permutations is clearly visualised. As shown in the figure, three clusters along the Pareto Front occurred.

The top seven performing Pareto Front optimisation strategies are summarised in *Table 7*. In order to identify the 'best' performing optimisations, a '*Composite MODO score*' was calculated, weighting performance between heating demand reduction and overheating risk mitigation. Equation (1) shows the calculation approach, which comprised the average of normalised Pareto Front results for heating demand and overheating performance.



Figure 6: Pareto Front of MODO simulations

Table 7: Pareto Front results	with lowest MODO score
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Sim. ID No.	Heating Demand (kWh/m <sup>2</sup> )	Overheating Risk (OHDH)	Composite MODO Score
001	95	168	0.496
002	114	95	0.459
003	114	80	0.442
004	145	26	0.464
005	145	20	0.457
006	146	18	0.458
007	147	16	0.457

The heating demand of a simulation (' $Q_{sim}$ ') was normalised relative to the maximum heating demand of the Pareto Front (' $Q_{max}$ '); simulation overheating risk (' $OH_{sim}$ ') was normalised relative to maximum overheating risk (' $OH_{max}$ ') of Pareto Front results.

$$0.5 \times \left(\frac{Q_{sim}}{Q_{max}} + \frac{OH_{sim}}{OH_{max}}\right) = Composite \ MODO \ Score \tag{1}$$

The resultant '*Composite MODO Score*' is included in the final column of *Table 7*. Using this final evaluation criteria, the simulation identified as *003* was noted as the top performer. The resultant heating demands across the entire Pareto Front ranged from 90 kWh/m<sup>2</sup> to 147 kWh/m<sup>2</sup>, while the overheating risk ranged from 16 OHDH to 395 OHDH.

*Table 8* shows the comparison of the performance of the results presented in *Table 7* relative to the baseline building model. This table highlights the percentage reduction (green), or increase (red) of heating demand or overheating risk relative to both the Vilnius 2020 baseline, and the Vilnius AWF baseline. In the seven cases presented in *Table 8*, as well as across all Pareto Front results, overheating risk decreased relative to both a present and future baseline. However, as noted in *Table 8*, some Pareto Front results actually resulted in a higher

heating demand than the baseline (both relative to present performance and the AWF resilience scenario).

The Pareto Front results in *Fig.* 6 that yielded a higher heating demand than the 2020 baseline (shown in the second column in *Table 8*), have been indicated in *Fig.* 6 as '*Pareto Front.*\*'

Tabl	le 8:	Optimised	result per	formance	v. l	baselines
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Sim.	Heating Demand		<b>Overheating Risk</b>	
ID No.	Redu	uction	Reduct	ion (%)
	v. 2020	v. AWF	v. 2020	v. AWF
001	-28	-13	-75	-90
002	-14	+5	-86	-95
003	-13	+5	-88	-95
004	+10	+33	-96	-98
005	+10	+33	-97	-99
006	+11	+34	-98	-99
007	+11	+35	-98	-99

**Best Performing Retrofit Permutations** 

As noted in *Table 8*, the optimisation of the building envelope resulted in major reductions in overheating risk as compared to the baseline case(s). The best performing retrofits included solar heat gain mitigation strategies in addition to general building envelope upgrades. *Table 9* summarises the best performing parameters.

 Table 9: Summary of Pareto Front input parameters

Parameter	Range	Mode
Exterior wall (W/(m <sup>2</sup> K))	0.3	0.3
Slab $(W/(m^2K))$	0.15 - 0.35	0.15
Roof $(W/(m^2K))$	0.15 - 0.35	0.15, 0.25
Air tightness (W/(m <sup>2</sup> K))	0.6	0.6
Glazing (W/(m <sup>2</sup> K))	0.85 - 1.45	0.85
Glazing (SHCG)	0.20 - 0.35	0.25
Overhang depth (m)	0.45 - 0.90	0.75

### Summary of the Impact of Using 2020, 2050, and Amalgamated Weather File (AWF) Data

*Table 10* summarises the variation in using a 2020, 2050, and an AWF in BPS. The MODO utilised the Vilnius AWF dataset, but the iteration identified as *003* in *Table 7* was secondarily simulated using the 2020 and 2050 Vilnius weather data to review the variability in performance resulting from using an AWF.

Table 10: Results variation based on weather file used

Weather File Used	Heating Demand (kWh/m <sup>2</sup> )	Overheating Risk (OHDH)
AWF (MODO)	115	80
2020	124	8
2050	102	80

As shown in *Table 10*, using an AWF provided the same overheating risk assessment as the 2050 weather data, while the heating demand resulting from the use of the AWF was roughly the mean of the 2020 and 2050 results.

### Summary of Optimisation Results Across Dfb Zone

The optimisation results utilising the Vilnius AWF were compared against the extents of the *Dfb* climate zone (Berlin and Winnipeg). The permutation identified as *003* in *Table 7* was simulated with the AWFs for Berlin and

Winnipeg; the results are summarised in *Table 11* for both heating demand and overheating risk reduction relative to respective Berlin and Winnipeg 2020 baseline models.

Table	11: AWF	' modelling	of Dfb	extents
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	Reduction v. 2020 Benchmark (%)		
City	Heating Demand	<b>Overheating Risk</b>	
Berlin	-6	-94	
Winnipeg	-22	-91	

### Discussion

The results of this study permitted review of building envelope retrofits, overheating risk mitigation, and the use of amalgamated weather data for optimising performance.

### Principal Multi-Objective Results: Pareto Front

The best performing retrofit strategies identified in the MODO, which demonstrated a balance between reductions in heating demand and minimisations in overheating risk, required significant building envelope upgrades. While the thermal transmittance of an envelope must be reduced, the reduced transfer of air in the form of infiltration represents a key consideration when seeking to improve building performance via retrofits. However, in order to mitigate overheating risk, summer solar heat gain reductions are paramount. All the simulation results along the Pareto Front included the use of shading overhangs and glazing with a low SHGC.

Given that study was a MODO that weighted heat demand reduction against reduction of overheating risk, the retrofits that resulted in the absolute lowest heating demand did not yield the optimal multi-objective performances. Critically, this study demonstrated that when assessing building performance across a span of thirty years, achieving optimal performance depends on the prioritisation of design objectives; this study gave equal importance to heating demand reduction and overheating risk mitigation, as shown in Equation (1), but depending on design objectives, greater prioritisation of future overheating risk reduction, for example, can affect the selection of acceptable retrofit strategies.

The most effective retrofits in this study deployed solar heat gain mitigation measures in conjunction with more general envelope improvements. Though high levels of insulation are effective to reduce heating demand, when used in isolation, the implementation of large amounts of insulation carries the inverse risk of increased summer overheating (van Hooff, et al., 2014). However, that risk was managed within the scope of this study through the use of shading overhangs and selective glazing properties. The effective use of external shades to mitigate overheating risk, demonstrated by the results of this study, was consistent with other similar studies (Dodoo and Gustavsson, 2015; Liu, Rohdin and Moshfegh, 2015; Mavrogianni, et al., 2014; van Hooff, et al., 2014).

## Impact of Amalgamated 2020 & 2050 Weather Data

The use of amalgamated present and future weather data as deployed in this study provided a template for future applications of this approach when seeking to optimise building performance over time. As shown in *Table 10*, the use of the AWF matched the overheating risk as assessed by the 2050 weather file. While both the AWF and 2050 weather files under-reported heating demand as compared to the use of a 2020 weather file in BPS, the use of an AWF reduced this underestimation by about 50%. The use of an AWF for overheating resilience has therefore been demonstrated as a viable consideration for future study applications and sensitivity analysis.

### **Impact of Study Findings on Retrofit Considerations**

This MODO study found that building retrofit approaches reducing envelope thermal transmittance must be paired with solar heat gain mitigation strategies in the form of shading overhangs on façades with direct solar exposure and glazing with a low SHGC. Alternately, shutters could be explored to permit the benefits of external shades coupled with greater seasonal operability. Consequently, retrofit design must include solar heat gain mitigation measures in optimisation studies, but must also ensure the use of future climate weather data within design workflows. Without assessing designs against future climate conditions, retrofits optimised for present conditions alone will fail to holistically quantify the potential overheating risk posed to building occupants, as the exclusive use of present climate data underestimates overheating risk (van Hooff, et al., 2016), as demonstrated by this study's results.

## Conclusion

This paper presented the analysis of building envelope retrofits' ability to reduce heating demand and simultaneously mitigate future overheating risk. The workflow utilised climate change adjusted weather files and a low-rise apartment typology with envelope performance parameters surveyed from apartments within the *Dfb* climate zone. The MODO weighted heating demand against overheating risk to determine optimal retrofit strategies and presented the appropriateness of using amalgamated present and future weather datasets for optimisation modelling.

Future studies should consider the application of this study's findings to specific contexts and unique building geometries, and further assess the usefulness of OHDH as an overheating risk assessment metric for ensuring that design solutions appropriately consider overheating event severity in their risk assessment framework.

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