Parametric clustering and shoebox modelling to evaluate environmental framework

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Abstract

The demand for housing in London's inner borough is increasing and with space limited this leads to densification of development. High density development poses several challenges in achieving an environment that promotes health and wellbeing. This study was developed to support the High Density Living Supplementary Planning Document for the London Borough of Tower Hamlets. The aim of the study was to develop an environmental and wellbeing framework tested through modelling, understand trade-offs between criteria and provide design guidance. A parametric modelling approach using Climate Based Daylight Modelling (CBDM) and Dynamic Simulation Modelling (DSM) was developed to model daylight, sunlight, overheating risk and heating demands. The results showed which criteria were achievable in a high-density context and that trade-offs were complex and difficult to balance. A set of design guidance based on vertical sky component and window to floor area ratio were developed, which can aid early stage design.

Introduction and aims

The high demand for housing in London is resulting in increasingly densified neighbourhoods with large numbers of tall buildings with inner boroughs such as Tower Hamlets, where available land is limited.

This study is part of a wider research carried out by the London Borough of Tower Hamlets (LBTH) seeking to assess well-being of residents living in high density and tall buildings. The project has led to the production of the High Density Living Supplementary Planning Document (SPD).

The aims of the SPD are to promote to provide a clear design vision and set expectations for future development in the borough, ensuring that future high-density homes and tall buildings support good quality of life.

The aim of the study is to support the LBTH policy guidance by developing a holistic approach to healthy high-density living environments. An environmental and wellbeing framework has been proposed and tested using parametric modelling to define achievable design targets, understand trade-offs between design drivers and provide design guidance.

Methodology

Purpose of modelling

The proposed environmental and wellbeing design framework covers internal daylight, internal sunlight, energy use, overheating risk and outlook. The assessment metrics and targets for each criteria have been developed based on a review of best practice. For each criteria an aspirational and a minimum targets are proposed.

CBDM and DSM are industry best practice methods to evaluate daylight, energy performance and overheating risk in buildings. These modelling approaches are proposed as part of the design framework.

As part of the overall study, the purpose of the modelling work is to:

- Test the feasibility and refine the proposed environmental and wellbeing design targets; and
- Develop design guidelines and provide an approach to deal with design trade-offs between drivers to support and integrated design approach.

Overview of modelling challenges

The proposed design targets have been tested on a range of typical typologies and overshadowing and massing context of nine case study buildings.

Conducting CBDM and DSM analysis across all dwellings within the nine case study buildings would be computationally intensive and was not practical within the constraints of this study.

Therefore, a novel "cluster and sample" approach has developed to test a large number of typologies for a large number of overshadowing and massing conditions.

"Cluster and sample" approach

A clustering and sample approach has been developed to represent the differences in context conditions across the nine case studies considered. This has been inspired by an approach developed by researchers at the MIT (Dogan and Reinhart 2017). The following factors are considered in the clustering of building facades:

- Orientation

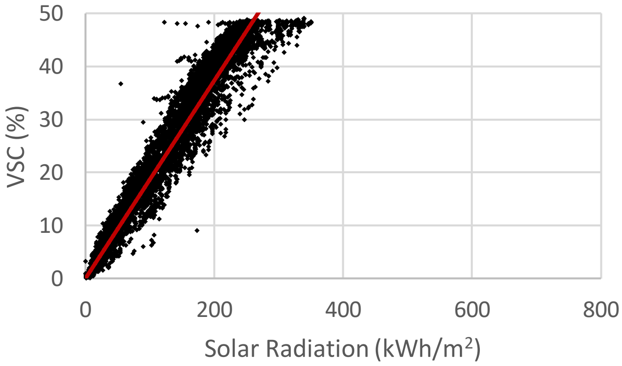

Figure 1: VSC vs Radiation North Facades

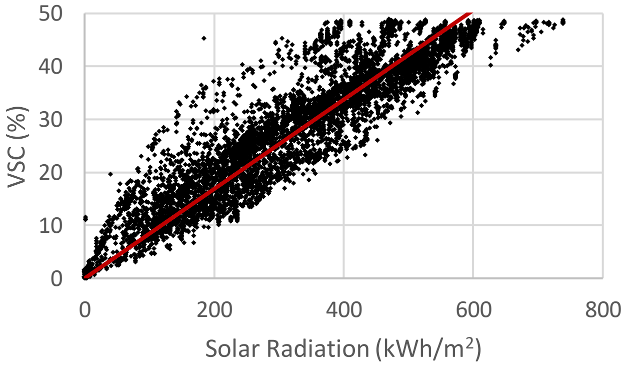

Figure 2: VSC vs Radiation East Facades

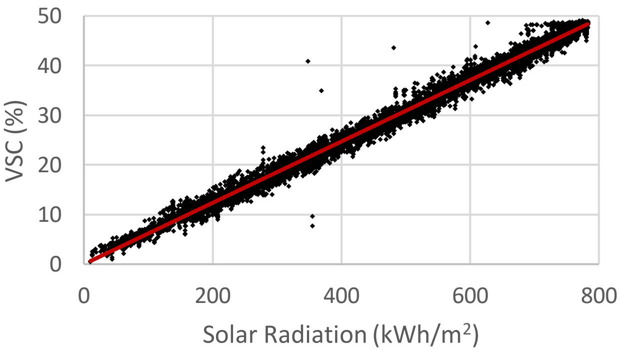

Figure 3: VSC vs Radiation South Facades

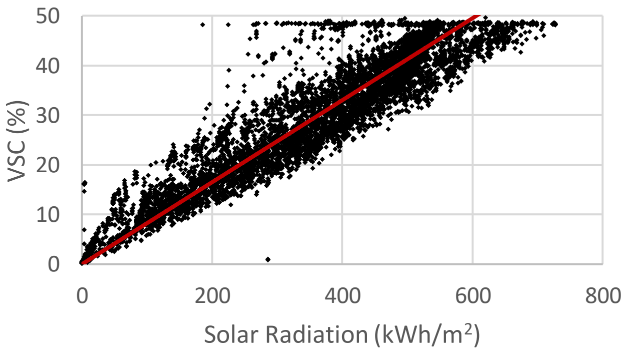

Figure 4: VSC vs Radiation West Facades

- Height
- Massing and overshadowing by surrounding buildings

The facades of the nine case study buildings have been analysed for the above factors on a 3mx3m grid of points.

Orientation

The results of the façade orientation analysis indicate that 75% of all facades are orientated within +/-10° of the cardinal directions, which is due to the regular street grid in this part of London. Based on the distribution of façade orientations, it was determined to cluster façade points into the four cardinal directions.

Height

A similar analysis has been carried out understand the response to variation in height across the case study buildings. Dwelling height influences natural ventilation and infiltration as wind speeds tend to increase with height. In urban environments, the mean wind speed increases notably above the mean building height (Micallef and Van Bussel 2018).

According to the LBTH Tall Buildings Study (London Borough of Tower Hamlets 2017) the majority of building heights within the borough range between 4 and 9 storey (15-30m) with localised tall buildings greater than 10 storeys (30m). The case study buildings are consistent with these findings, with about 60% of the façade points below 45m. Based on this information the façade points were split into two groups by height.

Massing and overshadowing

The Vertical Sky Component (VSC) is a measure of obstruction to the sky, which is commonly used to assess daylight access on building facades. VSC is a measure of the amount of sky visible from a point on the facade as a proportion to an unobstructed hemisphere of sky. The VSC is generally used as a proxy for daylight potential within buildings.

Massing and orientation also have an influence on annual incident solar radiation. Solar radiation is an important factor in overheating and energy use analysis.

An analysis of VSC and solar radiation was performed on the case study buildings across the grid of points. The results of this analysis were grouped by facade cardinal direction and plots of VSC vs solar radiation are shown in Figure 1- Figure 4

The figures illustrate the strong linear correlation between VSC and incident solar radiation, when grouped by cardinal orientation. The coefficient of determination (R^2) for the North, East, South and West orientations were 0.93, 0.83, 0.99, 0.85 respectively.

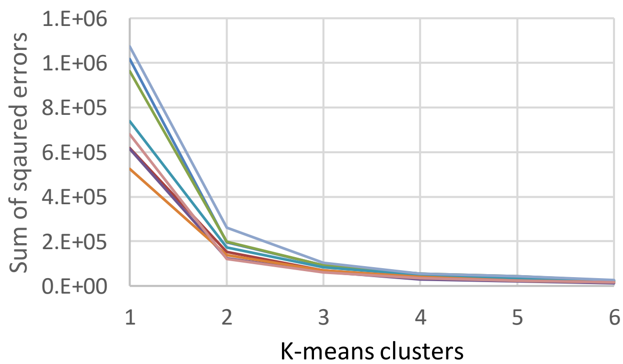

Figure 5: K-means elbow test

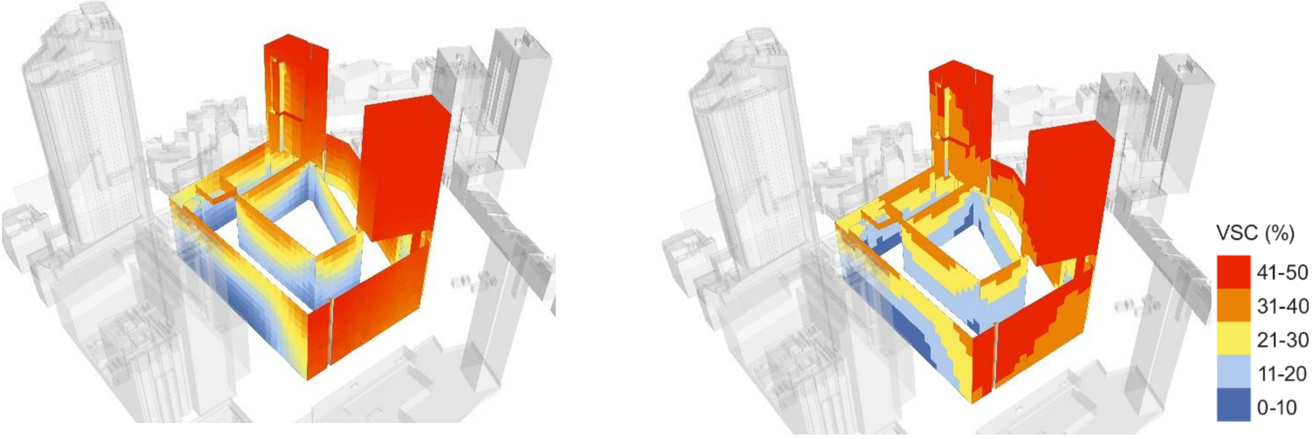

Figure 6: VSC facade clustering. Left, discrete VSC. Right, clustered VSC

This analysis suggests that considering VSC and orientation would also cover the variability in incident solar radiation. It was therefore decided to use VSC only to represent the influence of building massing and surrounding obstructions.

A k-means clustering approach was used to identify the minimum number of clusters. K-means clustering is a machine learning algorithm that minimises the within-cluster variance for a set of data points (Forgy 1965). K-means clustering was performed on VSC values for each cardinal direction and for locations below and above 30m in height.

The "elbow test" was used to determine the appropriate number of clusters (Thorndike 1953). A higher number of clusters results in lower total variance but would very significantly increase simulation times. The "elbow" tests (Figure 5) indicated that four clusters were optimal.

A visualisation of the facade clustering is illustrated in Figure 6.

Table 1: Generic dwelling typology characteristics

Typology	Aspect	Depth (m)	Width (m)	Balcony
S6-n	single	6	8.5	none
S7.5-n	single	7.5	5.75	none
S10-n	single	10	6	none
C8-n	corner	8	10	none
C7-n	corner	7	13	none
T11-n	through	11	9	none
T16-n	through	16	6	none
S6-e	single	6	8.5	external
S7.5-e	single	7.5	5.75	external
S10-e	single	10	6	external
C8-e	corner	10	8	external
C7-e	corner	13	7	external
S6-i	single	6	8.5	inset
S7.5-i	single	7.5	5.75	inset
S10-i	single	10	6	inset
C8-i	corner	10	8	inset
C7-i	corner	13	7	inset

A sensitivity and accuracy analysis has been performed in order to determine how much the performance metrics (daylight, overheating, energy use) would vary based on the different chosen context parameters (VSC, orientation, height). The analysis showed that there is a linear response between the input parameters and outputs metrics.

Typologies

LBTH provided a breakdown of the key dwelling typologies across the nine case study developments. The difference in topologies cover the following characteristics:

- Layout and plan dimensions
- Single/dual aspect; and,
- Presence and type of balcony

This was rationalised into 17 generic typologies, which are summarised in Table 1.

The typologies are grouped into three main categories:

1. Single aspect: units with one façade
2. Corner aspect: units with two facades oriented 90 degrees from each other
3. Through aspect: units with two facades oriented opposite each other

A standard balcony size of 1.5m deep by 4.5m wide was applied for the typologies with balconies present.

Building design parameters

Several key building design parameters have been tested:

- Glazing specification (G-value and light transmittance (LT))
- Glazing to facade ratio
- Floor to ceiling height
- Window opening depth.

The modelling ranges for the above parameters have been determined from the characteristics of the nine case study developments and are summarised in Table 2. The internal loads, occupant schedules and natural ventilation details have been taken CIBSE TM59 Guidelines (The Chartered Institution of Building Services Engineers 2017).

Building fabric parameters have been taken from the SAP 2012 Notional Building specification 0.18W/m^{2}K for external walls, 0.00 W/m^{2}K for party walls, 0.13 W/m^{2}K for roofs and floors, medium thermal mass and air permeability of 5 m^3/m^2/hr@50Pa (Standard Assessment Procedure 2012 2014)

The light reflectance of internal finishes were assumed to be 0.2 for floors, 0.5 for walls, and 0.7 for ceilings (British Standards Institution 2018).

The combination of all modelling inputs are summarised in Table 2. Combining the clusters, typologies, and environmental design parameters a total of 29,376 simulations have been carried out as part of this study.

To keep the modelling time within practical limits, the different typologies were modelled as single zone thermal and daylight models.

Daylight requirements are set for spaces with an expectation of daylight (bedrooms, kitchens, living rooms). Since the daylight simulations were on single simplified zones the results of the CBDM analysis had to be post-processed to remove the spaces without daylight expectation such as corridors, cupboards, and bathrooms.

Typical unit layouts were received from LBTH and the percentage of space with daylight expectation was calculated for each typology. This is summarised in Table 3.

The parametric model was built using Rhino and Grasshopper interfaces with Honeybee and Ladybug (Roudsari and Pak 2013) analysis plugins which interface with Radiance and EnergyPlus simulation engines.

Results and discussion

Testing framework

The environmental testing framework is summarised in Table 4 below. To test how achievable the proposed environmental and well-being targets are a notional baseline set of parameters was defined:

- Floor to ceiling height of 2.3m
- Glazing ratio of 35%
- Glazing visible light transmittance (VLT) of 80% and g-value of 0.65
- Natural ventilation opening depth of 150mm.

Table 2: Simulation inputs summary

Inputs	Range	Combinations
Glazing specification (G-value/LT)	0.36/0.65, 0.5/0.72, 0.65/0.8	3
Glazing to Facade ratio (%)	35, 50, 65	3
Floor to ceiling height (m)	2.3, 2.5, 2.9	3
Facade clustering	Based on VSC, orientation and height	32
Flat Typology	1-17	17
Building fabric	As per notional building	Fixed
Ventilation, top hung with opening depth	150mm, 250mm	2
Occupancy and internal heat gains	As per TM59 guidelines	Fixed
Reflectance of internal finishes	As per BS EN17037 guidelines	Fixed

Table 3: Daylight expectation areas

Typology	Aspect	Depth (m)	Width (m)	Daylight Expectation Area (%)
S6	single	6	8.5	80
S7.5	single	7.5	5.75	67
S10	single	10	6	61
C8	corner	8	10	71
C7	corner	7	13	56
T11	through	11	9	72
T16	through	16	6	63

Table 4: Environmental testing framework

Environmental Parameter	Metric	Minimum Target	Aspirational Target
Daylight	Spatial Daylight Autonomy	$sDA_{100/50}$=50% for bedrooms, $sDA_{200/50}$=50% for all other rooms with daylight expectation	$sDA_{300/50}$=50% for bedrooms, $sDA_{500/50}$=50% for all other rooms with daylight expectation
Sunlight	Sunlight hours on March 21st	1.5 hours direct sunlight in at least one habitable space	3-4.5 hours direct sunlight in at least one habitable space
Overheating	CIBSE TM59 Methodology	Criteria A: The number of hours during which $\Delta T \geq 1$°C from May-September shall not be more than 3% of occupied hours. Where $\Delta T = T_{op} - T_{max}$. T_{op}=operative temperature and T_{max} is derived from the running mean outdoor temperature. Criteria B: Bedroom operative temperature should not exceed 26°C for more than 1% of annual sleeping hours (10pm-7am).	
Energy Use	Heating demand intensity	Energy and carbon requirements of London Plan	

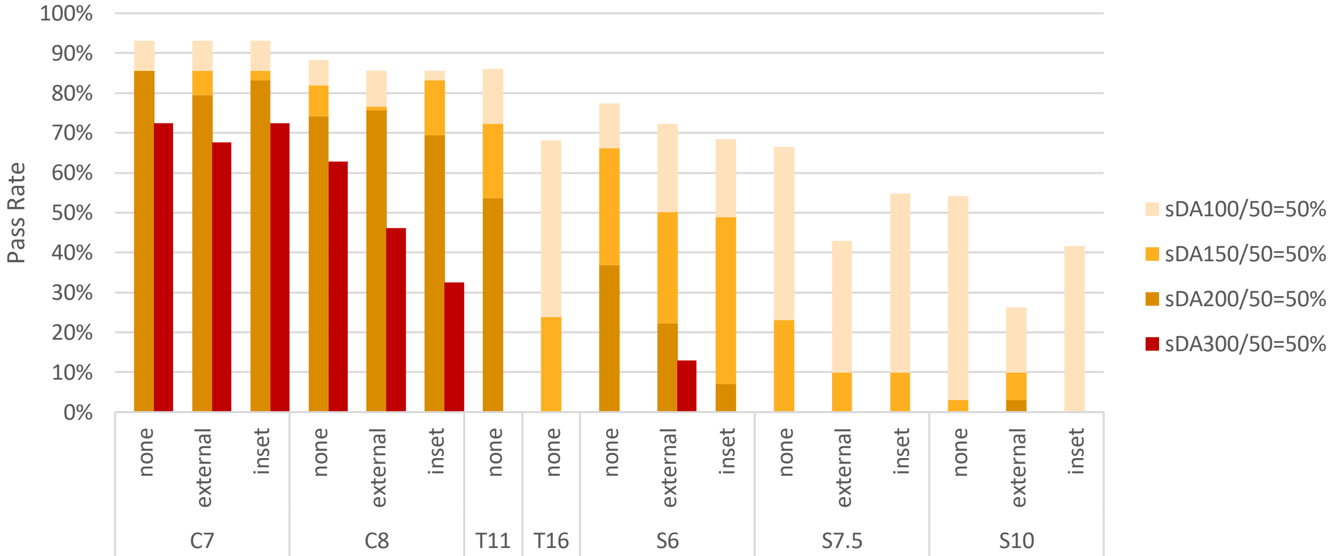

Figure 7: Pass rate against various daylight criteria

Daylight

The proposed daylight metrics include two Spatial Daylight Autonomy (sDA) (Illuminating Engineering Society 2012) requirements:

- The first requirement is to achieve sDA300/50 over 50% of the area with daylight expectations
- The second requirement is to achieve sDA100/50 over 95% of the area with daylight expectations.

The above metrics are the minimum recommendations from BS EN17037 (British Standards Institution 2018). In addition to these recommendations the UK National Annex to BS EN17037 (British Standards Institution 2018) provides further minimum recommendations for daylight provision which are more representative of daylight expectation in the UK context:

- sDA100/50 over 50% of area for bedrooms
- sDA150/50 over 50% of area for living rooms
- sDA200/50 over 50% of area for kitchens

The results show a low pass rate for most typologies for the BS EN 17037 requirements, shown in red in Figure 7.

The less stringent requirements of the UK National Annex have a higher pass rate across the typologies, shown in grades of orange. Therefore, the UK Annex requirements have been adopted as a minimum threshold with the BS EN 17037 requirements as aspirational daylight targets.

There are some clear differences between typologies with corner units having the best daylight performance while single aspect units with a deep floor plan having the poorest performance. Additionally, external and inset balconies tend to have a small negative effect on internal daylight.

Overheating

The same set of parameters were tested against their overheating risk. From Figure 8, it's evident that that the typologies that had high levels of daylight now have a higher risk of overheating and vice versa for the poorer daylit typologies. This is due to the increased glazing and subsequent larger solar gains. To reduce the risk of overheating, a scenario with increased ventilation opening

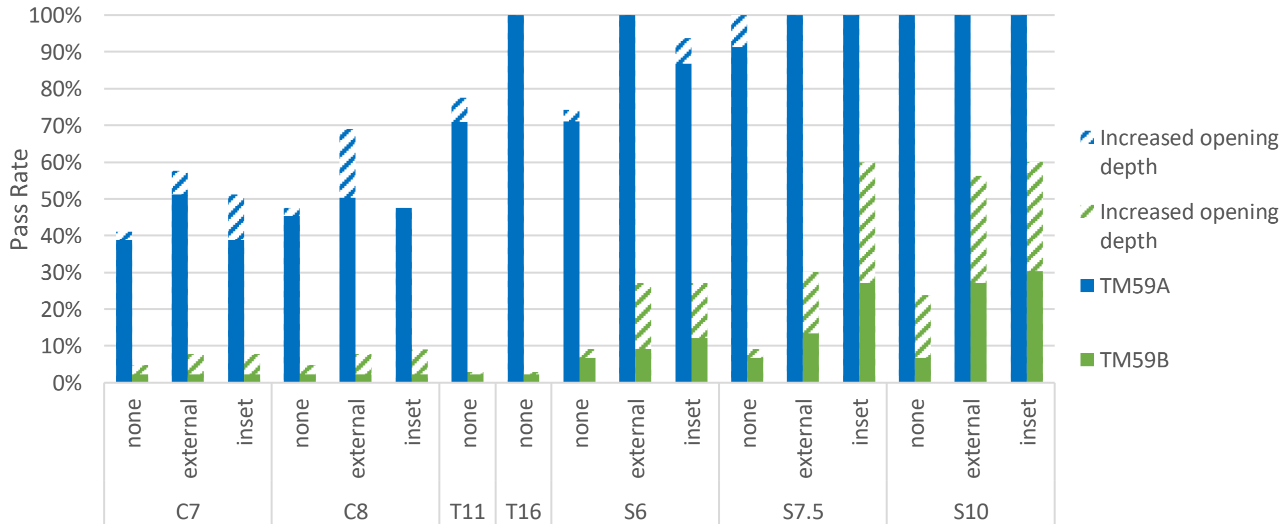

Figure 8: Overheating criteria pass rate, by typology

depth, 250mm, was tested. The results show that this reduces the overall risk of overheating.

Sunlight

The performance of the different typologies against the sunlight hours requirements included a minimum and aspirational target of 1.5 hours and 3 hours, respectively, based on BS EN 17037 recommendations.

All of the typologies perform well against the minimum and aspirational targets.

The results of the sunlight hours analysis are much better than daylight due to the fact that the sunlight criteria only specifies a duration of sunlight rather than a quantum. There has been ongoing research by (Mardaljevic and Roy 2016) developing the sunlight beam index (SBI) which provides a robust methodology to evaluate the quantum of sunlight entering a space.

Developing suitable targets using the SBI method would help provide more meaningful results and is an area of further research.

Trade-offs

The responses to varying environmental design parameters (glazing ratio, floor to ceiling height and glazing specification) have been plotted against the different performance criteria.

The results are shown in a series of parallel coordinate plots for the S6, C7 and T11 typologies in Figure 9 – Figure 11 . The plots show the different interventions to improve daylight and quantify the trade-offs with competing objectives such as overheating risk and energy use. The different interventions are labelled on the left, only 1 parameter was modified per scenario.

Increasing glazing ratios provides the largest improvement to daylight for all of the typologies. As expected, increasing glazing ratios results in a significant increase in overheating risk, but a smaller impact on heat demand intensity (HDI).

Floor to ceiling heights provides a similar increase in daylight, when compared to glazing ratio, for the single aspect typology but less of an improvement for the corner and through typology. The negative responses are similar to those associated with increasing glazing ratio.

Modifying glazing specification to reduce solar gains has a negative impact on daylight, most sizeable for the single aspect units. Low g-value glazing is the only parameter

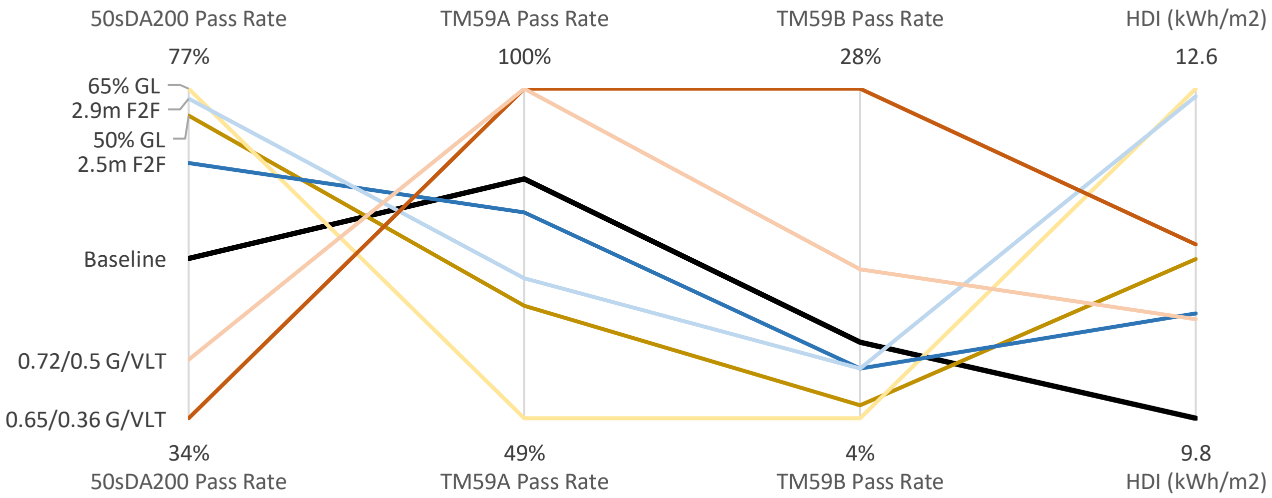

Figure 9: S6 Typology trade-offs

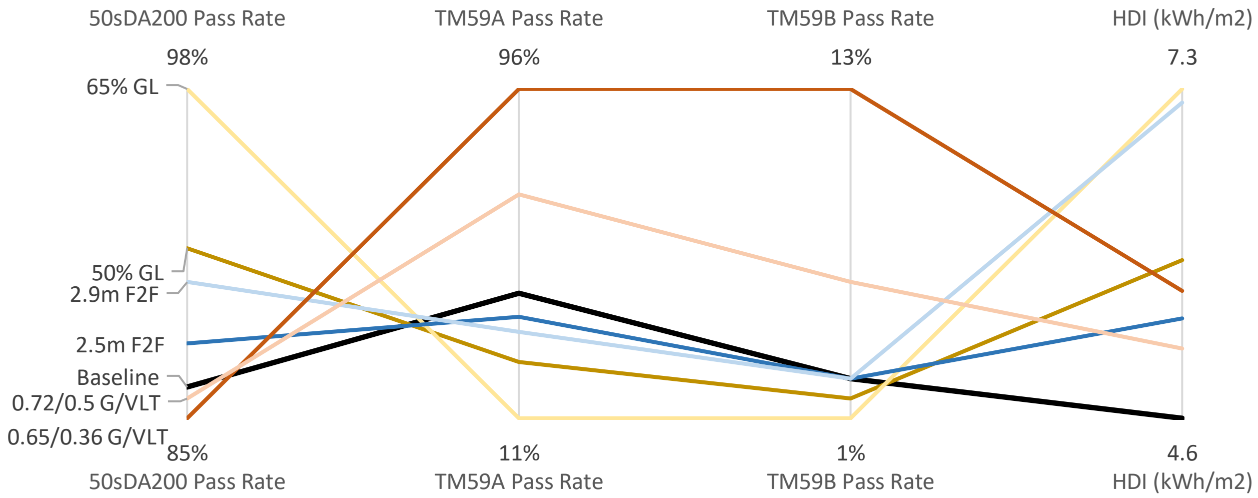

Figure 10: C7 Typology trade-offs

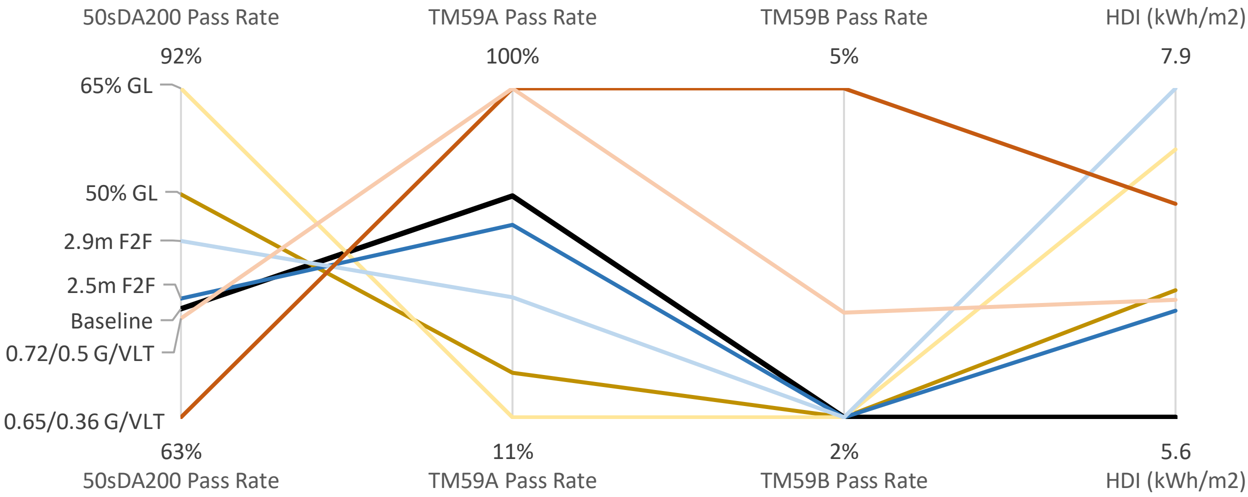

Figure 11: T11 typology trade-offs

that has a positive impact on reducing the risk of overheating but has a slight negative impact on HDI.

Design guidelines

The results of the parametric study have been analysed to draw generic design considerations.

The window to floor area ratio (WFR) has been considered as the key generic design parameter. Glazing ratio has a significant impact on daylight performance, overheating risk and envelope heat losses. Additionally, the results vary based on the typology with factors such as plan depth and aspect playing a key part.

The WFR accounts for all of the above parameters and is a generic design metric that can be calculated solely based on the geometry of proposed developments.

The modelling results have been analysed to plot variability of daylight and overheating performance against WFR and VSC, as shown in Figure 12.

Corner unit typology

For the average corner unit with a low VSC of 8-18% it would require a WFR in the range of 0.18-0.28 to achieve the minimum daylight target. Similarly, for corner units with higher VSC (18%-48%) a lower WFR of (0.8-0.18) would provide a similar level of internal daylight.

The trade-off with overheating risk can be quantified by reading down the charts. Corner units are at a higher risk of overheating, therefore a balance must be achieved between daylight and overheating. In general, keeping WFR below 0.28 for corner units will achieve minimum daylight targets while minimising the risk of overheating.

Singe aspect unit typology

Generally single aspect units struggle to achieve similar daylight levels as corner units, but they also have a lower risk of overheating.

Daylight levels in single aspect units with low VSC only increase slightly with increasing WFR, as the limit of

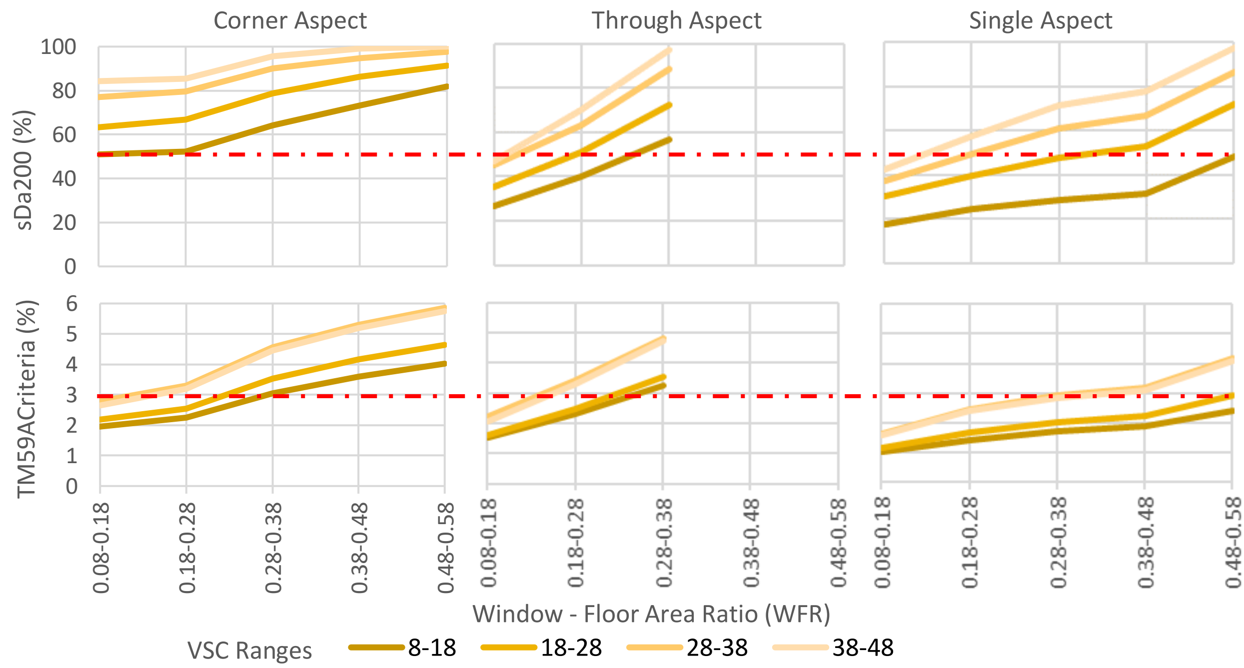

Figure 12: VSC and WFR impact on daylighting and overheating. Red line shows criteria threshold.

natural daylight penetration within a single aspect space is reached.

The minimum daylight criteria is achievable in locations where VSC is greater than 28% and WFR is greater than 0.28. Where the VSC is between 8 and 28%, the WFR will need to be increased to 0.28-0.58.

Single aspect units on average have a lower risk of overheating even with higher exposure (VSC) and higher WFR.

In general, a WFR of about 0.18-0.28 will likely achieve the minimum daylight targets while having a low risk of overheating.

Through unit typology

The through units are the middle ground between the single aspect and corner typologies. They have a slightly better response to daylight than single aspect units and lower overheating risk than corner units.

On average the through units can achieve the minimum daylight criteria with WFR between 0.13-0.23 while having a low risk of overheating.

The WFR ratios determined from this study are similar to a study performed by BuroHappold (BuroHappold Engineering 2018)

Conclusion

A modelling study has been carried out to test and refine the environmental and wellbeing design framework and associated targets.

This has been achieved by testing how different typologies perform in different massing and overshadowing contexts. The modelling has established achievable targets for the high-density context of LBTH.

The results of the analysis were not compared in detail with those of the occupant survey, but this could form the basis of further studies on detailed correlation between the surveys and this modelling work.

Sensitivity has been tested to a number of environmental design parameters, to establish the response against different performance criteria, and support considerations on design trade-offs as part of an integrated design approach.

Lastly, the modelling results have also been analysed to provide design guidance on environmental design parameters to improve daylight and control overheating for different typologies and massing and overshadowing conditions. From the results it was determined that WFR and VSC are two key factors which can be adjusted to balance daylight, sunlight, overheating risk and space heating demands.

Acknowledgements

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