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CHALLENGING CONVENTIONAL APPROACHES FOR CLIMATE-BASED DAYLIGHT SIMULATIONS OF MULTI-UNIT RESIDENTIAL BUILDINGS

Terri Peters[1], Noor Alkhalili[2], Ted Kesik[2] and William O'Brien[3]
[1]Ryerson University, Toronto, Canada
[2]University of Toronto, Toronto, Canada
[3]Carleton University, Ottawa, Canada

ABSTRACT

Multi-unit residential buildings (MURB) represent more than one half of the new housing built in the USA and Canada. To date, the majority of daylighting research has focused on offices, but MURB have a number of environmental performance challenges and quality of life considerations specific to their housing typology. Daylight is typically not sufficient in these dwellings, as many units are small and single-aspect, with a deep floorplate and a balcony that shades the living spaces within and below. There are no established metrics or methods specifically aimed to aid in daylighting design for MURB. There is a need for increased understanding of daylighting in these buildings, and better methods and metrics to simulate daylight performance. New early stage climate-based daylighting modeling (CBDM) tools such as DIVA allow designers to predict daylight performance in buildings. These tools were developed with offices in mind, and have underlying assumptions such as work hours and occupancy during daylight, and a focus on productivity and minimum sufficient lighting for a task, that make them difficult to adopt for MURB. This paper emerged from a study of the influence of balcony typologies on daylighting and presents a selective literature review of existing assumptions around daylight simulations for MURB. It identifies which assumptions in current tools and methods are problematic, with the aim of leading to more relevant CBDM assumptions and tools for this building typology. Drawing on recent literature, published studies, and rules of thumb, this paper identifies MURB-specific challenges with current assumptions about daylight simulation and tests some alternatives to typical simulation parameters. The aim is to begin to create MURB-specific thresholds for parameters including target daylight illuminance, metrics, and simulation grid height.

INTRODUCTION

MURB are the fastest growing residential building type in Canada (CMHC 2019) and due to global urban intensification, there is an urgent need to understand both the energy implications and human health and quality of life impacts of daylight in MURB. Access to daylight is necessary for people's health and wellbeing, impacts our moods and behaviours and is necessary for circadian rhythm. New digital tools have enabled designers to simulate and predict the performance of design options when they are at early stages and this feedback loop is critical for both meeting design intent and designing sustainable buildings (Peters and Peters 2018). They can now explore options in their own design environments (for example daylight plug-in DIVA that works with Rhino, a software tool designers likely already know). This can provide essential and timely feedback on aspects such as solar orientation, window to wall ratio, optimal floorplan layouts, and much more. Of course, it does not replace analysis and validation that happens by specialists at later design stages of a project (Peters and Peters 2018).

There is a need for more MURB-specific studies into performance of this residential typology as MURB design is not driven by daylight. In fact this building type is notable for its low levels of daylight, with many narrow and deep 1:2 or 1:3 aspect units, and façade design and window to wall ratios that are the same for every orientation. In MURB, it is common to see all orientations of the building have the same window-to-wall ratio and façade design, despite the dynamic nature of daylight. Balconies are a defining feature of the MURB typology and part of people's expectations in new MURB (Lorinc 2017). In Canadian cities such as Vancouver, there are a range of balcony types and sizes being constructed, but no design or building performance guidelines for comparing design options for suites with balconies. This paper presents preliminary findings of a simulation-based study focused on the impacts of balcony design on daylight and questions the assumptions designers make in simulating daylight in MURB. The typical simulation assumptions used in offices are not always appropriate for MURB. To gain a relevant understanding daylight quality and quantity in this paper the results of a simulation based study are presented. The main findings relate to 1) desirable target illuminance levels (what is a 'daylit' space at home?) and related to this a comparison of daylight metrics; and 2) the assumptions made about inhabitants and how we use rooms (are dining rooms for eating or working?) and comparison of appropriate heights for the analysis grid for daylight measurement.

DAYLIGHT SIMULATION AND MURB

Current State of MURB Research

There are relatively few published MURB-specific studies of daylight, and no accepted design tools, standards or metrics relevant for daylight in MURB. This paper builds on recent work by Dogan and Park (2017, 2018) that is starting to look at residential daylighting, but much more work needs to be done in this area. Most daylighting research is office-specific, although some focused on other non-residential environments like schools and hospitals. The research focused on daylight and housing tends to be focused on daylight autonomy concerned with energy savings and reducing the amount of time a space must be lit by electric lighting.

Andargie, Touchie, and O'Brien (2019) found that from an occupant perspective, MURB have distinctive design and control systems that distinguish them from other dwelling types. Compared to single family housing, their research found numerous MURB-specific parameters. MURB have a small living area and low number of occupants. In this building type there is a low amount of control over the unit's design or building systems, varying experiences depending on unit location and height in the building, and inhabitants are not able to control environmental systems in common spaces (Andargie, Touchie, and O'Brien 2019).

The current paper questions certain simulation assumptions because MURB present a very different program type when compared to offices, and naturally have different occupant behaviours and expectations and have diffferent façade elements such as balconies. To carry out a daylight simulation, assumptions must be made about desirable target illuminance and this is normally set at 300 lux as a proxy for daylight autonomy (or the annual percentage of time that a space achieves that lux level half of its occupied hours). The question of what are occupant perceptions of adequate lighting in MURB is unfortunately rarely explored in the literature. Other required assumptions are the number of and behavior of inhabitants: for example are dining rooms for dining or working? This is relevant because current standards for lighting levels are reported by assumed task in each space (IESNA 2012). This makes sense as there would naturally be varying daylight requirements from room to room. Another required input is the appropriate height for the analysis grid for daylight measurement. In the home this could be coffee table height or floor height, depending on who uses the room. Typically in daylight simulations "task height" is the default height and that is due to the assumption that people work at desks, and these are approximately 0.8m high. Since MURB are residential, and even though many people work from home, the apartment is not primarily a work space so the assumption for "task height" of 0.8m is not relevant. (Peters and Kesik 2018).

Daylight Simulation in MURB: Assumptions and Interpreting Results

Typically, daylight simulation in buildings is focused on productivity, not amenity or health, and this is reflected in the metrics and tools. The focus on lighting a "task" not a person or a space, requires the input of a presumed task height, and assumes that inhabitants have an assigned space, perform prescribed writing/reading communication tasks, are not free to move around the space, that people sit along the perimeter, and that glare from windows would be distracting and unwelcome. Compared to office settings, the role of glare and acceptable upper illuminance thresholds in housing are not only less of a concern (people can use blinds or move away), and also difficult to quantify (different rooms and different people have different glare tolerances). In a study of a 20-story office building assessing glare and view quality, there is less reported glare from inhabitants facing an interesting view than from a neutral screen or poor view with the same daylight glare index (Tuaychaoroen and Tregenza 2007). In residential settings, it could be argued that the role of daylight is even more valuable, and in connection to view and privacy are even more important than at work. In the 1960s, when much of the current housing stock of MURB were designed, views to the outside went from being an 'amenity' in lighting guides, to an element of the building acknowledged as required and beneficial for health (Tregenza and Mardaljevic 2018). The view-glare relationship seems related to the green-comfort 'forgiveness' factor in green-intended office buildings where people are more forgiving of discomfort in a green building observed by (Deuble and de Dear 2012).

Future Directions of MURB Lighting Research

The current directions for research in predicting and evaluating residential daylighting is using climate based daylight modeling (CBDM). This paper is focused on early stage design tools that designers use to gain feedback about their design decisions. With the availability of easy to use, validated digital tools, designers can carry out simulations at early stage design, but they must make certain assumptions. To know if these are the right assumptions, there needs to be more MURB-specific research that connects people's reported experiences with measured light levels at certain moments, in various rooms, and over time.

An important future direction for MURB research is developing simulation assumptions based on occupant satisfaction with daylight levels taking into account unit geometry and orientation. A 2019 study of lighting metrics in MURB by Jakubiec et al. to understand reported satisfaction and measured lighting levels, found a gap between self-reported inhabitant satisfaction levels and measured and simulated daylight levels based on room uses (Jakubiec et al., 2019). The results are based on a study of 17 MURB units with 35 participants in a MURB in Singapore. Despite the small sample size, the study is notable in MURB research because it compared satisfaction room by room, rather than by unit. The inhabitants scored their self-reported satisfaction with lighting levels and this was compared to site measurements and a daylight simulation model and concluded that people report being more satisfied with living rooms and bedrooms even when these rooms do not meet target annual daylight levels. The study by Jakubiec et al. (2019) is based on people's experience, and their expectations of daylight in certain rooms. It could be expected that this study would have different results in different seasons, and in different climates.

A future study could evaluate people's expectations of daylight in specific rooms in the Canadian context, as normally the living rooms and dining rooms are arranged on the building's façade, in a 1:2 or 1:3 aspect ratio, leaving the kitchen and entry as non-daylit zones. People's expectations of daylight vary by room, and likely between climates and countries but the current practice of solely daylighting living and often bedrooms, at the expense of dining, kitchen and entry spaces must be examined.

Another important future direction for MURB research relates to gaining an understanding of who lives in MURB and when and how they use their spaces . There is a disconnect between the advertising and cultural assumptions around MURB living (it is for young people 'starting out' and not a permanent "home") and yet statistics show rapidly increasing numbers of families, older people aging in place, and people working from home in MURB. Different people require different light levels (Boyce 2014) and this is reflected in emerging metrics and guidelines in lighting design. Studies show people need almost double the amount of light at age 50 than they do at age 20, due in part to presbyopia, the decrease in ability of the eye to focus on nearby objects (Sorensen and Brunnstrom 1994). People need different light levels in different seasons, requiring more daylight in winter, and some people experience seasonal affective disorder (Torrington and Tregenza 2007). Torrington and Tregenza stress the need for synomorphy in the home, the consistency between the apparent physical environment and social behaviour, and between the different senses of the physical environment specifically for people suffering from dementia. They note that "When synomorphy occurs, recognition of a place is usually below conscious awareness: the building is taken for granted, the focus is on the purposes of the user."

The recently established WELL building standard evaluates people's wellbeing in buildings and measures daylight for occupants, in a very different way than industry-leading LEED green building standard which focuses more on energy reduction. A future study could survey people living in MURB and gain an understanding of the number of people per household, and the age and activity level of people living in units. The data could begin to inform simulation inputs such as likely creating more variety in illuminance thresholds (older people need more lux so the 300 lux may need to change to 400 or 500 lux) and age also potentially relates to the illuminance plane height (for example children often sit on the floor).

Current Metrics and Assumptions about Program and Illuminance Levels

Climate-based task-oriented metrics evaluate a space by generating a grid of task-height sensors across a floor area and measuring how many of the sensors achieve a target illuminance over a specified time period, or annual target. The shift from static geometry based Daylight Factor (Moon and Spencer 1942) to dynamic climate based metrics such as Useful Daylight Illuminance (UDI), Daylight Autonomy (DA), Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) have emerged and adopted into standards specifying target illumiance levels by room use (IESNA 2012). The target illuminance levels are considered appropriate for all building types, but seem specifically relevant for offices. Researchers including Dogan and Park (2018) identify aspects that make these metrics less relevant to residential environments and call for new metrics.

Understanding what is the 'right' light for residential program functions, that have different sizes and orientations is a major challenge. This kind of programmatic granularity is not necessary in office spaces. MURB researchers must question: What is the right light for a living room for a family with small children? Or a small kitchen for someone who loves to cook? This may become more challenged in office designs as well, because requirements for lighting levels still focuses largely on tasks and productivity whereas much of the discussion is also shifting to wellbeing and employee satisfaction and retention. Also notable is that most standards are for a work plane, whereas most activity in the home is not on the horizontal plane at all, it relates to the human eye. In the literature, there is scope to rethink all requirements for daylighting in all spaces. The right light has yet to be defined in terms of specific illuminance levels, but there is enough evidence in the literature to indicate that illuminances in the range of 100 to 3000 lux are likely to result in significant reduction of electric lighting usage (Nabel and Mardaljevic, 2005). In recent years, a number of studies have questioned the horizontal task plane illuminance metrics and proposed occupant-centric, 'view-based' (as opposed to task-based) eye level illuminance methods that incorporate both visual and non-visual effects of daylight (Konis 2017, Rockcastle, Amundadottir, Andersen 2019, Amundadottir et al 2017).

METHODOLOGY

After presenting a background of daylight in MURB and a critique of certain simulation parameters requiring further investigation in relation to simulation assumptions for MURB, this study seeks to test some alternative simulation inputs. The findings of two main studies are presented: a comparison of target illuminance thresholds and associated metrics, and a study of simulation grid heights. The results presented here are part of a larger study to understand and quantify the impacts of balcony design on daylight in MURB. It is imagined that this study will help inform early stage design of new condos. In this paper, a single geographic location is presented, Vancouver BC, because after comparing the results of a number of Canadian climates and regions, it became clear that varying climate files does not seem to significantly impact daylight and balconies in simulations.

Simulation Method

Climate based daylight simulation was used to evaluate the impacts of the various balcony designs on daylighting in MURB units, as it uses realistic sun and sky conditions and building orientation at a given location. The daylighting software DIVA-for Rhino was used to carry out the analysis (Solemma 2018). Daylight Autonomy (DA) is a commonly used daylight metric, and this paper evalutes the unit interiors using DA and also Useful Daylight Illuminance (UDI). DA is an annual metric that describes the percentage of floor area that receives a specified target illuminance for at least half of the space's annual occupied hours. DA was evaluated, rather than sDA, another metric often used to understand annual daylight in spaces as noted above, as this study does not include the use of a blind control model that predicts the status of moving shading devices at all time steps of the year (Reinhart, Mardaljevic Rogers 2006).

Nabel and Mardaljevic (2005) defined UDI as the annual occurrence of illuminances that are within a range considered "useful" by occupants, initially considering 100-2000 lux. The most recent definition (2012) characterizes different lighting levels and defines that less than 100 lux is considered inadequate for users, 100-300 lux is considered supplemental, 300-3000 lux is considered autonomous and therefore the most desirable, and higher than 3000 lux is considered overlit (Mardaljevic et al 2012). This user-centered approach to daylight which can be appreciated by inhabitants is compared to DA in this study.

Overheating and glare are considered to be less of a concern in MURB than in offices, due to the typical 1:2 or 1:3 aspect ratio in condo floorplates, and also because it is not assumed that people are sitting along the facades in fixed positions. For these reasons, the study focuses on how much natural light can enter the unit with the different balcony options, due to the energy saving, quality of life, and health and wellbeing benefits of daylight. An upper illuminance threshold to study visual discomfort, glare, and overheating are not specified.

Table 1: Surface reflectance and glass transmittance used in DIVA simulations

MATERIALS	**REFLECTANCE/ TRANSMITTANCE***
Ceiling	70%
Floor	20%
Glazing	65%*
Glazed balcony panels	88%*
Solid balcony panels	70%
Outside ground	20%

Modeling Parameters

MURB units were modeled that represent typical construction. These are single aspect, side lit, mid-level, one bedroom units with a floor to ceiling height of 8' (2.4m). While our earlier research found that window to wall ratios above 70% did not positively impact daylight in this study we did not vary the WWR, we used 100% WWR to simplify our massing model and study the maximum amount of light that could possibly enter floorplans. The simulation software required certain assumptions to be made about occupancy, materials, target illuminances, orientation and climate. This study assumed the units are occupied 8am-6pm with Daylight Savings Time (DST) invoked, analyzed in 60-minute increments. For the analysis grid, the node height and spacing assumptions are 0.5 m high, the node spacing is 0.5 m apart. Furniture and partitions are highly variable and so the maximum potential illumination was examined. The façade glazing simulated represents commonly used MURB façade materials (Table 1). The weather files for Vancouver BC were used in the simulation program. In the larger study, numerious balcony geometries and positions on the façade were evaluted for DA, and the best performing of the options studied was Option 2 (see below) a balcony modeled at 2.0m wide and 2.0 meters long over half of the façade (typically the living room). In this case, the balcony is more of a useable outdoor room where the inhabitant could put a small table and chairs, and step outside and possibly see the sky. Two options were tested in terms of facade position for the balcony and unsurprisingly it was found that by staggering the balconies, and not stacking the units directly one atop the other, there is less shading of the interior. The larger study showed that a good-sized balcony can be designed for a small unit, as long as there is a glazed handrail and the balconies are staggered along the façade.

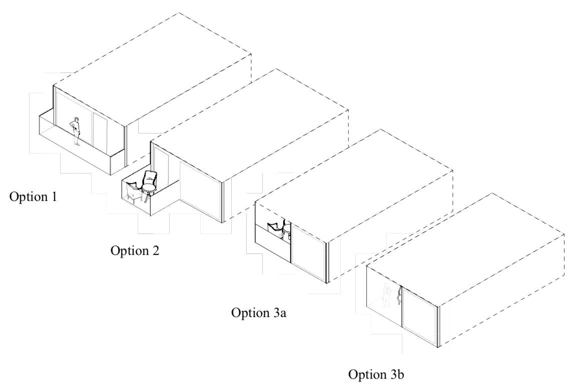


Figure 1: Options for balcony types were analyzed to study the impact on daylight in the unit. The best performing Option 2 with a staggered position on the façade was used as the base case in this current paper.

In this paper due to length constraints, the results of the best performing option are used as the base case (Peters and Kesik 2020). In the balcony studies, it was determined that the daylight levels would be evaluated both as an actual percentage, and also in relation to the best performing non-balcony option for that balcony type. This approach allows the comparison of the relative impact of different qualities of balconies on the daylight in condo units in this study against a comparable no- balcony option.

Target Illuminance and Metrics

There are no design guidelines or standards identifying the most appropriate target illuminance levels in MURB. It does seem obvious that in the home, there must be more consideration given to daylight, and that 300 lux must be further investigated before being deemed the threshold for determining “adequately lit” or “not”. Supplemental lighting is typical and expected in the home, and many “tasks” at home are relaxing, playing, watching TV or eating which may not require 300 lux at all times. For example IESNA (2012) recommends 100 lux for spaces limited to movement (perhaps like MURB corridors) and 300 lux for areas with simple visual tasks (perhaps like MURB living rooms) and 500 lux where visual tasks are moderately difficult and colour judgement may be required (perhaps like MURB kitchen).

Figure 2: Dining room in a well-lit MURB unit

Accounting for and appreciating lower light levels is part of what makes a home comfortable and cosy depending on season, time of day, room program, and activity. An upper threshold is also important as too much light is also not desirable and it is not necessarily true that all homes have blinds.

Varying Heights of Illuminance Planes

As expected, As discussed, the typical task height for evaluating a target illuminance in offices is desk height or 0.8m. Due to assumed occupant needs in the home, and room uses, the results are presented for four different heights to understand how balconies impact the daylight in the units. Four heights relating to MURB occupancy were identified and tested: floor height (0.0m), coffee table height (0.4m check), desk height for a typical “task plane” or kitchen table (0.8m) and a height that approximates eye level when sitting down (1.2m). The 1.2m height is typically used for evaluating circadian lighting for human expereince and wellbeing (WELL 2019).

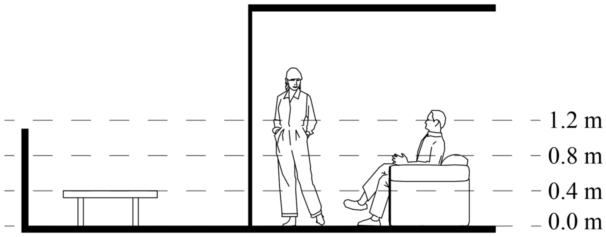


Figure 3: What heights are most relevant for MURB? The sensor height is normally 0.8m high but there is no single "task height" in the home

RESULTS

Influence of Balcony on Unit Daylight

Table 2 shows the DA results comparing daylight in MURB units with the balcony configurations identified in Figure 1 and with the sensor heights described in Figure 3. As expected, the results show that even in the best performing balcony geometry, Option 2, the balcony negatively impacts the daylight in the unit when the units are stacked one above the other achieving 80% of the DA at 1.2m height compared to the no-balcony option. The choice of a glazed or solid handrail for the balcony makes a small difference. The most significant impact is the shading of the balcony above. The study shows the off-setting or staggering of the balcony's placement on the façade mitigates most of the reduction in daylight, offering the best option at 91% of DA at 1.2m height compared to the no-balcony option. This shows that it is not only the balcony geometry, material and size but also the location of the balcony on the façade in proximity to other balconies that determines performance.

Table 2: DA results comparing daylight in units

Balcony Types	Reference Planes			
	0.0 m	0.4 m	0.8 m	1.2 m
No Balcony	100%	100%	100%	100%
Option 1 (glazed)	81%	78%	71%	65%
Option 1 (solid)	74%	73%	67%	60%
Option 2 Stacked (glazed)	91%	87%	84%	80%
Option 2 Stacked (solid)	87%	84%	81%	77%
Option 2 Staggered (glazed)	95%	95%	94%	91%
Option 2 Staggered (solid)	91%	91%	88%	84%
Option 3 (full height glazed)	83%	80%	76%	72%
Option 3 (solid)	80%	79%	76%	73%

Effect of Changing the Illuminance Plane Height

There is a significant difference in DA across the illuminance plane heights. The best performing option is the lowest level in the room, floor level height, then coffee table height, then task height and finally eye level. This is due to the changing sun angles used in an annual calculation. These findings imply that illuminance plane height needs to reflect residential daylighting requirements and that different heights may need to be applied for different room types, depending on who uses it, and when.

Comparison of DA and UDI

The comparison of DA and UDI was undertaken to see if there are significant differences in the two calculations. Table 2 summarizes the DA results and Table 3 summarizes the UDI 100-3000 lux. The DA metric is potentially less relevant in MURB because of the goal of autonomy from articifical lighting even though normally people at home expect to rely on supplemental lighting. Figures 4-6 use the best performing option from Table 2 and as expected show slightly lower percentages when calculating for UDI 300-3000 lux. The DA is higher (67%) than the UDI (52%) because the UDI excludes lux levels above 3000 from the calculation. UDI provides better indication of dark areas and identifies areas that are overlit and could lead to discomfort and glare. The comparison to a lower target illuminance threshold that considers areas that require supplemental lighting, UDI 100-3000 lux (Figure 6), shows that there is a significant difference between calculation that accounts for lower light levels (52% to 64%). A finding of this study is that spaces that do not achieve UDI 100 lux-3000 lux should not be inhabitable space, they could be suited for cupboards or storage but a design guide could be developed that excluded these areas from being regularly occupied space.

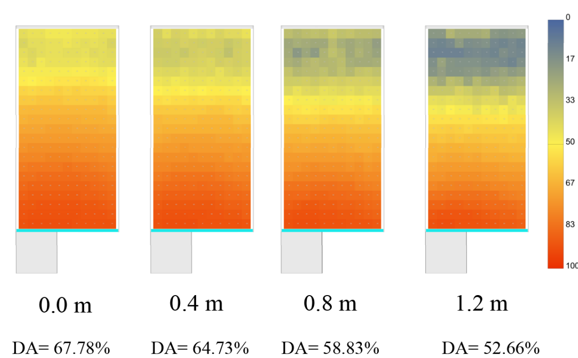
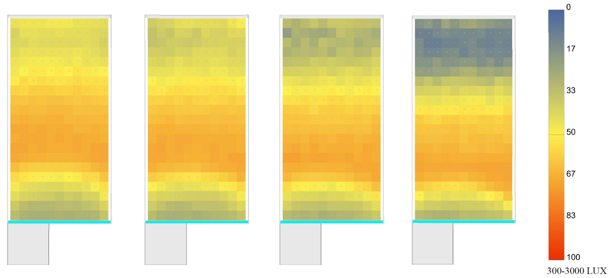


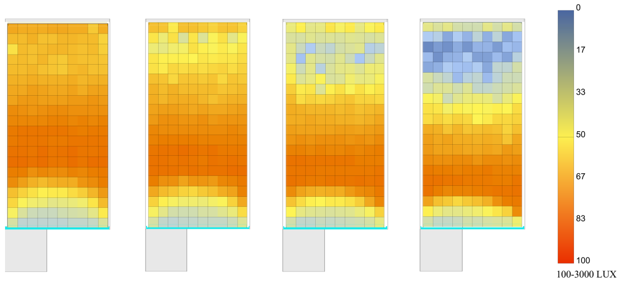
Figure 4: DA showing the target illuminance of 300 lux or more for the best performing balcony configuration.



0.0 m | 0.4 m | 0.8 m | 1.2 m

UDI= 52.27% | UDI= 50.96% | UDI= 48.57% | UDI= 42.53%

Figure 5: UDI with target illuminance of 300 lux to 3000 lux for the best performing balcony configuration.



0.0 m | 0.4 m | 0.8 m | 1.2 m

UDI= 64.10% | UDI= 61.30% | UDI= 56.32% | UDI= 49.10%

Figure 6: UDI with target illuminance of 100 lux to 3000 lux for the best performing balcony configuration.

Table 3 shows the UDI results comparing daylight in MURB units with the various balcony configurations. It seems that UDI could better inform balcony design as it provides information about unacceptably dark areas and indicates areas that are overlit and could lead to discomfort and glare potentialluy suggesting where operable shading devices would be best employed. Neither annual metric is particularly easy to interpret for designers, and this is true of all currently used daylighting metrics.

Table 3: DA results comparing daylight in units

Balcony Types	Reference Planes			
	0.0 m	0.4 m	0.8 m	1.2 m
No Balcony	100%	100%	100%	100%
Option 1 (glazed)	87%	81%	76%	73%
Option 1 (solid)	84%	77%	70%	64%
Option 2 Stacked (glazed)	95%	90%	85%	81%
Option 2 Stacked (solid)	93%	88%	85%	82%
Option 2 Staggered (glazed)	100%	100%	100%	95%
Option 2 Staggered (solid)	97%	96%	92%	90%
Option 3 (full height glazed)	81%	76%	73%	70%
Option 3 (solid)	84%	79%	73%	70%

CONCLUSION

This study identified the need for MURB-specific thresholds and parameters for daylight simulation and tested some alternatives to typical simulation parameters relating to illumance thresholds and relevant metrics, and to room use and relevant simulation plane heights. The results of this paper show that the way we evaluate daylight in MURB matters, because it reveals our underlying assumptions and priorities about housing. Are we designing and evaluating for spaces that can be primarily daylit (daylight autonomy) or are we designing for variety and quality of life (useful daylight that considers lower thresholds but not too low)? If we know that below 100 lux has basically no value to people, can a MURB unit that has a deep floorplate and cannot achieve a reasonable level of UDI be acceptable? The transparency and relevance of the metrics can enable designers to make better decisions about unit layouts and orientations, leading to better housing. The larger goal for this paper is to contribute to the MURB literature to develop relevant and tested simulation parameters for quantity and quality of daylight in this housing type to aid in better MURB design. Future directions for MURB-specific design guidelines are presented, including finding out more about people's expectations and satisfaction with light levels in various rooms, and also gaining more informtion about who actually inhabits MURB and their ages, activity levels and use of the rooms. Since different heights for illuminance planes can be modelled and the results vary significantly, without this deeper understanding of people and our behaviour, it is unclear which illuminance level or height is most appropriate for each room type in a MURB. This paper offers no singular answer but challenges the assumption that 300 lux is the most reliable metric, and that 0.8m is the most accurate height for evaluation. This paper instead calls for further research into MURB design for daylight and other aspects of quality of life and building performance.

What started as a study of balcony designs for MURB has uncovered the need for careful consideration of the parameters and protocols to be applied to meaningful assessments of daylighting in MURB.

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