Journal of Architectural and Planning Research
37:3 (Summer, 2023) 17

PRICING THE DAYLIGHT COMFORT FRONTIER IN URBAN HOUSING: A NONLINEAR HEDONIC REANALYSIS FRAMEWORK FOR TURIN APARTMENTS

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Daylight is widely valued in residential decision-making, yet the economic literature still tends to treat its contribution to housing value as a linear attribute or to proxy it with legacy compliance metrics. This article develops a benchmark-grounded nonlinear hedonic framework to investigate whether the market rewards daylight quantity alone or, more plausibly, a daylight comfort balance that combines useful illuminance, sunlight access, and manageable exposure. The study is anchored in the Turin condominium sample reported by Loro et al., which includes 100 apartments modeled through ClimateStudio and characterized by contextual, architectural, energy, and daylight variables. The empirical motivation is specific and bounded: in the published ordinary least squares benchmark, estimated on 90 units and checked on a 10-unit control sample, useful daylight illuminance achieved (UDI.A) and annual sunlight exposure (ASE) were significant, whereas average daylight factor (DFm) and spatial daylight autonomy (sDA) were not, and the model explained about 59% of variation in listing price per square meter. Building on that published pattern, the manuscript strengthens the theoretical motivation, clarifies the interpretation of listing-price capitalization as a noncausal market-signaling relation, and specifies a parsimonious semiparametric hedonic model with spline-based daylight terms and restricted interaction effects among UDI.A, ASE, blinds-closed time, and vertical sky component. The contribution is methodological and interpretive: a defensible comfort-frontier hypothesis, a transparent reanalysis protocol, and a benchmark-based validation path for future microdata implementation. By making explicit why comfort-proximate daylight metrics may matter more than legacy diffuse-sky indicators, the paper speaks directly to valuation practice, climate-based daylight assessment, and performance-based housing design.

https://doi.org/10.66033/japr2022-302

INTRODUCTION

Natural light is one of the few housing attributes that simultaneously affects health, visual comfort, spatial perception, and operating energy demand. In residential markets, daylight also possesses signaling value: buyers often read brightness, sun access, and visual openness as indicators of domestic quality, well-being, and long-term desirability (Aries et al., 2015; Knoop et al., 2020; Lee et al., 2022; Veitch & Christoffersen, 2012). Even so, the economic capitalization of daylight remains underdeveloped in residential valuation research. Most hedonic studies examine conventional structural or locational covariates, while building-performance studies focus on illuminance adequacy, glare risk, or energy savings without translating those outcomes into price effects.

A recent Turin case study offers an important step forward by linking 3D daylight simulations of 100 apartments with hedonic multiple regression (Mutani et al., 2019). In that study, two daylight variables—annual sunlight exposure (ASE) and useful daylight illuminance achieved (UDI.A)—were significant in the final model, whereas average daylight factor (DFm) and spatial daylight autonomy (sDA) were not (Mutani et al., 2019). This finding is theoretically provocative. UDI.A is a comfort-oriented metric that rewards illuminance within a useful band, while ASE captures a threshold beyond which direct sun may increase glare and overheating risk (European Committee for Standardization, 2018; Illuminating Engineering Society, 2012; Nabil & Mardaljevic, 2006). The simultaneous significance of both metrics implies that the housing market may be responding to a balance between adequate daylight and moderated sunlight exposure rather than to a monotonic “more daylight is better” rule.

That possibility motivates the present article. The core argument is that residential buyers do not capitalize daylight as a single linear amenity. Instead, they are more likely to value a *daylight comfort frontier*: a range in which useful daylight is sufficiently high, direct solar exposure remains tolerable or controllable, and the need for frequent shading does not erode perceived quality. If this interpretation is correct, the marginal effect of daylight should be nonlinear, and daylight metrics should interact rather than operate independently.

The article therefore advances a nonlinear hedonic reanalysis framework for the Turin sample. Its contribution is fourfold. First, it formulates a theory-grounded comfort-frontier hypothesis for residential daylight capitalization. Second, it explains why comfort-proximate daylight metrics should be more behaviorally plausible market signals than legacy diffuse-sky or compliance-oriented indicators. Third, it proposes a parsimonious semiparametric specification that can capture thresholds, diminishing returns, and interaction effects while remaining appropriate for a modest housing sample. Fourth, it translates building-performance information into a valuation framework that is useful for appraisers, housing economists, and design researchers alike. The paper does not claim a new causal estimate or a completed microdata rerun; rather, it delivers a technically tightened reinterpretation of the published Turin benchmark and an executable protocol for future nonlinear implementation once the unit-level matrix is available.

The research questions are as follows:

(RQ1) Does the capitalization of daylight in residential prices follow a nonlinear rather than a linear form?

(RQ2) Is the price premium associated with daylight strongest where useful illuminance is high *and* sunlight overexposure remains controlled?

(RQ3) Do comfort-sensitive daylight constructs outperform legacy compliance-oriented indicators in explaining listing prices?

LITERATURE REVIEW

Daylight as a multidimensional performance attribute

Daylighting research has moved well beyond static illuminance proxies toward dynamic, climate-based metrics that better reflect annual occupancy, useful illuminance ranges, and the dual role of sunlight as both a benefit and a potential source of discomfort (European Committee for Standardization, 2018; Illuminating Engineering Society, 2012; Leslie et al., 2012; Nabil & Mardaljevic, 2006). In residential environments, daylight is associated with visual well-being, circadian support, spatial quality, and reductions in electric lighting demand (Aries et al., 2015; Bournas, 2020; Figueiro et al., 2023; Knoop et al., 2020). Yet performance metrics do not carry equivalent meanings. DFm and VSC are fundamentally diffuse-sky measures. By contrast, sDA, ASE, and the UDI family capture time-varying and threshold-based aspects of daylight exposure.

This distinction is central to economic interpretation. A buyer does not experience daylight as an abstract simulation output. Rather, the buyer experiences a room as bright enough, too dark, pleasantly sunlit, or prone to overheating and glare. Metrics tied to these experiential states should therefore have a closer relationship with willingness to pay than metrics designed mainly for regulatory compliance.

Hedonic valuation of housing quality and environmental amenities

Hedonic pricing theory interprets the housing market as a mechanism through which buyers reveal implicit prices for differentiated attributes (Goodman, 1978; Malpezzi, 2008; Rosen, 1974). The approach has been applied to structural quality, accessibility, energy efficiency, neighborhood amenities, and environmental disamenities (Nesticò & La Marca, 2020; Pagourtzi et al., 2003). In the Italian context, a growing literature documents capitalization effects for energy performance certificates and related efficiency signals (Barreca et al., 2021; Bisello et al., 2020; Bonifaci & Copiello, 2015; Dell'Anna et al., 2019; Tagliabue et al., 2019).

Compared with energy labeling, daylight remains much less explored. In office markets, Turan et al. (2020) and Turan et al. (2021) showed that high daylight access and good views are associated with rent premiums. In housing markets, Zhong et al. (2022) demonstrated a positive willingness to pay for sunlight exposure in Shanghai. The Turin study by Mutani et al. (2019) is among the few residential analyses to combine detailed daylight simulations with hedonic estimation.

Why a nonlinear model is needed

The empirical pattern reported by Mutani et al. (2019) points directly to a modeling gap. If buyers reward UDI.A, but ASE also enters the model significantly, then daylight valuation likely involves a trade-off. Moderate sunlight can enhance desirability by signaling brightness and solar access, but excessive sunlight can increase cooling loads, glare, and shading dependence (De Luca et al., 2022; Nazari et al., 2023; Sepulveda et al., 2023). A linear OLS term is poorly suited to that mechanism because it assumes a constant marginal effect across the entire daylight range.

Semiparametric hedonic models offer a more appropriate alternative. Generalized additive models (GAMs) can recover smooth nonlinear functions from data while preserving interpretability and accommodating mixed predictor types (Hastie & Tibshirani, 1990; Wood, 2017). In housing research, nonlinear functional forms are especially useful when buyers respond to thresholds, satiation points, or attribute bundles rather than simple incremental changes. For daylight, such a model can identify whether the market prefers "more" daylight or instead prefers a bounded comfort zone.

STUDY CONTEXT AND BASELINE EMPIRICAL PREMISE

The present manuscript is anchored in the Turin apartment dataset assembled for the Pozzo Strada submarket, a semi-peripheral residential district divided into the Rivoli, Monte Cucco–Bardonecchia, and Ruffini micro-areas (Mutani et al., 2019). The source database contained 100 condominium apartments advertised during the last quarter of 2022 and excluded ground-floor units, attics, lofts, and special building categories (Mutani et al., 2019). Three-dimensional models were built from listing plans, photographs, and municipal GIS information, then simulated in ClimateStudio to derive daylight metrics including DFm, $sDA_{300,50\%}$, $ASE_{1000,250h}$, UDI.fell-short, UDI.achieved, UDI.exceeded, average illuminance, blinds-closed time, view, and VSC (Mutani et al., 2019).

The original benchmark regression used 90 observations for model estimation and 10 as a control sample. The final OLS specification explained approximately 59% of variation in unitary listing price and retained the following significant predictors: poor energy class (negative), unit status, elevator presence, terraces, balconies, window frame typology, ASE, and UDI.A (Mutani et al., 2019). DFm and sDA were not retained in the final model (Mutani et al., 2019). Because the benchmark outcome variable is listing price per square meter rather than a realized transaction price, the reported coefficients should be read as evidence on asking-price formation and market signaling, not as a direct estimate of ex post sale-price premiums (Horowitz, 1992; Knight, 2002). For the present article, those published findings are not the end point; they are the empirical starting point that motivates a nonlinear reanalysis.

Table 1: Baseline characteristics of the Turin dataset used as the empirical basis of the reanalysis.

Attribute	Baseline description
Study area	Pozzo Strada residential submarket, Turin, Italy
Initial sample size	100 condominium apartments
Estimation sample in benchmark model	90 units
Validation sample in benchmark model	10 units
Time window of listings	Last quarter of 2022
Daylight simulation platform	ClimateStudio for Rhino, using standardized material assumptions
Occupied hours for simulations	08:00–18:00 daily (3650 h/year)
Key daylight metrics simulated	DFm, sDA, ASE, UDI.fell-short, UDI.achieved, UDI.exceeded, Em, BCL, VSC, view
Significant daylight metrics in benchmark OLS	ASE and UDI.A
Non-significant daylight metrics in benchmark OLS final model	DFm and sDA
Benchmark explanatory power	Adjusted $R^2 \approx 0.59$

Source: compiled from the Turin daylight-housing dataset and benchmark model reported by Mutani et al. (2019).

THEORY AND HYPOTHESES

The conceptual claim of this paper is that the housing market prices daylight as a *comfort bundle*. Three mechanisms justify this claim: First, UDI.A is more behaviorally plausible than DFm or sDA as a market signal because it captures the share of occupied time in which illuminance lies within a useful range. Buyers do not purchase a daylight factor; they purchase a lived daylight condition. Second, sunlight is ambivalent. Direct sun can increase spatial appeal, seasonal warmth, and perceived openness, yet too much sun can trigger glare, overheating, and a need for frequent blind use. Therefore, a positive price premium for ASE is theoretically compatible with buyer preference only if ASE remains within a manageable band or is offset by other favorable attributes. Third, shading dependence matters. A room that appears bright in simulation but requires blinds to remain closed for substantial periods may underperform from the user's standpoint. Hence, the value of daylight should depend not just on daylight availability but on the relationship between daylight availability and controllability. These arguments lead to the following hypotheses.

H1. The marginal effect of UDI.A on listing price is positive but nonlinear, with diminishing returns at higher values.

H2. The effect of ASE on listing price is nonlinear and conditional: moderate increases in ASE are positively valued, but the marginal benefit weakens or turns negative when excessive sun exposure increases discomfort risk.

H3. The price premium associated with UDI.A is larger when blinds-closed time is low and VSC is adequate, indicating that useful daylight is most valued when it does not rely on frequent shading or poor sky access.

H4. A comfort-oriented daylight specification that combines UDI.A, ASE, BCL, and VSC provides better explanatory performance than a legacy specification centered on DFm and WFR.

MATERIALS AND METHODS

Data structure and variable strategy

The reanalysis uses the same empirical base reported for Turin, retaining the structural, architectural, and energy controls that were significant or theoretically relevant in the benchmark model. These include unit status, elevator presence, terraces, balconies, frame type, energy performance, and additional dwelling characteristics available in the original database (Mutani et al., 2019). The daylight side of the model centers on UDI.A, ASE, BCL, and VSC, while DFm, sDA, and WFR are preserved for benchmarking purposes. Because the dependent variable is asking price per square meter, the empirical target is the structure of listing-price differentiation within a relatively homogeneous submarket rather than realized transaction premiums.

Because the source study categorized several daylight metrics into ordinal performance bands, the preferred reanalysis should be run on the original continuous simulation outputs wherever available. If only categorized data are accessible, the spline terms proposed below should be approximated by monotonic ordinal smooths or by piecewise dummy blocks with ordered thresholds. The manuscript therefore distinguishes clearly between (i) the published benchmark evidence, which is already available and discussed below, and (ii) the future unit-level rerun required to estimate smooth functions and interaction surfaces directly.

Econometric specification

Let P_i denote the listing price per square meter of apartment i. The benchmark framework is a log-price hedonic model. The nonlinear extension proposed here is:

$$\begin{aligned}\ln(P_i) =& \beta_0 + \boldsymbol{\gamma}^\top \mathbf{X}_i + f_1(\mathrm{UDI.A}_i) + f_2(\mathrm{ASE}_i) + f_3(\mathrm{BCL}_i) + f_4(\mathrm{VSC}_i)\\ &+ f_5(\mathrm{FA}_i) + \delta_1\,\mathrm{UDI.A}_i \times \mathrm{ASE}_i + \delta_2\,\mathrm{UDI.A}_i \times \mathrm{BCL}_i + \varepsilon_i, \qquad (1)\end{aligned}$$

where $\mathbf{X}_i$ is the vector of structural and energy controls, $f_j(\cdot)$ denotes a penalized regression spline, and ε_i is an idiosyncratic error term.

Eq. (1) serves two purposes. First, it allows the price response to daylight metrics to vary flexibly over their observed ranges. Second, it permits testing whether useful daylight and sunlight exposure operate as complements, substitutes, or a bounded bundle. Given the modest estimation sample, the preferred implementation should use low-rank smooths with restricted basis dimensions and should retain the second daylight interaction only if cross-validation shows a stable incremental gain in fit and interpretation.

For model comparison, four nested specifications should be estimated:

Model 1: *Structural baseline:* non-daylight controls only.

Model 2: *Legacy daylight model:* structural baseline + DFm and WFR.

Model 3: *Linear climate-based model:* structural baseline + linear UDI.A, ASE, BCL, and VSC terms.

Model 4: *Comfort-frontier model:* full semiparametric specification in Eq. (1).

Identification logic

The identification strategy is not causal in the strict experimental sense; it is a market-pricing exercise within a relatively homogeneous submarket. The original study deliberately restricted spatial heterogeneity by focusing on a single Turin submarket, thereby reducing locational confounding (Mutani et al., 2019). The present article preserves that design choice and instead addresses a different threat: functional-form misspecification. If daylight enters prices nonlinearly, then a purely linear model can misstate both the direction and magnitude of capitalization. Because the dependent variable is a listing price, the estimates should be interpreted as capitalization in asking-price formation rather than realized sale-price premiums (Horowitz, 1992; Knight, 2002).

To reduce overfitting, spline complexity should be selected by restricted maximum likelihood, and model robustness should be checked with leave-one-out or repeated k-fold cross-validation (Wood, 2017). Heteroskedasticity-consistent inference, leverage diagnostics, and sensitivity checks that trim high-influence observations should also be reported. Standard variance inflation diagnostics should be reported for the parametric terms, while concurvity diagnostics should be examined for the smooth components.

Reproducibility protocol

A reproducible reanalysis should proceed in six steps:

1. Reconstruct the unit-level dataset from the same 100 apartments, preserving the original exclusion rules.
2. Recover continuous daylight outputs from ClimateStudio where possible; otherwise retain the categorized values and document any loss of resolution.
3. Replicate the benchmark linear model to verify consistency with the reported Turin estimates, including the published estimation/control split and the retained daylight terms.
4. Estimate the four nested models described above using low-rank smooths and a sequential interaction strategy.
5. Compare model fit using adjusted R^2, AIC, BIC, cross-validated RMSE, calibration plots, residual structure, and sensitivity to influential observations.

6. Visualize the fitted smooths and interaction surfaces to identify the daylight comfort frontier, but report nonlinear features only when they remain stable across validation folds and robustness checks.

RESULTS

Empirical patterns motivating the nonlinear specification. The benchmark Turin evidence already suggests that daylight is priced selectively rather than uniformly. The original model retained UDI.A and ASE but not DFm or sDA (Mutani et al., 2019). This is consistent with the idea that buyers respond more strongly to conditions tied to lived daylight usefulness and sunlight exposure than to compliance-centered or diffuse-sky metrics alone. The descriptive distributions reported for the 100 simulated units also reinforce this interpretation: most units underperformed the DFm and sDA thresholds commonly invoked in regulation or certification, yet the market still differentiated among them on the basis of daylight-related signals (Mutani et al., 2019). From a substantive standpoint, that pattern implies that the market premium is unlikely to be generated by a single threshold such as DFm $> 2\%$ or sDA $> 55\%$. Instead, buyers may be rewarding units that combine adequate useful daylight with a tolerable amount of direct sun and limited shading dependence. The nonlinear model is designed precisely to test that mechanism.

Expected output structure of the reanalysis. Because the unit-level Turin matrix is not publicly reported in the benchmark article, the present manuscript documents the published evidence that motivates the nonlinear specification and makes explicit the validation criteria that a completed rerun must satisfy. First, the benchmark comparison must establish that daylight contributes explanatory information beyond structural and energy controls and that comfort-proximate metrics outperform legacy diffuse-sky indicators in the published linear model. Second, the descriptive daylight distributions must be interpreted together with the benchmark regression outcome: wide heterogeneity in UDI- and exposure-related variables is informative only if the retained daylight terms are also the ones most closely aligned with lived comfort. Third, any future nonlinear rerun must demonstrate not only better fit but also stable and interpretable smooth shapes, since apparent thresholds in a small housing sample may otherwise reflect overfitting rather than economically meaningful behavior.

Illustrative figure material from the Turin daylight dataset. The refined source Figures 1,2,3 are retained in the article to document the empirical daylight landscape of the Turin sample and to motivate the nonlinear reanalysis.

DISCUSSION

The proposed nonlinear interpretation has substantive implications, but the benchmark evidence should be read with appropriate discipline. What the published Turin results already show is not that a nonlinear comfort frontier has been definitively estimated, but that comfort-proximate daylight indicators appear to align more closely with asking-price variation than legacy diffuse-sky or compliance-oriented metrics. This is an important distinction. It reframes residential daylight value as a balance problem rather than a sufficiency problem and helps explain why a dwelling may satisfy a static threshold yet still provide mediocre lived daylight conditions, or conversely fall short of a legacy threshold while still offering a daylight condition the market finds attractive. The Turin benchmark narrows the plausible interpretations to three economically meaningful cases. First, the true relationship may be *monotonic but concave*, implying that more useful daylight is generally better but with diminishing returns. Second, it may exhibit an *interior optimum*, in which additional solar exposure improves desirability only up to the point at which glare, overheating, or blind use becomes intrusive. Third, daylight may behave as a *bundle attribute*, meaning that the value of UDI.A depends on simultaneous shading and sky-access conditions. A completed microdata rerun is required to distinguish among these cases, but the published benchmark evidence makes the nonlinear question legitimate rather than speculative. These distinctions are consequential for both valuation practice and building design. For appraisers, the relevant implication is that daylight should not be reduced to qualitative descriptors such as “bright” or “sunny,” nor should asking-price evidence be confused with realized transaction premia. For designers and developers, the sharper message is that maximizing window area or direct sun penetration is not, by itself, the economically optimal strategy. The market signal suggested by the published Turin evidence is more conditional: useful daylight appears most valuable when overexposure and shading dependence remain controlled.

THEORETICAL AND PRACTICAL CONTRIBUTIONS

The paper offers four main contributions: First, it advances hedonic theory by treating daylight as a nonlinear and interaction-dependent amenity rather than a uniformly increasing housing attribute. This shifts the analytical focus from average attribute premiums to comfort-conditioned marginal values. Second, it bridges building simulation and real-estate economics in a way that is methodologically explicit. Much of the daylight literature remains performance-oriented, while valuation studies rarely operationalize high-resolution daylight metrics or explain clearly why some metrics are more behaviorally plausible market signals than others. Third, it clarifies the empirical meaning of the available evidence by distinguishing asking-price capitalization from realized transaction premiums and by stating the noncausal scope of inference directly. That clarification strengthens, rather than weakens, the contribution because it aligns the claims with the data actually available. Fourth, it provides a parsimonious and reproducible reanalysis protocol that can be replicated in other neighborhoods, climates, and housing segments once unit-level data are accessible. This matters because buyer perceptions of daylight likely vary with latitude, urban density, façade depth, seasonal solar patterns, and local pricing conventions.

LIMITATIONS

The most important limitation is that the article depends on access to the unit-level Turin dataset. The benchmark publication reports distributions, variable definitions, and the outcome of the final OLS model, but not the full apartment-level matrix required for rerunning semiparametric models (Mutani et al., 2019). Accordingly, the present manuscript can validate the nonlinear motivation against the published benchmark evidence, but it cannot report new spline estimates or interaction surfaces without introducing unverifiable values. A second limitation concerns the dependent variable. Because the Turin study models listing prices rather than realized transaction prices, the results concern asking-price formation, seller expectations, and market signaling more directly than closed-sale premia (Horowitz, 1992; Knight, 2002). That does not invalidate the analysis, but it does narrow the interpretation that can be defended. A third limitation concerns sample size. Even with the original 100-unit dataset, a nonlinear specification must be parsimonious enough to avoid overfitting. Penalization, low-rank smooths, and cross-validation are therefore not optional add-ons but integral parts of the methodology. A fourth limitation concerns generalizability. The Turin sample represents a controlled submarket, which is advantageous for reducing locational heterogeneity but constrains broader inference. Replications in other Italian and non-Italian contexts would be needed to determine whether the same comfort frontier appears elsewhere.

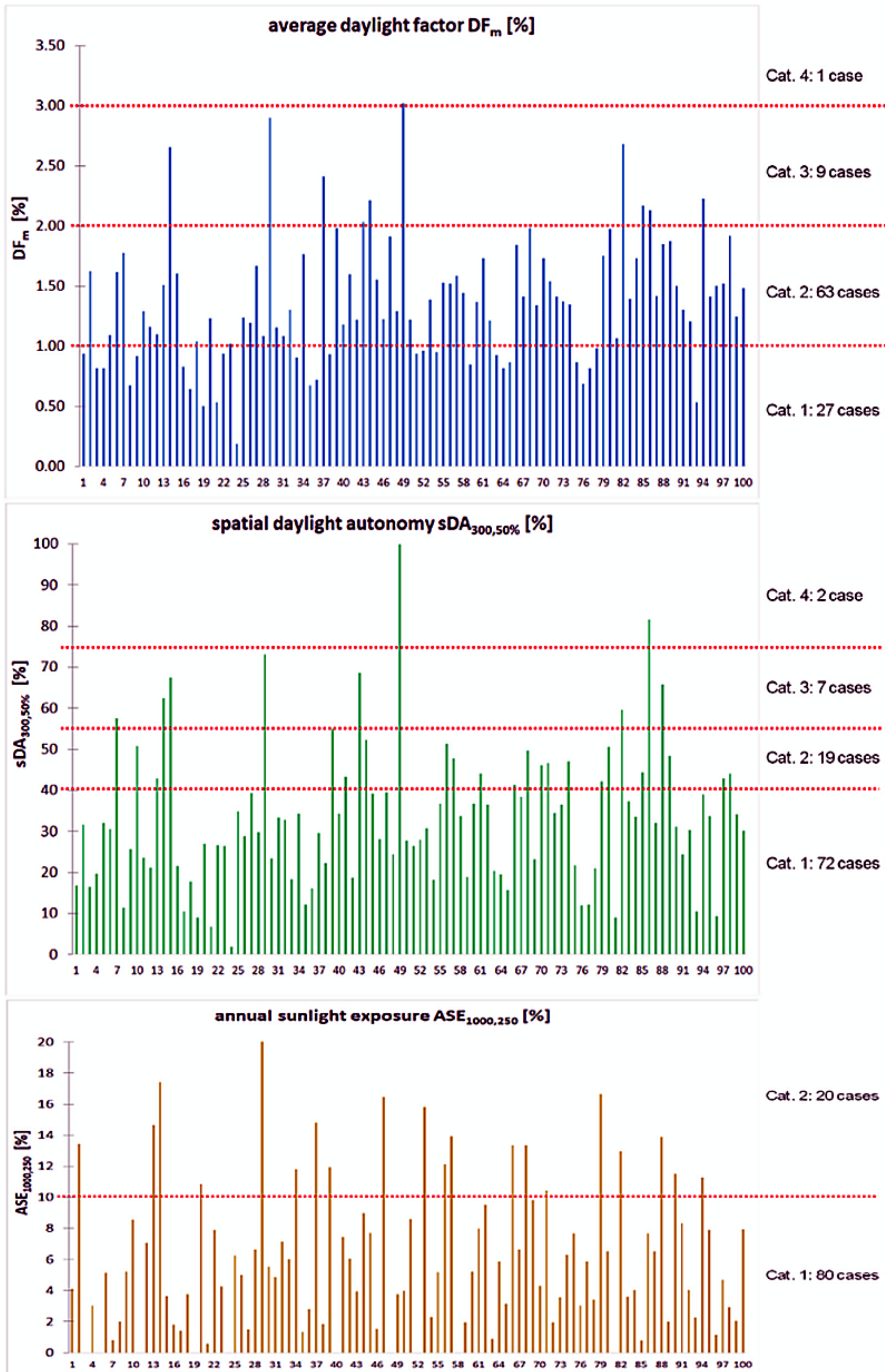

Figure 1: Distribution of DFm, sDA, and ASE across the sampled Turin apartments. The figure documents wide variation in daylight metrics but also a strong concentration of units below conventional DFm and sDA performance thresholds. Source image extracted from the Turin case-study figures reported by Mutani et al. (2019).

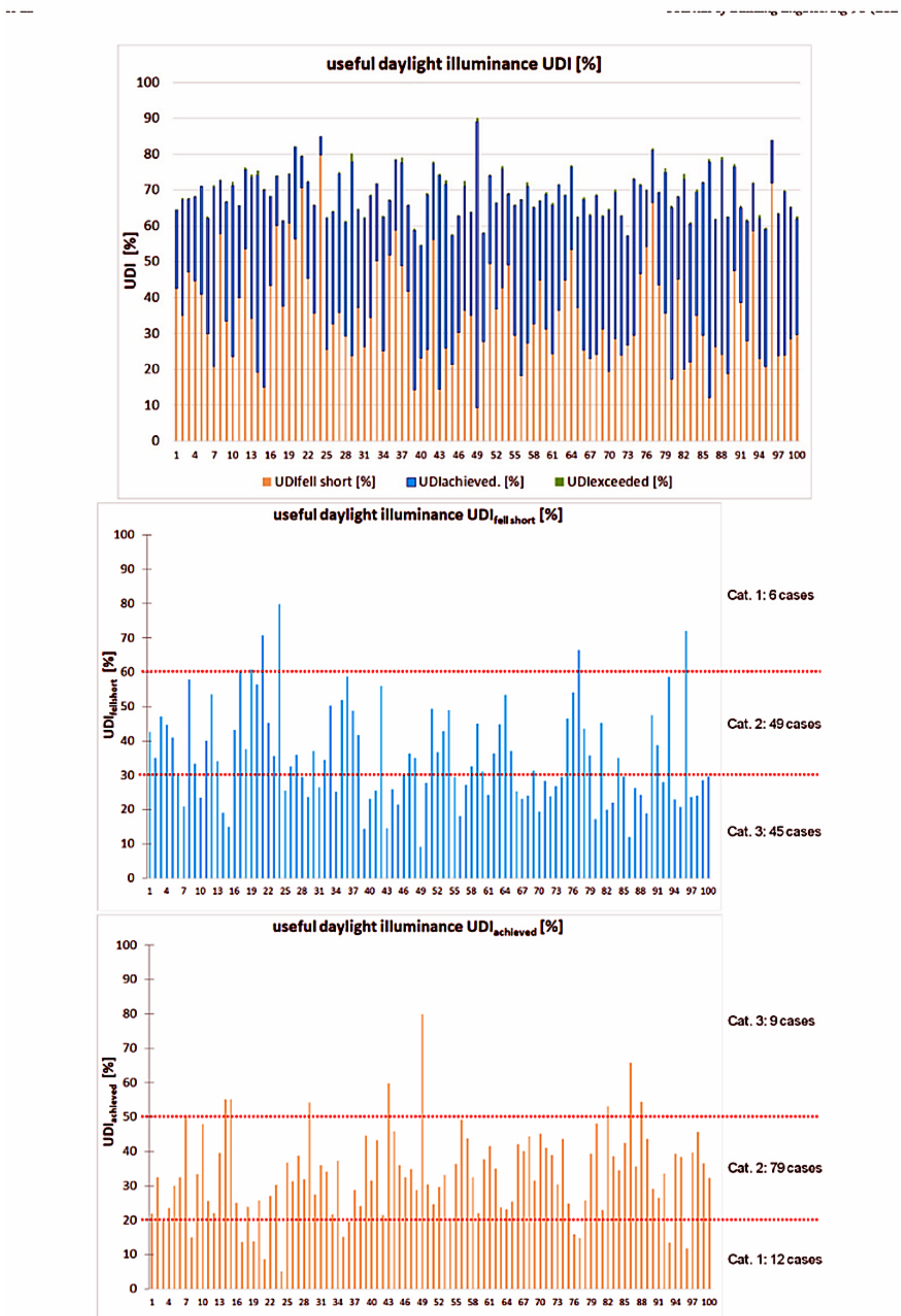

Fig. 3.b. Results from ClimateStudio daylighting simulations: (b) UDI (Source: Authors' elaboration).

Figure 2: Distribution of UDI-based daylight metrics across the sampled Turin apartments. The figure is especially relevant to the present paper because UDI.A is the principal comfort-oriented daylight variable retained in the benchmark price model. Source image extracted from the Turin case-study figures reported by Mutani et al. (2019).

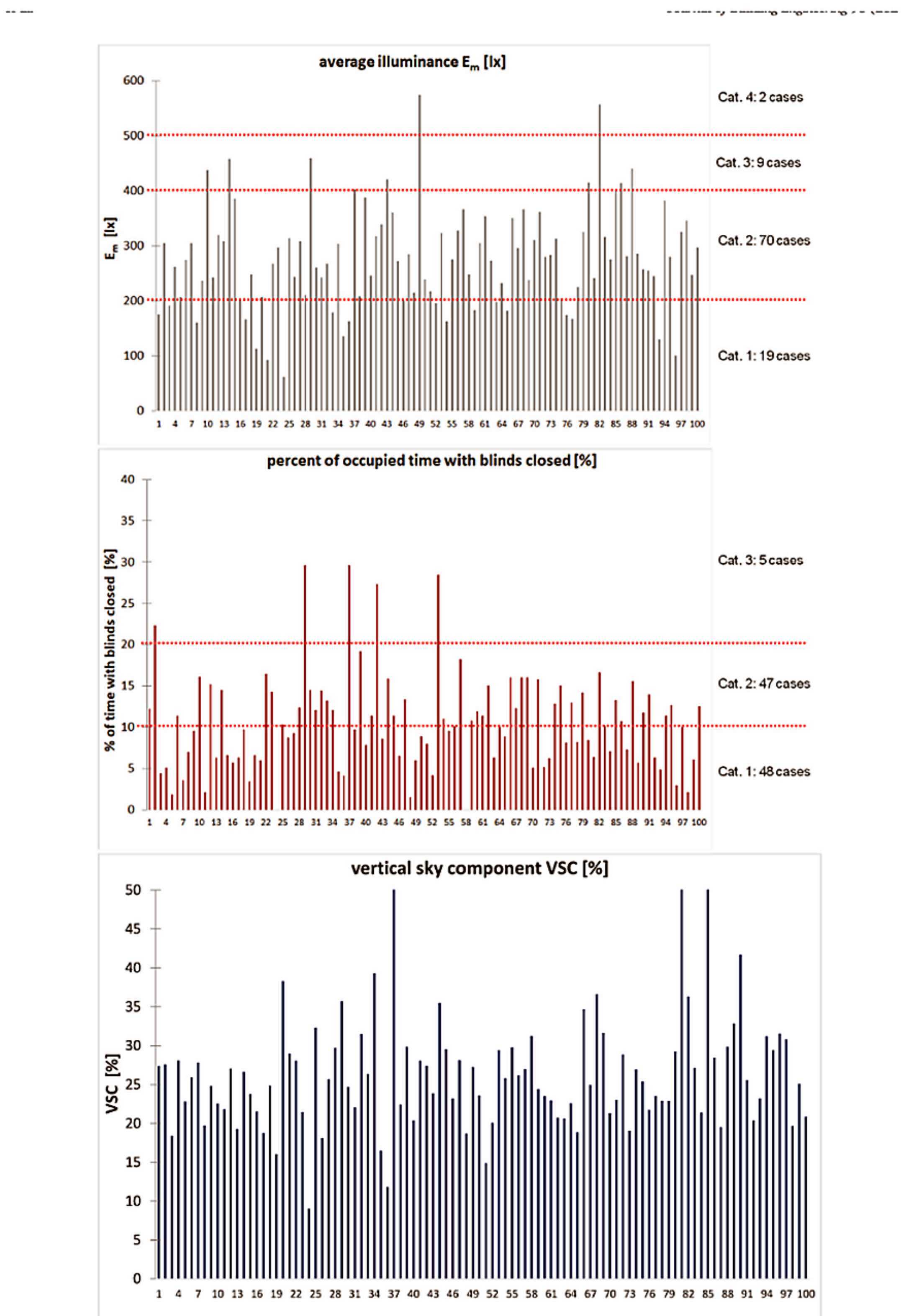

Fig. 3.c. Results from ClimateStudio daylighting simulations: (c) E_m, blinds closed, and VSC.

Figure 3: Distribution of average illuminance, blinds-closed time, and VSC across the sampled Turin apartments. These variables are used here to motivate the controllability dimension of the daylight comfort frontier. Source image extracted from the Turin case-study figures reported by Mutani et al. (2019).

CONCLUSION

This article argues that residential markets are unlikely to value daylight as a simple linear amenity. The published Turin benchmark—namely the significance of UDI.A and ASE, coupled with the non-significance of DFm and sDA in the final model—suggests that the market responds to a more refined construct than daylight abundance alone: a daylight comfort frontier in which useful illuminance, controllable sunlight, and manageable shading dependence jointly shape asking-price differentiation. The contribution of the present manuscript is therefore to tighten the theoretical motivation, align the claims with the benchmark evidence actually available, and provide a parsimonious semiparametric protocol for future microdata implementation. The benchmark evidence is consistent with the comfort-frontier hypothesis, but it is not yet sufficient to confirm the exact shape of the capitalization function. The key substantive implication is nevertheless important: in residential real-estate markets, the economically relevant question is unlikely to be how much daylight a dwelling receives in the abstract, but whether that daylight falls within a market-preferred comfort range. Future work with the released unit-level matrix should determine whether that range appears empirically as diminishing returns, an interior optimum, or interaction-dependent bundle effects.

DECLARATION OF COMPETING INTEREST

The author declares no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Manuscript revisions completed 03 March 2023.