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Zonal Reconstruction of Daylighting in Historic Built Environments: A Workflow to Model and Evaluate Light in Spatial and Temporal Domains

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Abstract: Computer simulation allows to study daylight conditions in the past that afforded activities in antique buildings. The Python module PHOS4DTOOLS implements the efficient computation of zonal daylight metrics that are considered to indicate affordances. It was employed to solve horizontal and vertical illuminance for different orientations and elevations in the House of the Priestesses, a unit of the Hadrianic Garden Houses complex in Ostia. A reconstruction model of the unit was produced by collating an existing, detailed 3D documentation with other sources and our own survey data. The spatially and temporally resolved results of daylight simulation employing PHOS4DTOOLS were imported into a GIS database. Assuming typical reflectance properties, illuminance thresholds were determined that are required for the perception of contrast detail and colour differences. Integration over temporal periods and spatial zones that are eligible for residential activities was implemented by queries to the database. First, preliminary results indicated different distributions of affordances by daylight, depending on the characteristics of the considered visual tasks. Horizontal illuminance decreases quickly with increasing distance to the aperture, suggesting that activities bound to a horizontal work plane were constraint to the immediate adjacency of windows and potentially open doors. Vertical illuminance, on the other hand, reaches deep into the building when the receiving surface is oriented to a window, particularly in the absence of exterior obstructions. The exemplary application of PHOS4DTOOLS shows its potential in the interdisciplinary research on daylight and its implications on living practice in antique buildings.

Keywords: daylight; Ostia; antique dwelling; phos4dtools; Raytraverse

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1. Introduction

1.1. Spatial and Temporal Dimensions of Historical Lighting

Lighting is a key quality of any built environment. The study of historic lighting relates building practice, building design, and technological development in natural and artificial lighting, e.g., luminaires, fuels, and window glass, with the lighting conditions that afford the use and perception of architecture. Artificial lighting commonly illuminated the private and public buildings but also the streets of Ostia [1]. On the one hand, antique lighting devices such as lamps made of clay or glass, as well as bronze chandeliers and candelabra, allow to reconfigure the illumination of buildings, at any time. On the other hand, they depend on the availability and affordability of olive oil as fuel, and can only produce a dim environment. Consequently, daylight was the primary source for lighting until the modern omnipresence of electrical lighting. While it may be difficult to tell when and where in a building lighting devices had been used, affordances due to the admission and distribution of daylight can be studied as intrinsic features of architecture.

Due to the loss or alteration of architecture, historic lighting often cannot be studied in situ, only by reconstruction and simulation [2–4]. This requires plausible assumptions in terms of light sources, reconstructed geometry, and material properties of a building [5]. Based on such models, the open source simulation suite RADIANCE can model light propagation in buildings [6,7]. It combines stochastic and deterministic ray-tracing to account for specular and diffuse light paths. Virtual sensors produce scalar readings, e.g., illuminance or imagery, including luminance maps, for given positions and directions. However, lighting conditions are variable, and the positions and view directions of occupants are often unknown. This is most obvious and relevant for daylighting and has motivated the expansion of lighting simulation into the temporal and spatial domains, i.e., climate-based daylight modelling and zonal evaluations of illuminance and derived metrics [8].

The computational demand and complexity to calculate metrics that are not reduced to planar, i.e., horizontal or vertical, illuminance still hinder scholars to investigate potentially more telling expressions of the luminous conditions in historical built environments. The development and application of such metrics typically fall into the field of (modern) lighting research and are detached from the realm of scholars studying, e.g., the functional and social correlation with historic activities and building practice: these are typically confronted with the results of metrics produced by other experts or suggested by off-the-shelf tools rather than including them in their research.

The recent development of the RAYTRAVERSE adaptive sampling strategy in spatial and temporal domains allows to include contrast- and image-based metrics that were computationally too expensive and extend the range of illuminance-based metrics beyond the commonly reported horizontal illuminance. This is achieved by focusing the simulation only on the most relevant regions, e.g., image regions of high contrast, time periods with sudden changes of sky conditions, or areas where the luminous conditions change significantly [9,10]. RAYTRAVERSE employs RADIANCE as its back-end, and it is freely available as a Python module.[1]

The Python module PHOS4DTOOLS implements the computation of a set of daylight metrics that are considered to indicate affordances in the historical context of the assessed site. It prepares a simulation model by translating a layer naming scheme into material attributions and evaluation zones, and then controls the spatio-temporal daylight simulation using RAYTRAVERSE [11].

1.2. Objectives

The application of PHOS4DTOOLS shall be demonstrated for the case of a residential complex in Ostia. Integration with a Geographical information System (GIS) is suggested to allow evaluating and overlaying the simulation results with other, spatially organised archaeological research data such as site plans and the location of finds indicating activities. It is intended to cross the barriers between those performing daylight simulations and developing daylight metrics on the one hand, and those correlating them to other sources on the other. This shall foster inter-disciplinary collaboration in the research of historic lighting.

2. Method

2.1. Modelling a Residential Unit in the Garden Houses in Ostia

The uniformly planned building complex of the Garden Houses (Italian Case a Giardino) occupies a ground area of just under 13,000 m^2 in the southwestern part of the port city of Ostia (Regio III, insula ix). Built in Hadrianic times between 125 and 130/40 AD, the multi-storey complex comprises a closed-block perimeter, a centre occupied by eight luxurious medianum apartments, combined rented flats, workshops, and tabernas [12,13]. The initial construction phase of one residential unit, the House of the Priestesses (Italian Casa delle Ierodule, also called House of Lucceia Primitiva, Ostia III, ix, 6), situated in the western wing of the Garden Houses (Figure 1), was reconstructed based on an existing 3D documentation of the insula[2]. The methods are described by Borrmann et al., 2015 [15], and Nuechter [16].

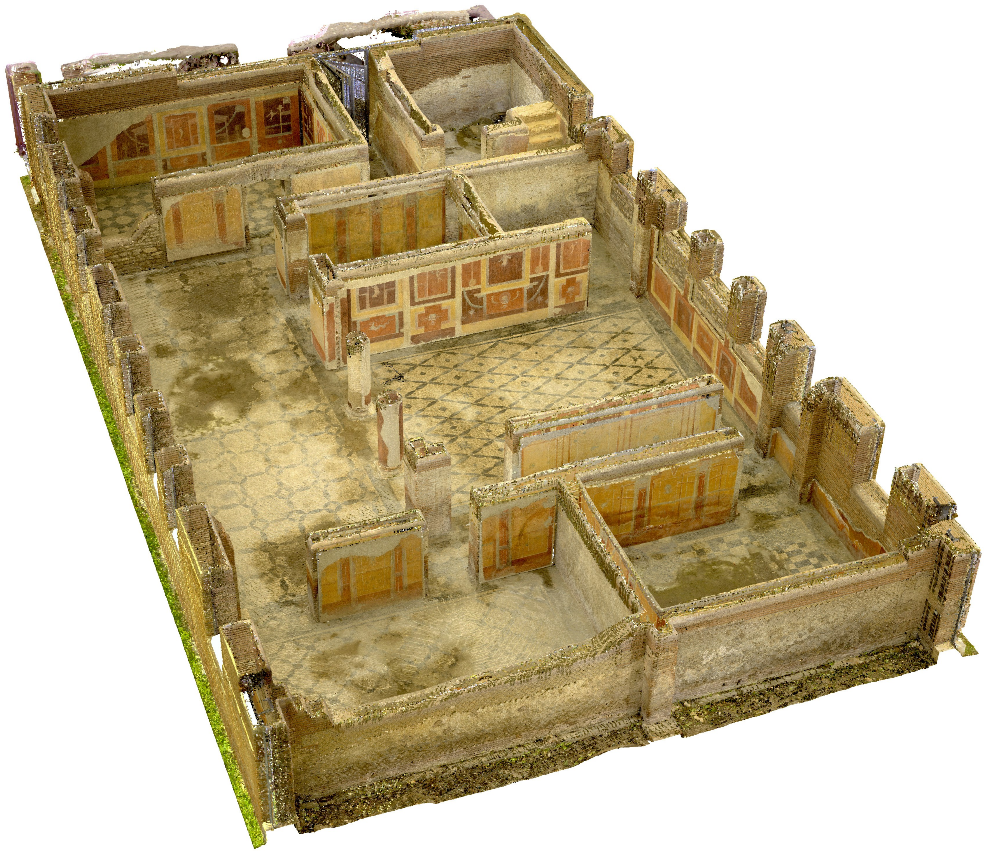

Figure 1. Three-dimensional documentation of the House of the Priestesses in Ostia as of today.

In addition to the 3D documentation, a wide range of primary and secondary sources was evaluated prior to the actual modelling. These included information from the literature (e.g., Falzone and Pellegrino [17]), survey data, photogrammetric recordings, room by room documentation [14], archival material [18], excavation reports (e.g., Pavolini [19]), and our own survey and documentation work, which were taken into account for the reconstruction. On that basis, a georeferenced reconstruction model of the House of the Priestesses was developed, including a simplified representation of the solar obstructions formed by the other building blocks of the insula (Figure 2). The simplified reconstruction of the whole insula is conceptually based on the reconstruction drawing by M. A. Riccardi [17] (p. 36 Figure 20).

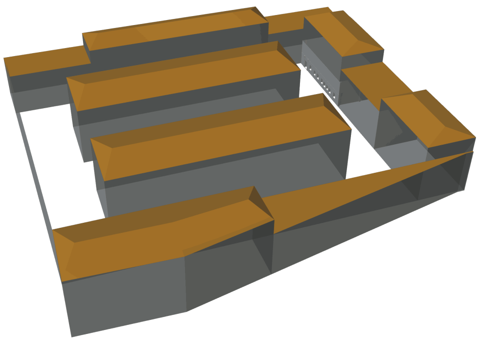

Figure 2. Geometric reconstruction of the unit and occluding buildings.

As in most cases of ancient residential architecture, the state of preservation of the House of the Priestesses (Figure 1) requires the reconstruction of large parts of the building's geometry. The room height was reconstructed according to Falzone and Pellegrino [17] (p. 33), respectively Stevens [20] (p. 116 with note 20). The existence of inner and outer staircases indicates that the apartment was two-storied. The ground floor, with the exception of the kitchen and the inner staircase, had a primarily representative character; the private rooms and probable further service rooms are to be assumed on the upper floor, which makes a further room subdivision conceivable [21] (p. 267) and [22] (p. 31). Since all the preserved walls show equal thickness, no well-founded statement can be made about the room layout on the upper floor. Likewise, the literature postulates for representative rooms to be sometimes of double height [13] (p. 116), [23] (pp. 151–153) and [22] (pp. 118, 119). Therefore, in the reconstruction model, the so called tablinum opening onto the medianum with a colonnade is modelled as a two-storied room [24] (p. 166), whereas the rest of the upper floor, due to the considerable uncertainties, was not integrated in the simulation model but by its outer walls.

All window openings and doorways are only preserved in their bare brickwork dimensions, and whereas the width of every opening is given, their height is mostly unknown. Here, the reconstruction had to be drawn upon comparable and better-preserved building remains and adapted to the actual conditions in the House of the Priestesses [25]. It is assumed that the windows featured glass panes, and that frames and glazing bars covered a third of the window area.

Based on diffuse reflectance measurements of mosaic materials and different tones of wall paint, the reflectance values of the building surfaces in the House of the Priestesses are set to an average of 0.20 for outer walls and roofs, 0.15 for inner walls and ceilings, and 0.48 for the floor. Diffuse reflectance—a unitless quantity in the range 0.0 (no reflection) to 1.0 (all incident light is reflected)—was measured from calibrated photography [26] (pp. 674–675). Applying such measurements to reconstructions introduces error due to deterioration effects on the surfaces of archaeological finds, which are reflected by light-scattering characteristics [27]. The measurements on wall surfaces addressed this by aiming at wall surfaces in good condition, and where they were applied to the reconstruction of the ceiling that had not been preserved.

The reconstruction model maps the building's topology (insula, unit, storey, room, building element) to a hierarchical layer structure. The approach is applicable to any edifice and guarantees that each element of the geometric model can be allocated a specific material with a specific reflectance value. A further differentiation of both, the geometry and the surface properties, is possible at any point in the project. At the same time, the developed structuring of the reconstruction model allows an automated transfer of the model into the simulation engine for further processing.

Finally, the model is exported in a WAVEFRONT OBJ format. The nested layers transporting information about the building, storeys, rooms, and surface types are flattened and become group names that organise the exported geometry.

2.2. Zonal Daylight Simulation and Application of Illuminance-Based Metrics

The initialisation of the simulation starts with interpreting the OBJ file holding the reconstruction model. Surface types are mapped to reflection properties, and evaluation planes are produced from the floor areas of the model. Attributes such as room numbers and the geographical reference are maintained. When the definition of all referenced material properties is confirmed, a simulation model in the RADIANCE scene description language is produced. To test the success of the import, imagery for a sequence of views is generated for each zone (Figure 3), allowing preliminary visual checks on the model import. This is of particular importance, since model errors can be difficult to spot later in averaged spatio-temporal metrics.

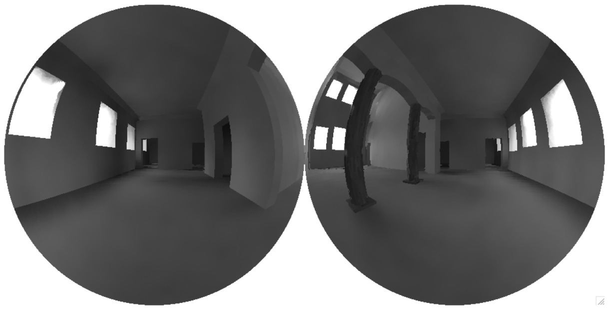

Figure 3. Imagery for one view point in the evaluated rooms to test model integrity.

To produce representative results for the local climate conditions, the simulation employs a weather file for a typical meteorological year. Since no such records exist for antiquity, data based on modern observations at Rome are employed. This assumes that the sky conditions have not significantly changed over the centuries.

In the presented case, lighting conditions are simulated at three levels. The samples distributed on the levels approximate sensor positions and directions of interest. Positions close to the rooms' boundary surfaces tell us more about the illumination of the latter and—when combined with their reflectance—their apparent brightness. The same applies to imagery surfaces, e.g., a working plane constituted by furniture that has not been preserved. Positions in the rooms' volume inform us about the eye illuminance, i.e., the overall brightness of a view to a given direction. A height of 1.50 m corresponds to the eye level of a standing building occupant. At a level of 1.00 m, the illuminance on horizontal surfaces such as desks and counters is investigated, as well as vertical illuminance, a proxy for the illuminance that would reach, e.g., the eye of a half-lying person on a kline. A third evaluation plane is placed just above the ground at a height of 0.10 m.

For each level, an initial grid of viewpoints is generated by PHOS4DTOOLS, determined by the scale of the room to ensure sufficient resolution. Viewpoints are iteratively refined to adapt to the local variance of the annual distribution of incident sun- and skylight. At each viewpoint, a full 360° panorama is sampled by a sparse set of few view rays, chosen so that any image from the point can be reconstructed. This sampling strategy, adaptive over the spatial and temporal dimensions of location, direction, and sky condition, forms the core of the RAYTRAVERSE method and was initially developed for zonal glare assessment. The method also allows to derive, e.g., planar (e.g., horizontal and vertical), spherical, hemispherical, and cylindrical illuminance. A set of such illuminance measures was implemented in PHOS4DTOOLS. Finally, PHOS4DTOOLS resamples the locations to regular grids for each zone for easier processing.

The simulation results in a dataset spanning temporal (e.g., hourly time-steps) and spatial (e.g., locations) domains. Among the results are, e.g., the horizontal illuminance or the vertical illuminances from four directions at each location. Since seasonal and diurnal activity patterns are to be evaluated, and the month and temporal hours shall be maintained, the day of the month is reduced to percentiles (including the median). The result of this temporal data reduction is, for each metric and percentile, a table with a row of 144 metric values (12 months $\times$ 12 temporal hours) for each location. Further attributes are the area represented by each point, the identifier of the room containing it, and the coordinates in the chosen geographic reference system. These tables are exported by PHOS4DTOOLS as tab-separated values (TSVs) in text files.

2.3. Deriving Illuminance Thresholds from Visual Tasks

The metrics are assessed for correlations with requirements attributed to activities in an antique residential context. Modern norms, e.g., the European Standard EN 17073 "Daylight in Buildings" [28], cannot be applied to pre-modern buildings. They reflect the characteristics of electrical lighting (generous illuminance thresholds due to constant and almost unlimited availability, measurement of light from above on horizontal planes), space usage (supplementing electrical lighting during hours of occupancy to reduce energy demand, reducing contrast to avoid glare for office workers), and building practice (feasibility of large transparent facade areas providing daylight supply and view connectivity, systems to control glare and solar gains). Since little is known about requirements in terms of photometric quantities, the evaluation relies on fundamental considerations of the physiology of vision.

Distinguishing detail requires contrast. Human sensitivity to contrast is not constant but increases with adapted background luminance up to approx. $3\,\mathrm{cd\,m^{-2}}$, assuming an object contrast of 50% and a resolution of 8.8′ [29] (p. 66). Assuming a minimum luminance ratio of 1:5 and a typical reflectance of 0.20, an illuminance of about 50 lx provides conditions where contrast can be sufficiently well perceived.

Contrast information is complemented by colour, a reported requirement for practically all activities that involve visual tasks. Compared to contrast, the luminance threshold for photopic vision, which enables good colour vision, is set significantly higher at approx. $10\,\mathrm{cd\,m^{-2}}$ [30] (p. 81) and [31]. Assuming again a typical reflectance of 0.20, a minimum illuminance of 160 lx is required on the viewed object.

The proposed thresholds do not represent sharp separations. They rather approximate the point where good contrast and colour vision start to gradually decrease. An illuminance well below 160 lx could, for example, still support mesopic vision, hindering but not prohibiting colour differentiation.

2.4. Evaluation within a Geographical Information System

The computed metrics tables are imported into a GIS database as non-spatial attributes of point entities. Since these are chosen to ensure a minimum number of locations per room; they represent areas of different sizes, depending on their density (Figure 4).

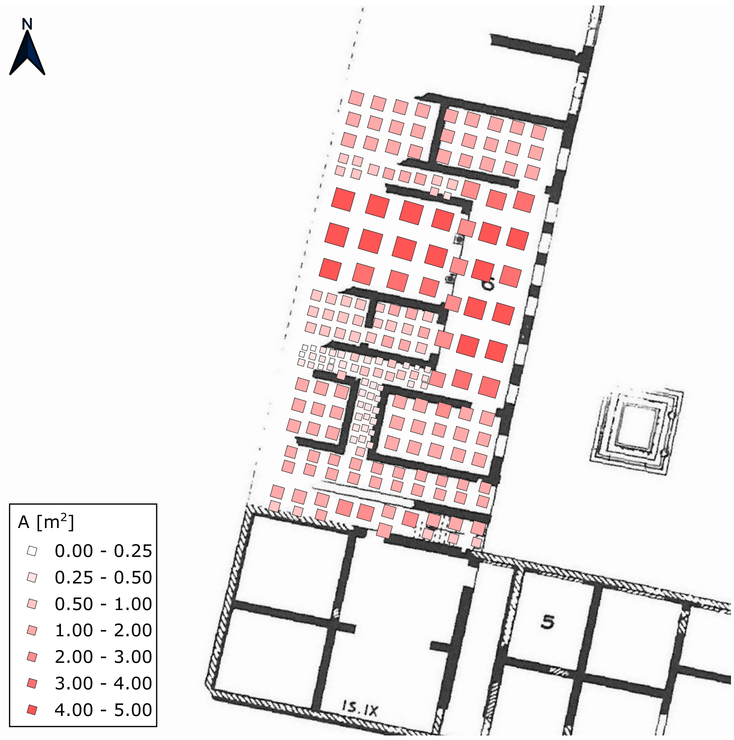

Figure 4. Areas represented by the adaptive sampling (basemap by Cervi [12]).

Since the geometry inherits the projected coordinate system from the reconstruction model, the tables can be directly loaded into the GIS. The interface between simulation and GIS is implemented in QGIS[3] by importing the TSV files exported by PHOS4DTOOLS. Each table becomes a layer in QGIS. Stored in a POSTGIS[4] schema, it is shared and accessible to other researchers with access to the GIS database. While the ESPG:3004 [32] reference was used to align the research with local practice in Ostia, the data could be transformed into a European UTM-based coordinate system, e.g., to combine it with other sources.

Besides physiological thresholds for contrast and colour vision, the spatial and temporal positioning of activities provides clues about the feasibility of daylight conditions in a room. While most activities in permanently inhabited residential buildings can be assumed to be seasonal invariants, they are part of a diurnal behavioural pattern. In pre-modern times, these typically followed a temporal segmentation of the time between sunrise and sunset into equal temporal hours: longer in summer and short in winter. Figure 5 illustrates the variable length of temporal hours as red lines, which divide daytime (vertical axis) into twelve periods of equal lengths, changing with the day of the year (horizontal axis).

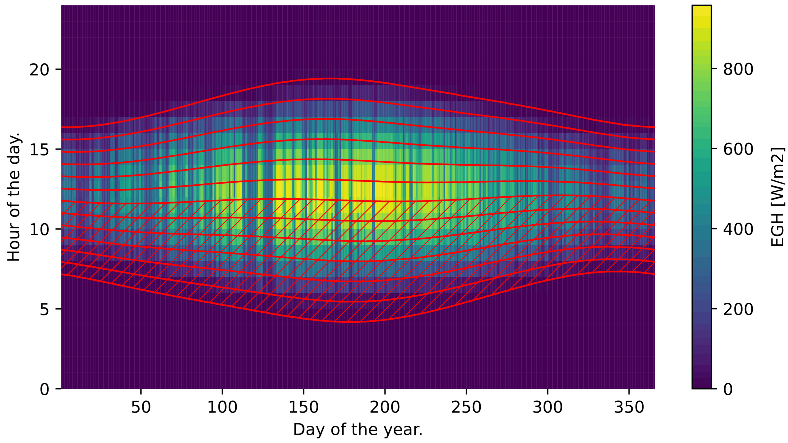

Figure 5. Temporal daylight hours (vertical distance between red lines) and exemplary evaluation period (hatched) overlaid on a heatmap that illustrates the exterior global horizontal irradiance (EGH).

The evaluation of lighting conditions for a specific activity has to choose a time frame within these diurnal and seasonal dimensions. In this research, this is demonstrated by the hypothetical attribution of activities to periods only to demonstrate possible applications of the method. Dressing and personal hygiene are examples for such activities that might be attributed to the morning hours and impose visual requirements. For personal hygiene, for example, the entire first half of the day would be considered (hatched in Figure 5, while dressing would be expected to happen only in the first hours. Other activities are expected in later hours of the day, with dining and related activities such as serving food and cleaning being obvious examples.

In many cases, a view direction close to horizontal appears plausible, and the orientation around the vertical axis may be variable and potentially chosen for the best daylight conditions unless constrained by fixed installations. This is translated to the evaluation of the maximum of the four illuminances received from orthogonal directions. Assuming a standing person, an eye level of 1.50 m is evaluated. In other cases, when activities are related to horizontal work planes, such as desks or counters, horizontal illuminance may be evaluated.

The zonal simulation data in the GIS table allow the combined evaluation of all the stated requirements—illuminance thresholds, seasonal and diurnal periods, and orientation and elevation of the illuminated surface. This is implemented by filtering the results for the defined period. When activities are not constrained to a certain direction, the maximum vertical illuminance from four directions is picked, assuming that one chooses a favourable orientation when possible. For each location, this produces one value per seasonal and diurnal period (month and temporal hour).

3. Results and Discussion

Figure 6 maps the typical (median) horizontal illuminance at an imaginary work plane of 1.00 m during the first six temporal hours of all days in the month with the lowest daylight availability. Figure 7 contrasts this with the maximum vertical illuminance out of the four orientations at eye-level. It is obvious that high values for horizontal illuminance up to 1600 lx occur in small areas directly beside windows, while most of the evaluated zone receives less than 100 lx.

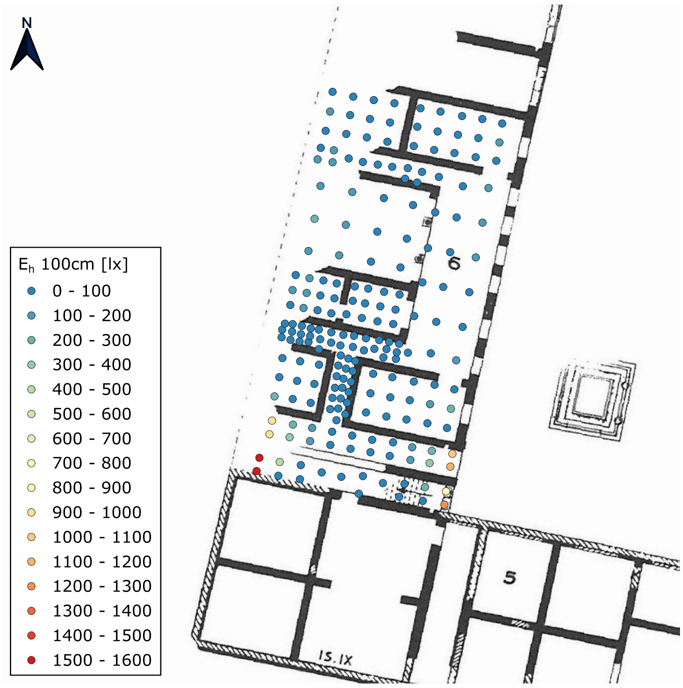

Figure 6. Median horizontal illuminance at 1.00 m during the first six temporal hours of all days in the month with lowest daylight admission (in lx, basemap by Cervi [12]).

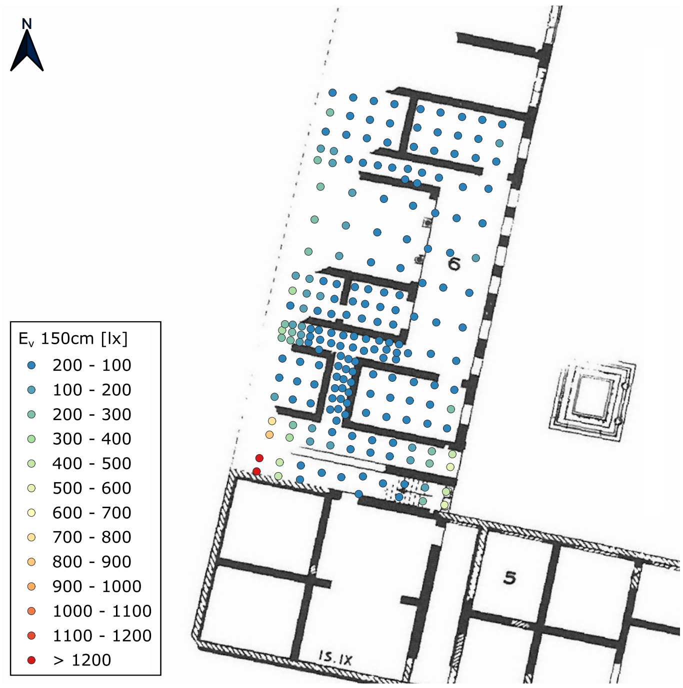

Figure 7. Median vertical illuminance at 1.50 m height duringthe first six temporal hours of all days in the month with lowest daylight admission (in lx, basemap by Cervi [12]).

Figures 8 and 9 are the results of the applications of the illuminance thresholds (of 50 lx for contrast, and 160 lx for colour vision) to the median horizontal and vertical illuminance values shown in Figures 6 and 7. According to these, contrast vision is typically supported by most of the rooms, while optimum colour vision is possible only along the (in the model unobstructed) west facade and in the immediate proximity to some of the apertures in the east. Comparing Figures 8 and 9 suggests that activities with requirements for contrast, and even more colour perception, are performed better close to windows(or door) openings if performed on horizontal surfaces. The area where vertical illuminance (under the assumption of a favourable orientation toward the daylight aperture) exceeds the threshold for contrast and even colour vision is slightly larger and covers the entire medianum.

The discussed typical daylight conditions obfuscate the fact that even areas, where the median illuminance may not support a given visual task, may offer favourable conditions at particular times of the day. Figure 10 describes the fraction of the assumed period (first six temporal hours) in which daylight affords colour vision on a vertical surface for the poorest performing month. It turns out that the west-oriented rooms that have more than one window pointing toward the outside consistently provide the required illuminance over at least half of the six evaluated temporal hours and more than the east-oriented rooms, particularly regarding the east-oriented rooms at the north and south of the medianum, which feature only one window each. These provide sufficient illuminance only directly beside the windows. Surprisingly, at first, the higher daylight availability in the morning hours at west-oriented rooms may be explained by the unobstructed view to the sky, which contributes most of the vertical illuminance but is obstructed by the insula's buildings at the east side. This, however, raises questions about potential obstructions at the west of the building that cannot be fully excluded based on the state of research.

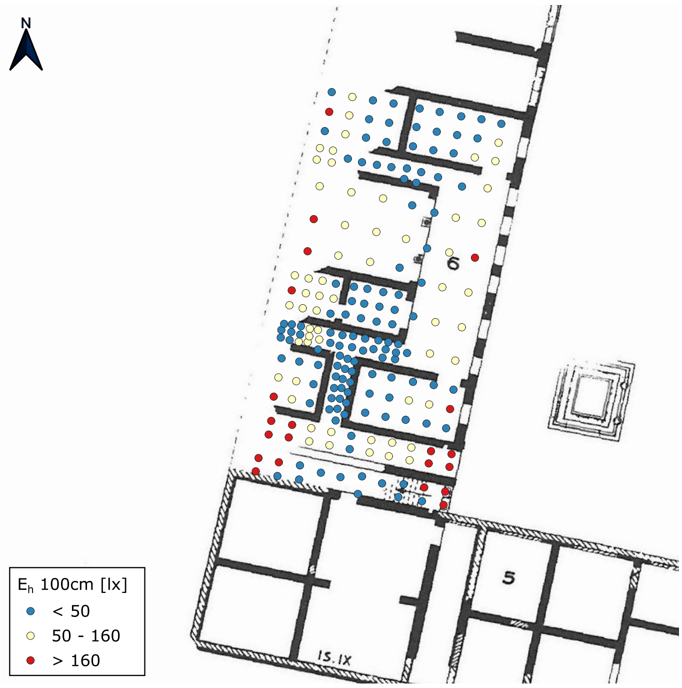

Figure 8. Annual daylight conditions by thresholds for contrast and colour vision on horizontal surfaces at 1.00 m height during the first half of the day in the month with lowest daylight admission (basemap by Cervi [12]).

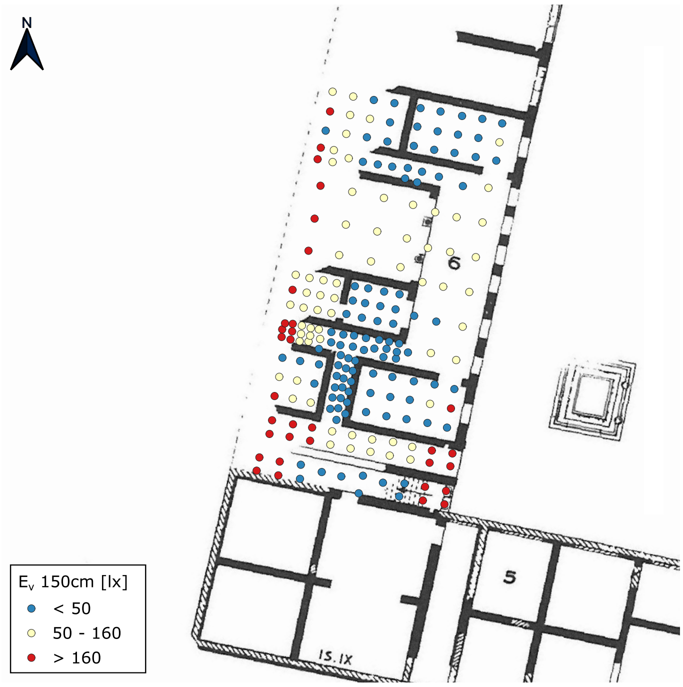

Figure 9. Annual daylight conditions by thresholds for contrast and colour vision on vertical surfaces at 1.50 m height during the first half of the day in the month with lowest daylight admission (basemap by Cervi [12]).

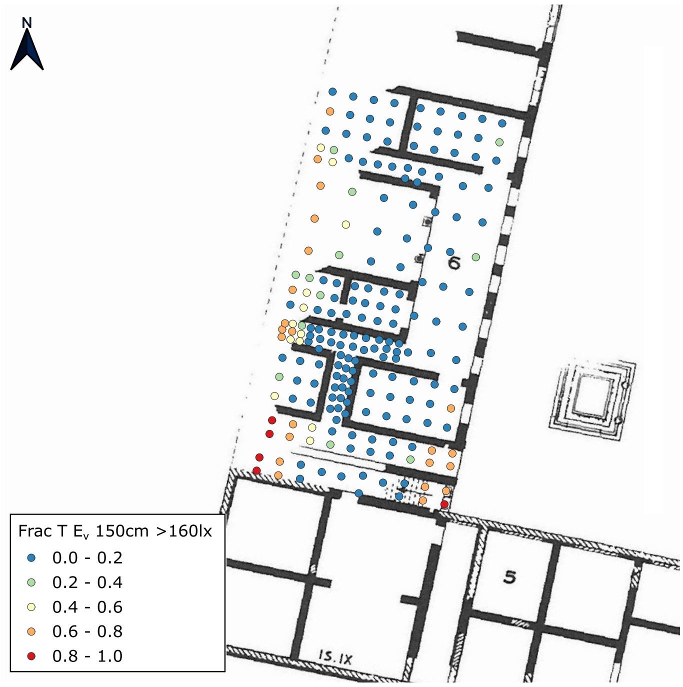

Figure 10. Annual daylight conditions supporting colour vision on vertical surfaces during the first half of the day in the month with lowest daylight admission (unitless fraction of time in the range 0.0 to 1.0, basemap by Cervi [12]).

4. Conclusions and Outlook

This paper outlines how a digital process chain can support interdisciplinary cooperation between archaeologists, historic building researchers, and lighting engineers to help understanding ancient residential buildings. Based on a reconstruction and necessary assumptions, PHOS4DTOOLS allows to evaluate which activities are afforded by particular rooms. The differences in the spatial distribution of vertical and horizontal illuminance raises the question whether activities requiring horizontal surfaces had precedence in the building perimeter, where high horizontal illuminance is received. Furthermore, the presented method quantifies the lighting conditions under which activities took place, or the requirement of complementary artificial illumination. The domain-specific metrics implemented in PHOS4DTOOLS suit such evaluations and can be further developed.

The capability of the method to produce a GIS layer representing a set of zonal daylight metrics that can be overlaid with other, spatial research data was demonstrated. The first results show the potential to integrate daylight metrics in future interdisciplinary research. Relying on open and well-documented GIS standards further opens a robust path to archiving and reusing daylight simulation data, which align with practical applications in historical research.

A possible extension of GISs' integration to maintain the temporal dimension of simulation results is currently being investigated. This would make it possible to develop data-processing workflows, such as the formulation and application of metrics, entirely within the GIS environment. This would allow us to overcome one more difference between the realms of simulation and historical research.

The main limitation of the method is its dependency on a complete reconstruction model and assumptions on conditions such as sky conditions in the past, but also on behaviour such as the opening and closing of doors and shutters. Here, the method relies on plausible inputs from other sources. Systematic research addressing these unknowns in the model setup is proposed to leverage the potential of simulations in archaeology and historical building sciences.

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Data Availability Statement: The simulation environment PHOS4DTOOLS is distributed under an open source license at https://igit.architektur.tu-darmstadt.de/phos-4d/phos4dtoolss (accessed on 16 October 2024). Simulation results for Ostia are published as GeoPackage datasets under an open-access license at https://zenodo.org/doi/10.5281/zenodo.11526919 (accessed on 16 October 2024).

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Conflicts of Interest: The authors declare no conflicts of interest.

Notes

1. https://pypi.org/project/raytraverse/ (accessed on 16 October 2024), latest documentation https://raytraverse.readthedocs.io (accessed on 16 October 2024)
2. The 3D documentation is a result of the project "The 'Case a Giardino' in Ostia—archaeological context and virtual archaeology"—which was conducted by the Austrian Academy of Sciences and the Austrian Archaeological Institute between 2019 and 2022 and supported by the Austrian Science Fund (FWF, #P31438) [14].
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