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PARTICLE – Participatory Lighting Design in Urban Environments Using AR/VR Technologies

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Abstract **The PARTICLE tool is a hardware and software system that facilitates collaborative and immersive co-design processes for environmentally-sound outdoor lighting in urban spaces. Using an interactive touch table, VR headsets and AR tablets, participants can adjust lighting scenarios in real time and experience their effects on light pollution or visual comfort. This paper investigates how such immersive, multi-modal visualization changes the way non-expert stakeholders assess lighting scenarios compared to conventional, abstraction-based presentation formats. The system allows several people to work on the same scenarios simultaneously across different locations. As part of the EU Interreg North Sea Programme DARKER SKY, PARTICLE was developed from a predecessor project, PaKoMM, and successfully used for two pilot projects in the Borough of Altona in Hamburg. This paper presents the co-design concept, the system architecture and the findings from the workshop processes involving a broad network of stakeholders.**

Keywords— participatory lighting design, co-design, urban planning, augmented reality, virtual reality, digital twin, light pollution, DARKER SKY

I. INTRODUCTION

Artificial light at night (ALAN) is increasingly recognized as a challenge for both biodiversity and human well-being. Recent reviews highlight ecological impacts on species' behavior, ecosystem functioning and urban nightscapes, while emphasizing the need for evidence-based lighting strategies [1].

Lighting in public spaces is far more than just an infrastructural necessity: it shapes the sense of visual comfort and wayfinding for pedestrians and cyclists, influences ecosystems and biodiversity, and accounts for significant energy consumption [2]. At the same time, lighting design is a highly technical field – involving standards, complex regulations, and specialized simulation tools with technical vocabulary that presents barriers to non-specialists [3].

The result is that participatory processes in urban lighting planning often fail not because of a lack of will or knowledge on the part of experts, but due to structural barriers. The public is largely unfamiliar with the subject; stakeholders do not immediately recognize the added value of good lighting; decision-making processes within local authorities are complex; and the staffing capacity in local councils for comprehensive participatory procedures is constrained.

The hardware and software tool PARTICLE (Participation, AR, Reality, Transparency, Interaction, Co-Design, Lighting, Enlightenment) addresses these challenges with an innovative approach: an immersive, multi-modal co-design system that conceals technical complexity, enables intuitive interaction and supports cross-location collaboration in the context of outdoor lighting. PARTICLE was developed as part of the EU Interreg North Sea Programme DARKER SKY and tested in Hamburg.

This paper examines how immersive, multi-modal visualization changes the way non-expert stakeholders assess lighting scenarios compared to conventional (illuminance-map-based) presentation formats.

II. PROJECT BACKGROUND: DARKER SKY

DARKER SKY is a transnational project under the EU Interreg North Sea Programme, involving 13 partners from four countries, with a total budget of €4.2 million and ERDF co-financing of €2.5 million (April 2023 – October 2026). The aim is to reduce light pollution and develop environmentally-sound lighting infrastructure at eight demonstration sites in municipalities close to the North Sea [4].

The project structure follows a three-phase approach: (1) Framing – analysis and conceptual framework; (2) preparation, installation, testing and evaluation of pilot lighting systems; (3) roll-out and scaling of lighting solutions. Measurement methodologies for light pollution, sociological surveys and scientific monitoring accompany all phases.

The HAW Hamburg team is responsible, at a transnational level, for the lighting measurement methodology and the application of innovative AR/VR systems in participatory processes; locally, it provides scientific and technical support for two demonstration sites in the area of the Borough of Altona: the walking and cycling path 'Strandweg' and the area around the small road 'Bullnwisch'. As support for the Borough of Altona team, HAW Hamburg is undertaking the evaluation of the lighting installations and developing the PARTICLE framework to assist the co-design processes [5].

III. Pilot Projects in Hamburg-Altona

A. Strandweg

The Strandweg is a section of a popular European cycling and walking route along the River Elbe, which is heavily used and situated in an ecologically sensitive location on the riverbank. The focus here is on striking a balance between road safety and minimising environmental impact.

A particularly detailed digital twin has been created for the Strandweg, which also considers and allows for the assessment of the dense tree cover and the water surface of the River Elbe, as well as the light pollution from industry on the opposite bank. In the VR experience, users can virtually explore and evaluate various scenarios – ranging from reduced, minimal lighting to lighting adapted to high usage levels – under different weather conditions and at different times of day.

B. Bullnwisch

The small road Bullnwisch on the outskirts of Sülldorf in Hamburg-Altona is a typical example of a lighting system in need of improvement. As part of the DARKER SKY project, the old lighting infrastructure was replaced with adaptive warm white LED luminaires capable of adjusting colour temperatures from 3000 K to 2200 K. At the same time, by increasing the number of light points on existing poles whilst maintaining the total luminous flux, a significantly higher degree of lighting uniformity was achieved. The aim was to enhance biodiversity compatibility while maintaining visual comfort, which is supported by a uniform, non-glary lighting, that allows wayfinding and see surroundings effectively.

The before-and-after documentation of the lighting installation at 'Bullnwisch' (Fig. I) clearly shows the change in light quality: the warmer colour temperature is the result of a reduced proportion of short-wavelength light in the blue spectrum, which is generally considered beneficial for insects and nocturnal mammals.

Fig. I Pilot project 'Bullnwisch'; Left: Old installation before modification, warm white at 3000 K light but low uniformity at street level; Right: New installation after modification with warmer coloured light at 2200 K and high uniformity at street level (Photos: C. Liedtke)

Light measurements taken before and after the retrofit in 2024 documented the illuminance and correlated colour temperature values of both installations and validated the design objectives. In detail, the lighting has changed from a static illumination (not dimmable, fixed correlated colour temperature 3000 K) to an automated switched and dimmed illumination depending on the time of day and year. The luminous flux of the installation did not change during the modification, but instead of 3 poles used for the lighting, 5 poles with a shorter distance from each other were equipped, each with a lower lumen output. This supported to raise the uniformity of the lighting on street level significantly – which is a requirement in street lighting standards - while the average illuminance slightly increased from 3 lx to 4 – 5.5 lx). During the vegetation period from March to November, the lighting is dimmed down (from 5.5 lx to 4 lx average illuminance) in the night hours (appr. after 10 and before 5 o' clock, depending on the time of year) at 2250 K CCT. In the winter period CCT 3000 K is used in general, while keeping the dimming down in night hours (same levels as in summer).

IV. Challenges in Responsible Urban Lighting Design

Practical experience reveals recurring structural barriers to genuine participation in lighting planning when applying a comprehensive approach to achieving responsible urban lighting design. Obstacles identified during the DARKER SKY project can be grouped into four categories:

A. *Lack of public awareness*

For most people, lighting only becomes an issue when it causes a complaint. Its negative environmental impacts are not widely understood, nor can they be properly assessed in relation to other forms of pollution [2]. The positive aspects – environmentally friendly lighting (e.g. sensibly directed, shielded, warm white, adaptive) – and its benefits for people and the environment are scarcely known.

B. *Complexity for stakeholders*

Even experts – administrative representatives, transport planners, nature conservation officers – find it difficult to assess the consequences of different lighting concepts without visualization [3].

C. *Administrative complexity*

Coordination processes between authorities follow formal procedural channels that have so far made little provision for genuine co-creation. Policy screenings carried out as part of the DARKER SKY project confirm these structural challenges [6].

D. *Limited municipal resources*

Staff available for extensive public engagement processes or the evaluation of alternative options are limited. Tools that enable efficient and high-quality civic engagement are therefore essential for holistic urban lighting planning, rather than mere conveniences.

V. Co-Design Stages for Lighting Design

PARTICLE employs a phased co-design strategy that combines analogue and digital participation formats into a hybrid approach [7]. The four stages follow a progression from physical presence to full digital immersion.

A. *Analogue – On-site workshop:*

The process begins with traditional on-site participatory formats: site visits, scenario discussions and analogue mapping workshops. This phase serves to understand the planning area and identify stakeholders' needs at an early stage.

B. *2.5D – Interactive touch table:*

The touch table displays a 2.5D top-down view of the planning area – whilst simultaneously representing the perspective of a human observer – on a very large wall-mounted monitor, and allows users to manipulate light sources, colours and intensities via multi-touch [8].

C. *3D AR – Augmented Reality:*

AR tablets superimpose the planned lighting onto the real-world camera view of the planning site – particularly suitable for on-site workshops where spatial orientation within the real-world context is crucial.

D. *3D VR – Virtual Reality:*

VR headsets enable immersion in the digital twin of the planning area. Participants can virtually walk along a street or cycle path and experience different lighting scenarios with a sense of spatial depth. Multi-user VR allows several people to be present in the same virtual space at the same time [9].

One or more formats can be used for a single planning task, either with the same users or as part of a multi-stage process.

VI. The PARTICLE Tool

A. *System architecture*

The technical foundation is a shared, physics-based digital twin of the planning environment, created from survey data, 3D photogrammetry and GIS information. The lighting visualization adheres to real-world lighting specifications, e.g. colour temperature in Kelvin, luminous intensity distribution curves (LDC).

In the urban and built-environment context, a distinction is commonly made between a digital model (no automated data connection between the physical and virtual counterpart), a digital shadow (automated, one-way data flow from the physical object to the digital model), and a digital twin in the narrower sense, which establishes a bidirectional feedback loop between the virtual and the physical environment [10]. The representations used in PARTICLE are created once from survey and photogrammetry data and subsequently updated manually when the physical lighting infrastructure changes; they therefore correspond most closely to a digital shadow, while the term "digital twin" is retained here in its broader, commonly used sense as a high-fidelity spatial replica used for simulation and co-design.

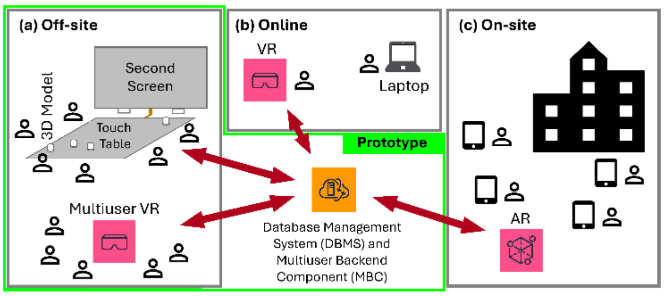

Fig. II PARTICLE's system architecture: (a) off-site setup with a touch-screen table and multi-user VR, (b) online access via VR and laptop, (c) on-site use with AR tablets. All components are connected via DBMS and MBC. (Image: [3], Fig. I, font size changed by authors)

All end devices – touch tables, VR headsets and AR tablets – are connected via a central database management system (DBMS) and a multi-user backend component (MBC), as shown in Figure II. Changes are transmitted in real time, enabling simultaneous co-creation across different locations [5].

B. Digital twins of the DARKER SKY pilot sites

High-resolution digital twins were created for both pilot sites in Hamburg. The ‘Strandweg’ at the river Elbe (see Figure III) and the small street Bullnwisch (see Figure IV) in Sülldorf – both located in Hamburg-Altona were captured using photogrammetry and integrated into VR and touch-table environments.

FIG. III VR-SCREENSHOT OF THE HIGH-RESOLUTION DIGITAL TWIN OF THE ‘STRANDWEG’ PILOT PROJECT (IMAGE: B. ASSIG, SHAPESHIFT)

FIG. IV VR-SCREENSHOT OF THE HIGH-RESOLUTION DIGITAL TWIN OF THE ‘BULLNWISCH’ PILOT PROJECT (IMAGE: B. ASSIG, SHAPESHIFT)

VII. STAKEHOLDER NETWORK AND CO-DESIGN PROCESS FOR THE DARKER SKY HAMBURG PILOT PROJECTS

A. Stakeholder mapping

A key first step was the systematic identification of all relevant stakeholder groups [11]. The network comprises local authorities, transport and environmental associations, user groups (cyclists, pedestrians, residents, tourists) and the operator of the lighting infrastructure, which in Hamburg is the public utility company 'Hamburg Verkehrsanlagen' (HHVA).

In a second step, the stakeholders were grouped into clusters to enable specific issues to be addressed in a more targeted manner, using the most appropriate format in each case (depending on time constraints, local availability, etc.).

Both the overall overview and the breakdown into clusters are important resources within the overall process and serve, following each participation format, to reflect on intermediate results and plan further activities.

As the participation activities progress, the PARTICLE tool itself is evaluated by the participants at each stage and subsequently further developed directly by the researchers, with implementation carried out by third parties.

B. Evaluation Method

To assess how the immersive, multi-modal visualization approach affects stakeholder engagement with lighting scenarios, the co-design workshops were accompanied by a structured evaluation. Participants were drawn from the stakeholder clusters identified in Section VII.A, comprising representatives from local authorities, transport and environmental associations, and members of user groups (cyclists, pedestrians), for a total of 21 participants across both workshops.

Feedback was collected through semi-structured group discussions and moderated plenary feedback rounds], focusing on three dimensions: (1) usability of the PARTICLE tool itself, (2) perceived comprehensibility of the lighting scenarios compared to conventional illuminance-map presentations, and (3) acceptance of the proposed lighting solutions with respect to safety, visual comfort, and environmental impact. Where relevant, feedback was analysed separately by stakeholder group to identify differences in assessment between, for example, technical experts and lay participants.

The AR/VR model itself has not yet been validated, against physical installation. An on-site comparison of luminance and illuminance values, as well as participant cross-checks, are planned in future steps.

C. Workshop Process

At the heart of the development and application of the PARTICLE tool are facilitated co-design workshops that combine in-person participation with digital immersion. In spring 2024, the first major workshop, ‘Sustainable Lighting Strategies for Altona’, took place [12], followed in autumn 2024 by the second workshop, ‘Cyclists’ and Pedestrians’ Perspectives on Environmentally-Sound Lighting Planning’, organised in cooperation between the Altona Borough Office and HAW Hamburg [13].

Fig. V Left: Co-design workshop with a touch table (2.5D). Workshop at HAW Hamburg, May 2024 (Photo: R. Greule / DARKER SKY), Right: Participants join simultaneously the PARTICLE Online mode via VR glasses, September 2024 (Photo: A.C. Mosler)

The workshops followed a phased programme: an introduction to the planning area and the objectives (analogue), joint scenario development at the touch table (2.5D), an immersive site visit using a VR headset (3D) and a concluding evaluation discussion in a plenary session. Feedback collected during the workshops suggests that this phased approach was well received: participants confirmed that the physical introduction helped them familiarize themselves with the planning area before digital tools were introduced.

A key factor in the process was the user-friendly nature of all the tools. Even participants with no prior technical knowledge were able to operate the touch table, with its intuitive multi-touch controls, independently after a brief introduction.

VIII. Discussion

A. *The benefits of the co-design approach*

PARTICLE demonstrates that immersive technologies can substantially break down communication barriers in participatory urban planning. Three mechanisms of impact are particularly worth highlighting:

- Experiential engagement rather than abstraction: Whilst conventional presentations using illuminance maps require abstract specialist knowledge, the immersive walkthrough of the digital twin enables a direct sensory experience. Participants can directly evaluate how a change in lighting affects the perception of safety or the atmosphere along a route.
- Shared reference object: The digital twin creates a shared artefact to which all stakeholders – planners, representatives of public authorities and members of the public – can refer simultaneously [3]. This significantly accelerates iterative decision-making processes.
- Location-independent collaboration: PARTICLE's network architecture enables stakeholders in different locations to participate simultaneously – particularly relevant for external specialist planners or regulatory authorities.

B. *Limitations and outlook*

Challenges lie in the scalability of digital twins: their creation requires specialised GIS and 3D expertise, as well as a considerable investment of time. Future steps aim to achieve automated or semi-automated twin generation from open data sources (OpenStreetMap, official geodata) [14].

The assessment module is to be expanded to include acoustic parameters, glare estimates and more detailed biodiversity indicators.

The perceived safety of the new lighting solutions was outside the scope of the present pilot projects and has therefore not yet been systematically evaluated; this is planned as a subject for future assessment.

PARTICLE highlights the close interconnection between lighting design and urban mobility: visual comfort at night, orientation in the street environment and the appeal of active mobility depend significantly on the quality of the lighting.

IX. Conclusion

The PARTICLE system demonstrates how digital twins and immersive AR/VR technologies can be integrated into a comprehensive co-design process to substantially improve participatory urban planning. The multi-stage strategy – ranging from analogue on-site workshops through to interactive touch-table scenarios and VR and AR immersion – caters for different user profiles and levels of abstraction within a unified system.

While shared visualization has already been shown to support collaborative participation settings [3], and the underlying system architecture builds on prior work [5], PARTICLE extends these contributions by combining touch-table, AR, and multi-user VR modalities within a single, real-time-synchronized system that allows stakeholders at different physical locations to co-create using the same lighting scenario simultaneously.

The pilot projects in Hamburg-Altona, carried out as part of the DARKER SKY initiative, demonstrate the practical viability of this approach. PARTICLE is not an isolated tool, but an integrated process-based approach that combines technical innovation with social science expertise in participatory planning, thereby contributing to the democratisation of complex planning processes.

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