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XR Smart Environments Design and Fruition: Personalizing Shared Spaces

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Abstract. The rise of urbanization, overpopulation, and resource depletion in recent years has triggered interest in developing more efficient solutions that could offer sustainable development and improve the quality of life in cities. The increasingly wider and more advanced availability of computational power throughout the anthropic space—which saw the emergence of the so-called "ubiquitous computing" paradigm—has opened new possibilities for the design of smart cities. In particular, the emergence of Extended Reality technologies (XR), such as Virtual Reality and Augmented Reality, has provided a new interface to bridge the gap between the physical and digital realms, enabling immersive experiences and interactions within Smart City environments. This paper, based on three case studies at different scales of smart environments, explores the current and prospected relevance of XR to both design and experience spaces enriched and characterized by layers of digital information and sensorial interactions.

Keywords: Ubiquitous Computing · Smart City · Smart vehicle · User Experience · Extended Reality

1 Introduction

The increasing individual use of connected smart devices, the rapid growth of the worldwide urban population, the gradual ageing of society in many countries, and the rising demand for sustainable energy resources have encouraged the research about Smart Cities and smart spaces [1]. However, even though the Smart City concept is an advanced solution for recent cities, the practical opportunity for smart cities is still to be revealed due to the different development of technology in various cities. Extended Reality (XR) has the potential to replicate or simulate the experience of smart cities and product-service systems [2], thus also helping future Smart City planning. This paper explores how XR technologies can support smart space design and fruition by providing three case studies.

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2 Background Frameworks

2.1 Extended Reality

Extended Reality. (XR) is a term that encompasses several technologies, including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). To define XR, one must first understand what Milgram et al. [3] call the Reality-Virtuality Continuum to facilitate a better understanding of AR, MR, and VR and how these concepts are interconnected.

The continuum has two extremes: the fully real world and the fully virtual environment, i.e., Virtual Reality (VR). Everything in between, excluding the extremes, is defined as Mixed Reality (MR) [4]. Different types of MR can be defined differently depending on the degree of immersion and the mix between the virtual and real environments. In this fluid category, we can find technologies defined as Augmented Reality (AR, a mostly real environment augmented with some virtual parts), Augmented Virtuality (AV, a fully or partially immersive virtual environment to which a certain amount of reality is added), Mediated Reality [5] (XY-R, which refers to a technology that transforms reality for a specific purpose, for example, allowing color-blind people having a more accurate view of the environment) or Diminished Reality [6] (DR, which refers to the removal diminishing of real-world physical objects from users' perception). Thus, this definition shows that VR is not part of MR, and AR is only a subset of MR.

In the most recent publications, XR is defined as the combination of VR and all technologies referring to MR.

2.2 IoT, Ubiquitous Computing, and Smart City Design and Fruition

Internet of Things (IoT) is the concept of connecting everyday objects to the internet and enabling them to communicate and interact with one another, which is in turn powered by real-time digital connectivity (Ubiquitous Computing, a.k.a. UbiComp) and increasing bandwidths and lesser latency. IoT has opened new opportunities to tackle the challenges and trade-offs that rapid urbanization and anthropization have been causing to the global environment.

One significant area where the application of XR can have a profound impact is the design and development of smart cities. The concept of Smart City is to develop, deploy, and promote sustainable development practices to address growing urbanization challenges via an intelligent city information system. Some key areas related to the development and fruition of smart cities are urban intelligent Cyber-Physical Systems (CPS), intelligent vehicles, as well as user experience.

Challenges and prospected issues - from ethical to legal to technical - are numerous, but it is worth devising a conceptual approach to help steer such technologies in directions that align with global goals such as sustainability, efficiency, and inclusivity [7, 8].

2.3 XR Integration

While some challenges and trade-offs shall be solved and addressed by a combination of various technologies which are not the focus of this paper, the well-thought use of

XR as the interface between humans - including urban planners and designers, as well as the public within the urban spaces at large - and the data-enriched space of CPSs can allow for more efficient use of resources, achieving more personalized spatial fruition while using fewer resources, thus making it possible to share spaces among different users, yet providing a more tailor-made and attuned experience to all.

A well-designed XR experience, powered by a real-time data flow and on-the-fly AI data analytics tools, could indeed exploit the multimodal capabilities to channel the multidimensionality of data collected from the smart environments and from other data sources, as well as their interpretation by AI, in the most personalized and hence effective way to every user. As a significant example thereof, the learning environments [9], where the impact of XR technologies on spatial perception and cognition cannot be underestimated: in this context, the unique learning abilities of each student can be considered, bridging the notions and the personal cognition [10–12].

The Human-in-the-Loop (HitL) paradigm [13], a recent approach to AI whereby the user is not a passive recipient of the technology but an active participant in the AI workflow and in the decision-making processes which might stem therefrom, aligns well with the immersive design of smart cities using XR. Based on HitL processes, an increasingly efficient, tailor-made, and user-centric smart city design can be achieved by integrating XR technology.

3 Case Studies

The case studies will introduce the applications of XR in planning smart cities. They include three fields of smart city design, such as urban planning, intelligent vehicles, and user experience.

3.1 XR for Urban Planning and Public Space Fruition

Within the framework of BASE5G—Broadband InterfAces and services for Smart Environments enabled by 5G technologies research project, proposed by a consortium of public and private actors, including various departments at Politecnico di Milano and nation-wide industrial partners, such as Vodafone, a test bed was set up to evaluate the use of XR in the urban public space, along with many other converging and enabling technologies, as a foundational technology for "smart environments" [14]. These environments encompass diverse areas such as urban spaces, campuses, and learning environments, but also private or shared enclosed spaces, as we will see in the next case study.

More specifically, within Work Package 2 – Smart City, Smart Campus – we tested a workflow centered on the urban area of the campus Leonardo of Politecnico di Milano, in Milan, Italy, to evaluate the effectiveness of XR in supporting urban planning and design decisions, but also to better grasp the potential of such technologies for the fruition of public space by users, given designing a more inclusive, yet more personalized and engaging spatial experience [15].

The main underlying idea about the XR experience we wanted to enable to both urban planning professionals, including policymakers, designers, and academics, as well as the public, was to allow for a varying degree of immersion, from basic augmented reality experiences using mobile devices to fully immersive virtual reality experiences using head-mounted displays, but also device-less experience which could nonetheless become personalized for the single user. In other words, the underlying idea was the creation of a sort of “plug-in” toolbox allowing a nuanced use of XR technology, with a varying degree of interaction depending on the specific user devices and needs.

The project involved the creation of a virtual model of the campus, starting from a collection of different sources, ranging from the BIM models of the new campus buildings designed by ODB architects, based on an idea by Renzo Piano, to 3D models, GIS, and drone photogrammetry survey data (Figs. 1 and 2).

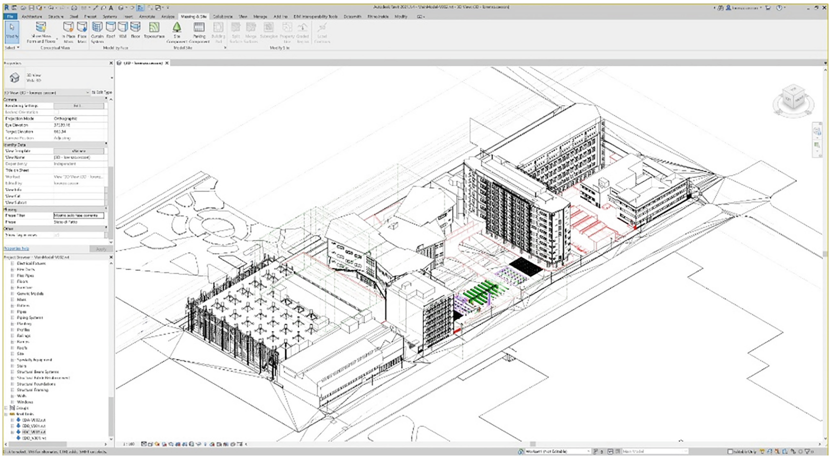

Fig. 1. The BIM model of Campus Leonardo of Politecnico di Milano.

The model had to be thought because of its fruition by a series of different software packages and devices, hence it was adapted for the potential “weak link” of the chain, i.e., low-end mobile devices, yet maintaining some of the informational dimensions from the BIM models and the survey. Spatial subdivisions - classes, corridors, courtyards - as well as other “semantic” elements were included so that meta-geometrical features could be used by the system to help interpret the contingent spatial context (Fig. 3).

This substrate of information would allow, for instance, the selective isolation of specific classes of elements in the model, or be used to calculate parameters of spatial fruition such as room crowdedness.

The main tool adopted for this aim was McNeel Rhinoceros 3D modeling package, enhanced by the Visual Programming Language (VPL) Grasshopper for Rhino, in turn with some relevant plugins installed, including Rhino-Inside-Revit for seamless integration of BIM geometries inside the NURBS modeler, as well as Fologram for Grasshopper, a package which enables the real-time sharing of a model across devices, including HoloLens visors and simple smartphones, and to even modify the model geometries and appearance according to the user gestures.

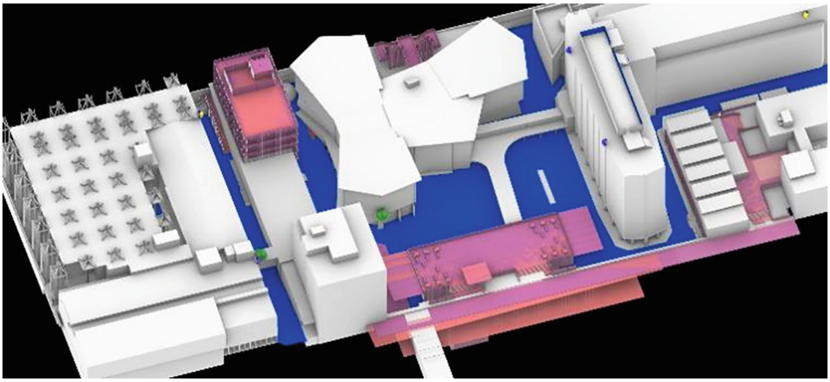

Fig. 2. The BREPS model of Campus Leonardo of Politecnico di Milano.

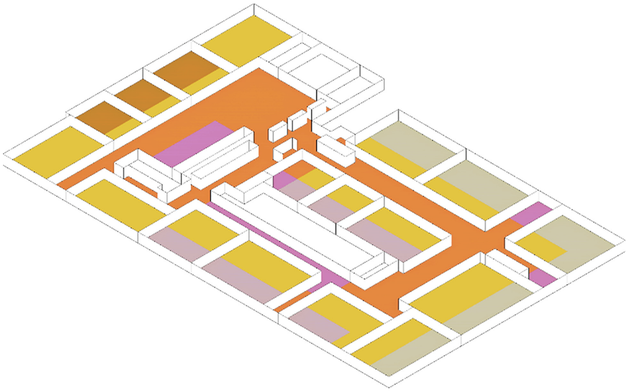

Fig. 3. The semantic subdivision of interior spaces – Campus Leonardo.

Moreover, the game engine "Unreal Engine" was also utilized for more realistic, immersive, and interactive visualization of the virtual campus model. One of the useful features of this platform was its ability to react to real-time inputs and even to simulate some "natural" behaviors through the embedded VPL "Blueprint", as well as through the inbuilt AI-powered behavior trees (Fig. 4).

Given the foreseen flow of real-time information – which would enrich the model of real-world data, as well as interact with the XR world based on the system responses – a series of actuators were also successfully installed along with the sensors (cameras), to test the feasibility of incorporating physical changes in the virtual campus model, and the I/O data flow.

A series of experiences by the research team, involving also students and contingent users, has successfully proven that an "asymmetrical" and multimodal XR experience can be set up to allow the real-time fruition by different audiences and determine a varying degree of engagement (and invasiveness), hence potentially providing a tailor-made

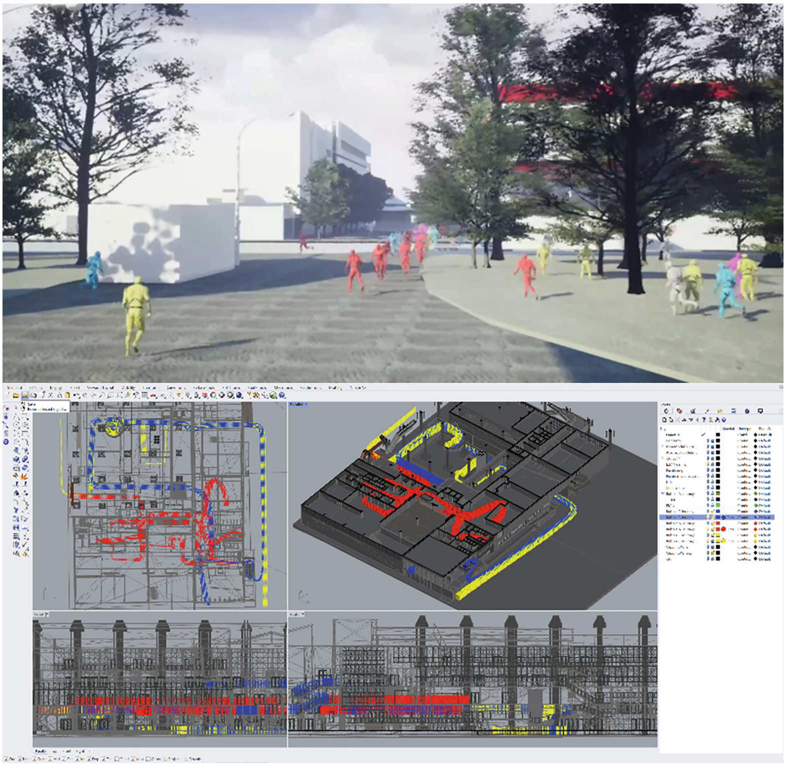

Fig. 4. The simulation of user's movements in space, both in the gaming engine and in BREPS modeler – Campus Leonardo.

experience for any user and user type, possibly avoiding a one-size-fits-all approach, with its ethical and personal implications.

Based on such flexible models and model fruition platforms, it was possible to achieve two main goals. On the one hand, we could share a simulated environment in real-time among teachers, researchers, and students, allowing them to collaborate and explore the virtual campus together – even at a distance – and even to conduct virtual experiments and simulations related to the public space, its design, and fruition, yielding different user experiences based on the tools available to each user (smartphone, in-ear wireless headphones, etc.). On the other hand, it was possible to simulate user behaviors, potentially adjusting the simulation based on real-time data, along the paradigm of the Digital Twin.

The data gathered from the simulated environment could then be analyzed and used to improve the design and functionality of the smart city, as well as the data acquired from the real users within the environment – as captured and analyzed by a series of cameras and AI-powered tools – could indeed enrich the model of real-time information and work as a feedback loop to continuously refine and enhance the virtual campus model [16–18].

The final aim of the research was also to demonstrate that—provided we create a flexible XR experience, based on a plug-in set of toolboxes each user may opt in for, and not limited to the use of immersive devices such as the HoloLens visors—a more nuanced and casual XR interaction is possible, which is both more customized and more inclusive. It appeared evident that the underlying mechanics of immersive design in smart city development can be significantly enhanced through the application of XR technology. It serves both as a means of visualization and interaction on the side of the planners and policy-makers and on the side of the users of the public space, which may opt for a personalized experience through the integration of XR technology (Fig. 5), along a new paradigm which in the project has been named "Smart Bubble".

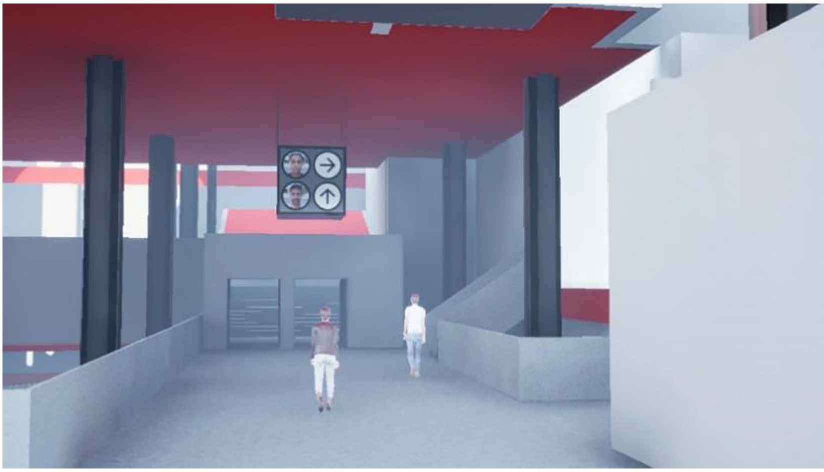

Fig. 5. The simulation of XR-based adaptive space – Campus Leonardo.

In such spatial experience, based on Cyber-Physical Systems (CPS) and Ubiquitous Computing (UbiComp), XR is somewhat inherent to the idea of space itself, a space where the physical and the virtual merge and blend, creating a seamless and immersive environment for users to interact with, and navigate through, the smart city [19]. Very importantly, in the following approach, the layer of information and sensorial interaction characterizing the XR experience is a variable one – the Smart Bubble – based on the contingent user needs, preferences, and available tools, so to avoid imposing a standard spatial fruition experience top-down, and rather providing users, including planners and designers, with a customized level of immersivity, interactivity and, therefore, inclusivity [20, 21].

3.2 XR for Smart Vehicle

Concerning the XR applied to smart vehicles, the case study presented in this research refers to a hyper-connected car with a special focus on the interior and the in-car experience. The case study was developed as part of the BASE5G multidisciplinary research, specifically in Work Package 3, which identified new urban mobility scenarios and applied some of these to an interactive prototype car and simulated driving experience. The design followed an iterative process of testing design proposals in a virtual environment to simulate and assess the effectiveness of the concept. The BASE5G vehicle's design suggests a hyper-connected and shared mobility system experimenting with a new concept.

The research process consisted of four main phases:

1. *Research Framing:* This first phase deals with analyzing the specific state of the art using desk research, which was fundamental for understanding the trends in the automotive sector, analyzing competitors' landscape, and discovering new user behavior and needs.
2. *Concept Development:* The second phase translated the research into project actions through co-design activities during several structured workshops involving technology providers and technical project partners (such as automotive experts) to redefine the project objectives and outline directions to implement a prototype.
3. *Prototyping:* To validate the concept proposed, a virtual simulation was implemented on the iDrive driving simulator (Fig. 6) of Politecnico di Milano by assessing the effectiveness of the overall in-car experience.
4. *Testing:* A between-subjects design was planned in which subjects were divided into two groups. The subjects were asked to follow instructions from a pre-recorded neutral voice and interact with the driving simulator. Time and errors were monitored during the test using eye-tracking data. In addition, after the test, participants were asked to complete two questionnaires (Raw NASA-TLX and AttrakDiff) [22].

The final output of the design process was the prototype of a vehicle implemented on a driving simulator that reproduces an autonomous driving experience and thus allows testing of the human-machine interaction.

The research considers the main drivers reshaping the future of the automotive industry, which can be summarized in four main trends: 1) electrification to reduce reliance on fossil fuels, 2) autonomous driving technology, 3) connectivity of vehicles to the online world, and 4) sharing mobility. In this scenario, smart vehicles are becoming part of a complex ecosystem to simplify the driver's life, increase road safety, improve efficiency, and minimize environmental impact. Thus, a smart car can be delineated as a broader concept of a vehicle that is not only electric and self-driving but also connected and able to communicate and exchange data with the surrounding infrastructure and the people using it [23]. In this smart car concept, it has been suggested that future mobility should be considered in both physical and virtual form, with the physical bridging the virtual and the virtual emphasizing the physical [24].

In the BASE5G car, the interior has been reconfigured assuming that automation will change the driver's role and, consequently, the interior. Thanks to the possibility of diverting attention from the driving scene, the driver becomes a "passenger" [25, 26], who can perform different actions. Therefore, the space of future smart cars is essentially a space beyond the driving experience itself [27]. In the BASE5G project, this translates into a new dashboard model emptied of the superfluous: the steering becomes retractable, not eliminating it but appearing automatically according to the level of driving automation (Fig. 7).

Fig. 6. The prototype simulator during a demonstration event of the BASE5G project.

As mentioned, the project assumes that integrating IoT platforms and 5G connectivity would transform cars from only being modes of mobility into true digital platforms [28]. Cars are increasingly digitalized and are blurring the limit between the physical and digital dimensions, affecting the in-car configuration and how the user interacts with the vehicle. Considering this, the car is part of an integrated communication and data exchange known as the "Vehicle-to-Everything" [29], which includes communication with both infrastructure and people's devices in addition to vehicle-to-vehicle data exchange [30]. The smart infrastructure provided by the smart city enables the car to exchange dynamic information. This lets the user connect to the decentralized and proactive data exchange to personalize the driving experience. Users can bring their data into the vehicle and facilitate integration with personal devices and cloud storage using their digital identities, making the vehicle's interior highly personalized. The data users share under the terms and privacy consents provided may include details about status, preferences, health issues, and more.

The in-car experience then changes based on the driver's profile and data, adjusting the compliance of the environment as needed. In this way, augmented reality also augments or diminishes the experience. In other words, the technology should be able to use data to create an in-car environment that is as comfortable as possible for the driver, adopting changes such as driving parameter settings, light settings, seat layout, and interface accessibility settings, as well as data and device synchronization.

Moreover, to lessen the cognitive burden on the user and ensure that only the relevant information is presented on the interface at the proper moment, the automobile is proactive and adjusts to varied driving scenarios.

The car thus becomes a "Smart Bubble", a personal and customized space for the user, which communicates with the external environment to enrich the in-car experience. The car can isolate the user from the outside environment and allow him to concentrate as if they were in a smart office (Fig. 8) or become a space interacting with the outside world, providing information about the surrounding environment in a smart

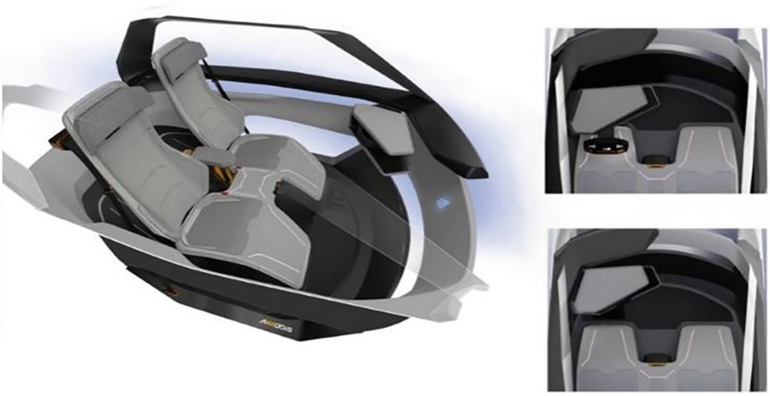

Fig. 7. The new dashboard model of the smart vehicle in which the steering becomes retractable during autonomous driving.

entertainment scenario (Fig. 9). In this second case, Augmented Reality is essential for the in-car experience, providing continuous (synchronized with the car's movement) and multimodal access to information (Fig. 10).

In the BASE5G car, the interface is projected directly onto the windscreen thanks to a full-screen Head-Up Display (HUD), with which one can interact through a gesture-based control system implemented by haptic feedback. In addition, visual outputs and haptic and auditory feedback have been integrated to allow the user to interact with the vehicle. On the windshield, the user can activate communication with the environment through HUD that provides various kinds of information, for example, historical information about the building, useful information about the places of interest they encounter, or even on-demand information on businesses that might be useful during the journey.

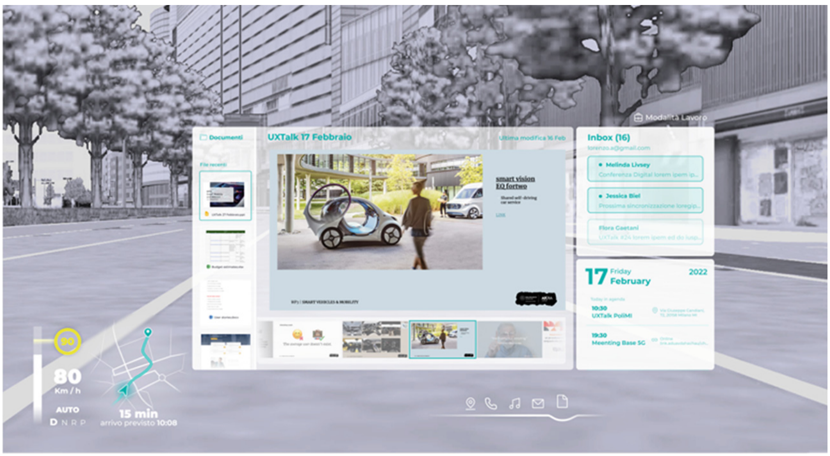

Fig. 8. AR User Interface showing AR in the smart office scenario.

Fig. 9. AR User Interface showing AR in the smart entertainment scenario.

According to the literature [27], the HUD can improve speed control and reduce drivers' reaction time to emergencies. During assisted driving, the HUD allows information to be shown close to the driver's field of view, thus reducing eye movements and making important warnings more effective. This allows the XR to be used in an integrated manner, communicating directly with the environment through a 3D representation of the vehicle projected onto the interface, enabling the user to proactively control the state of the car about the road and surrounding vehicles.

Fig. 10. AR User Interface showing AR in the smart driving scenario.

As in the case study above, in the approach followed during the Smart Vehicle project, the level of information and sensory interaction must be carefully dosed to be effective without being invasive. Inclusivity is, also in the project described, a fundamental value and, in the amount of data that can potentially be exchanged between the car and the external environment, completely feasible.

3.3 XR for User Experience

Regarding the XR applied to user experience, the case study demonstrated in this research refers to a design protocol that enables designers to develop concepts of products and services in the context of a smart city. The previous case studies show the advantages of first-person immersion to check concepts from spatial experience and interaction aspects [14, 20, 31]. To develop a new concept of a smart city, designers need to translate human needs into targeted design qualities and design problems, define relevant design elements, and explore possible solutions to ensure these qualities, then fulfill the needs [32].

The design process model indicates the mind flow of designers across design processes [33]. A well-acknowledged design process model is the Double-Diamond Model (DDM) which describes two circles of a divergent-convergent process [34]. Since designing is a "solution-driven" activity, the designer's thinking is composed of iterative loops where they are continuously learning to understand the user's experience via "defining", "prototyping" and "testing" activities [32, 35, 36]. In this case study, the focus is thus on the effects of immersion to support the designer's thinking among design processes in the context of smart city design.

Designers showed a divergent way of thinking about the approaches to integrating XR experiences throughout their design processes. This case study aims to analyze the thinking styles of designers under immersion and thus develops a protocol that simulates realistic design processes following the Immersive Cycle aligning with the DDM [37] (Fig. 11). The protocol was developed on an XR platform -Tvori. co[1], which supports immersive prototyping and animating scenarios by using the Google Poly library or importing external files, like videos, audio, or 3D models. An HTC VIVE headset (1080 x 1200 pixels per eye with 6 degrees of freedom) was used to support navigating in the immersive environment and uses hand controllers to interact with virtual objects. The immersive environment was synchronized to a 19-inch LED display in front of a researcher and a 50-inch screen for the other team members.

Four design teams with seven design professionals participated in the study, representing different types of designers including corporate designers, senior designers, junior designers, and part-time designers [2]. Each team has a designated session to replicate a true-to-life design process:

1. *Design task definition:* A specific design task was defined together with each team and the researchers asked what they wanted to explore in the immersive session.
2. *Protocol customization:* The protocol was customized to include texts, videos, or models that could be used for the abovementioned design task.
3. *Protocol setup:* The start point was set at the "User" dock in the Tvori protocol.

[1] https://tvori.co/tvori.

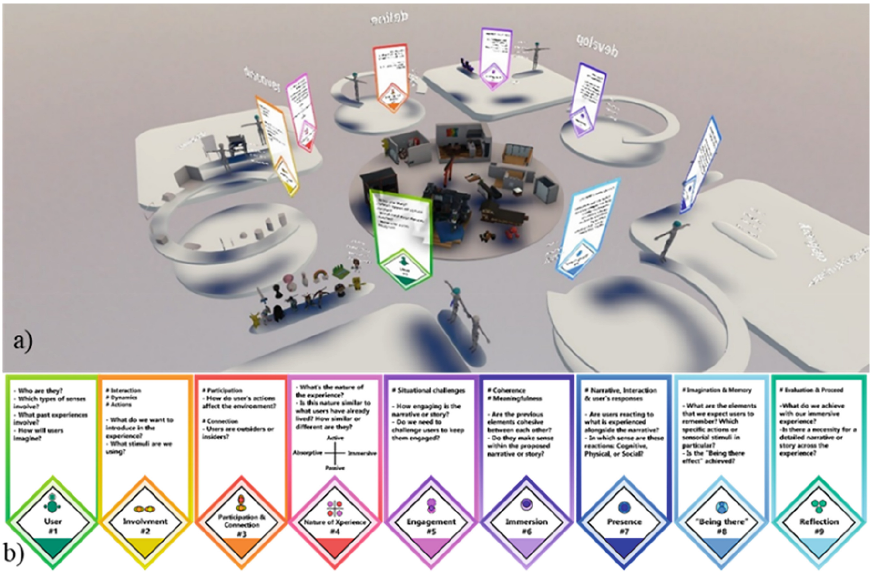

Fig. 11. The immersive design protocol is developed with the XR platform – Tvori. co. a) a bird's view of the immersive protocol that guides the sessions. b) the protocol is composed of nine phases.

Each immersive design session included four steps. 1) the researchers introduced the goal and the procedure of the session and then demonstrated how to move around and interact with the protocol. 2) One participant from each team put on the headset to try

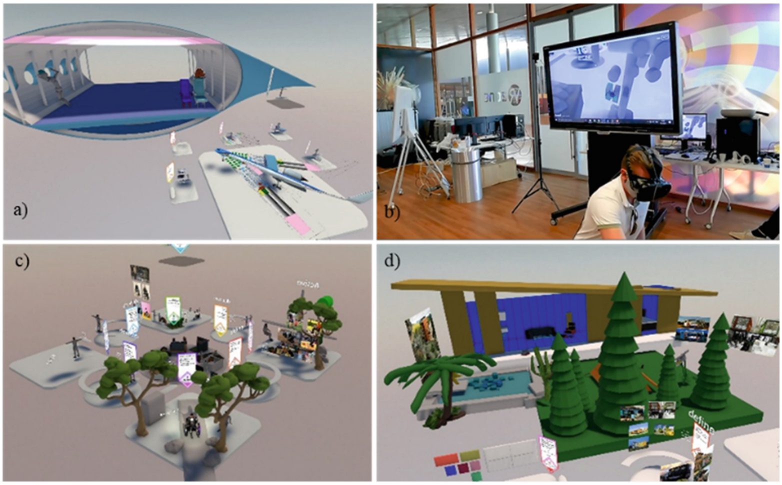

Fig. 12. The examples of the outcome of the immersive design sessions. a) conceptual safety training setup for crews; b) the configuration of a dialysis machine in hospitals; c) a conceptual scenario of a wheelchair for youths; c) a concept of a container house for a middle-aged couple.

out the protocol till he or she felt confident enough to interact with it. 3) The participant with the headset guided the team throughout the protocol to complete a concept of the design task within two hours. The team could decide whether to switch between different members to guide through the protocol. When a team couldn't complete the protocol in 140 min, the researcher asked the team to leave the design process and move to the final part. 4) The last part was a briefing where the team could give general comments, recommendations, or expectations on future XR design platforms. Then the researcher thanked the participants for their contribution to the study.

The teams created various concepts within 120 to 150 min (Fig. 12). The service designer created an airplane cabin to organize safety training for crews (Fig. 12a). The senior product designer team checked the configuration of the dialysis machine and reviewed reachability both from the patient's view and the nurse's view (Fig. 12b). The junior designer team built a 3D persona for youth and ideated an outdoor wheelchair in context (Fig. 12c). The part-time architect generated a container house for a middle-aged couple (Fig. 12d).

Table 1. The benefits and barriers of the XR design protocol

Stages	Benefits	Barriers
Discover	+ Prototyping is the key to discovering users' needs. Testing and observing (recording) are the key design activities + Creating personas in 3D is creative and fun, especially for young designers + Working with low polygon models is nice + The opportunity to share design proposals across mobile and PC	- Feel floating and nauseous - Collaboration would be nice with two players - Designers need to search for pictures inside the environment - Teleport within the environment is difficult
Define	+ The Environment has the function of being an experience + Designers could work in the real size + Posturing digital humans freely in the scene is useful and fun + By simulating realistic experience, it's a tool to observe users from different angles + Simulating scenes with people (like a crowd in a cabin) + Zoom in and out to check the layouts and scales	- Designers would be careful if they have real sizes - Introducing eye-tracking could help to understand the designer's thinking processes - Sketching is difficult - Missing a whiteboard in the environment - Similar functions with different controls in various XR platforms
Develop	+ Opportunities for participatory design: people understand VR and concepts better if they create a bit of it themselves + Exploring the stories behind the use scenarios + The experience simulation can be both immersive or absorptive depending on use cases	- The difficult control of resizing objects - Various challenges should be brought to the scene to build up the purposes and goals of XR applications - An XR system should provide intuitive sketching while including different possibilities to explore user experience
Deliver	+ Users feel better acceptance and ownership when designing together in XR + The opportunity to personalize user experience	- The heavy weight of the headset makes the neck discomfort - Using a virtual camera is difficult

Each team acknowledged the immersive session as engaging and creative. Learning basic interactions like navigation and object manipulation took 30 min to more than an hour, whereas junior designers took a shorter time to learn, and senior designers needed a longer duration to understand basic functions. The senior designers viewed the immersive protocol as a replacement for cardboard prototypes to explore different layouts and examine ergonomics; while junior designers appreciated creating personas with 3D polygons and showed interest in simulating interactions with animation. Both senior and junior designers naturally put digital humans in the scenes they created either to represent the human sizes or to indicate the target users. The benefits and barriers of this immersive design protocol are summarized in Table 1.

4 Discussion

This section deals with the commonalities among the foregoing case studies, both as regards the opportunities, and as to the envisaged limitations and criticalities of XR technologies.

The case studies, with their ample range of disciplines and applications, clearly show the inherent multidisciplinarity of XR technologies. Moreover, as highlighted mainly in the third case study, XR can be a back-bone technology throughout the design process, as well as in the subsequent phases, including the fruition by the final users.

Such a wide array of possible uses of XR is rooted in its key characteristic of working as a filter between the users and the environment, much like a pair of glasses that enhances or alters our perception [38]. In various types of environments, XR demonstrates the capability of merging the physical and digital layers of information and enhances sensorial interactions with spatial experiences [20]. XR bridges the physical and digital environments to create a seamless experience for the user and take advantage of both dimensions [24]. As shown in the “Smart Campus” case as well as in other space planning projects, XR can support design decisions and make the processes of both spatial design and spatial fruition more inclusive yet more personalized and engaging, along with the concept of “Smart Bubble” [15].

XR technologies span across a Reality-Virtuality Continuum [3], where its multimodal and multisensorial reach varies depending on the contingent technologies and user needs, as explained in the “Smart Bubble” concept in the smart case. Moreover, human understanding does not derive merely from impressions but from the interaction between the mind and the empirical world [39]. XR can naturally integrate proprioception within the spatial experience, making users’ responses towards closure environments like cabins more intuitive and realistic [22, 31].

Drawing parallels from the notion of XR as a ‘pair of glasses,’ this technology can be considered an additional layer of ‘sensibility’. It is an interactive framework that reshapes users’ perception of the real world, providing a structured, novel, and augmented understanding of our surroundings [5, 6]. For example, in the user experience case, designers can check the overall layout from a bird-view and then review the details in the user’s personas. XR technologies are becoming increasingly crucial in interacting with and understanding the digitalized environment. Soon, thanks to technological progress, XR will become more and more accessible and cross-sectoral, enabling physical and digital reality to be transformed for a specific purpose [5] where the user is not a passive beneficiary of technology but an active participant in the decision-making process [13].

5 Limitations and Future Work

These promising use case scenarios are nevertheless facing some issues and limitations. On the one hand, some major technological bottlenecks – such as still limited data bandwidth, as well as uneven multimodal and multisensorial capabilities of the available devices (typically, taste, smell, and touch are not yet well dealt with) – make the immersive experience still not on par with a more traditional experience in presence, as the (until now) failed promise of the Metaverse has clearly shown [40]. The possibility of overcoming spatial and sensorial barriers is still very limited, and the authors can only hypothesize that in the future the provided experience will be good enough to even "augment" the users' perceptions without limiting their sensorial experience. Once this is possible, in line with the presented case studies, the inclusivity of the experience could indeed be increased by connecting users in a network – even at a distance – where each user receives a customized "translation" of the shared environment.

On the other hand, the idea of a network based on the Ubiquitous Computing paradigm, where everything and everyone is present in a unified Cyber-Physical Space, raises some relevant ethical concerns. The impact on people's lives would arguably be quite different in case the adhesion to the network is on a truly voluntary basis or not. In a sense of data security, the choice between one/few central computing units or countless devices networked with no central computing and direction is critical. At the level of digital equality, whether the network and the data flow can be controlled and directed/blocked by any entity (including governments and corporations), as well as whether a legal mechanism is in place to guarantee transparency, accountability, and public scrutiny are of paramount importance.

6 Conclusion

When new technologies are invented, their adoption in real-life scenarios seems to require fine-tuning. Researchers shall avoid *a priori* acceptance or rejection of such technology, rather asking for a more nuanced and specific consideration of the key features such technology brings, its potential unique advantages and drawbacks, and possibly trying to find a good balance over time and for the contingent situations in the trade-offs its use may imply.

A truly immersive experience of smart environments requires a joint design integration of engineering and perceptual requirements stemming from human senses, cognition, and physiology [1].

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