Sustainability Design in Mobile Augmented Reality

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Abstract. This paper describes the sustainability design process of a mobile augmented reality (MAR) application called AudioNear. Through a four-step process and a dedicated workshop with developers, the Sustainability Awareness Framework (SusAF) is applied to capture and connect sustainability issues into dimensions and levels of effects. Among twenty sustainability issues in MAR applications, eight functional issues that are essential to creating a sustainable MAR travel guide experience were identified and developed for AudioNear. First, a comprehensive list of design suggestions was formulated to facilitate sustainability design in MAR applications. Then, high-fidelity mock-ups of AudioNear were developed based on design suggestions, indicating promising results in terms of the sustainability design process. This work contributes to the field of sustainability design and MAR.

Keywords: Design Suggestions · Mobile Augmented Reality · Sustainability Awareness Framework · Sustainability Design.

1 Introduction

As technology evolves, so does our responsibility to incorporate sustainability goals into design and development processes. User-centered design has long been a key focus, while it is equally important to address other dimensions of sustainability, such as the environmental, social, and economic impact of software applications [26, 5]. Developers can significantly impact and improve longevity and durability in software development through actions like prioritizing resource conservation, using renewable energy sources, and designing intuitive and culturally sensitive user interfaces while facilitating user needs, preferences, and experiences [28, 12, 26, 4].

Collaboration in teams, among developers, designers, users, and stakeholders in software development could ensure the inclusion of multidimensional sustainable design. Design tools play a crucial role in supporting teams to design for sustainability. Such tools empower multidisciplinary teams by providing them with structured methods, visualizations, and analysis capabilities to design for

sustainability [10]. Additionally, they enhance collaboration, enable informed decision-making, and contribute to the development of innovative and sustainable solutions[10].

However, certain software technology domains come with unique requirements and challenges when it comes to sustainable development. Augmented reality (AR) is one of those domains, and its sustainability considerations can differ from other technologies in several ways. Regarding their environmental impact, AR applications often require more computational power and energy than traditional computing or mobile devices. The rendering of immersive 3D graphics, real-time tracking, immersiveness, and high user engagement can be resource intensive, leading to higher energy consumption. At the same time, since AR experiences are commonly accessed through mobile devices, such as smartphones or tablets, sustainability considerations arise from the manufacturing, life-cycle management, and e-waste aspects of these devices and, since their content delivery and real-time data processing often relies on cloud infrastructure and content delivery networks, the environmental impact of data centers and network infrastructure should be considered [19, 20]. Finally, AR devices are equipped with high-quality sensors that can collect large amounts of sensitive user data, including biometric and spatial data, making it essential to address privacy concerns, data security, and potential societal impacts. Although the use of AR for sustainable design has been highlighted in research [1], the application of sustainability design in AR remains under-explored.

This paper aims to take the first step toward investigating the sustainability design of AR applications. To do so, the Sustainability Awareness Framework (SusAF) [14] is applied to a use case of a MAR travel guide application named AudioNear. The contribution of this work is threefold: i) it enriches the existing literature on the sustainability design of AR applications; ii) it enriches the existing literature on the design suggestions for developing sustainable MAR travel guide applications; and iii) it practically applies the SusAF in a sustainability-design context, thus developing and presenting a structured and reproducible methodology for sustainability design.

The paper is organized as follows: Section 2 describes the case study of an MAR travel guide app, AudioNear. Section 3 describes the adopted methodology in four steps. SusAF guides the sustainability design process in MAR applications, where sustainability-related issues are identified, leading to design suggestions and mock-up development. The paper ends with concluding remarks and a discussion of future work.

2 Case Study: AudioNear

The AudioNear tour guide is an audio MAR experience that provides real-time, speech-based auditory information about places of interest in the user's vicinity [8]. AudioNear was developed in 2018 as a web-based mobile application utilizing a 4G broadband connection. Users wore headphones and initiated the audio tour guide app on their personal mobile devices. Based on their GPS-based loca-

tion, when users entered a designated radius around a specific location, an audio track provided detailed information about that place. On the back end, the system used the device's GPS coordinates to get the basic AR content about the AudioNear POIs and external links to content (e.g., audio tracks, images/icons). On the front end, the application's main menu offered functionalities like use instructions, a test audio track, a map, and the option to start using the main exploration functionality. The application was designed for the city of Oslo and featured 16 sights as places of interest and corresponding audio tracks in English with information about history, architecture, and visiting hours. Based on previous work and the existing literature in the field, the previous version of AudioNear v1.0 was designed following four design suggestions (DS1.1-4) addressing the topics of user interaction, interface design, and content delivery [8].

- **DS1.1:** *"The tour guide service should minimize the distraction arising from interaction with mobile devices"*. It was implemented in AudioNear through the design of a minimal-attention user interface.
- **DS1.2:** *"The interaction with the tour guide should minimize the cognitive load coming from extensive use instructions"*. This suggestion was utilized in the application by designing intuitive interaction metaphors.
- **DS1.3:** *"The tour guide should utilize a robust spatial audio-activation method that supports social interaction and shared multi-user tour experiences"*. It was implemented in AudioNear by using radius-based audio activation zones.
- **DS1.4:** *"The tour guide service should satisfy various types of tourists"*. This suggestion was implemented by designing two different touring functionalities: exploration and route planning/navigation.

Since AudioNear's design and development, several technical characteristics have become obsolete, such as the third-party service (i.e., Layar), which was discontinued. This situation initiated a process for the sustainable redesign of AudioNear based on current developments in the field. Afterward, the sustainable design of AudioNear V2.0 considers both front- and back-end characteristics.

3 Method for Sustainability Design

Addressing sustainability in MAR applications is a significant and complex challenge that has the potential to impact MAR's role in society profoundly and, specifically, in travel guidance and tourism. However, what exactly does prioritizing sustainability as a fundamental consideration in developing these applications entail? System developers are responsible for the long-term consequences of their applications, regardless of the system's primary purpose [4]. To understand the broader sustainability issues bound to the use of MAR travel guide apps and redesign the AudioNear app, an adapted version of a sustainability-oriented process is applied [4]. Following a top-down approach to sustainability design, Step 1 identifies the common issues with MAR travel guide applications, while Steps 2-4 focus on the specifics of the examined application, AudioNear.

- **Step 1:** Capturing sustainability dimensions and corresponding issues of the application using the SusAF tool.
- **Step 2:** Using the Sustainability Awareness Diagram (SusAD) tool in a workshop, drawing connections between sustainability issues and clustering the issues into levels of effects.
- **Step 3:** Formulation of design suggestions and development of high-fidelity mock-ups.
- **Step 4:** Synthesis of results and future steps.

3.1 Step 1: Applying the Sustainability Awareness Framework

Sustainability design starts with the holistic consideration of influential factors in the focal system to allow solutions that minimize negative impacts and maximize positive contributions. The SusAF is a tool for sustainability design of software products and services [14]. Based on SusAF, the sustainability of software systems encompasses five dimensions: social, individual, technical, environmental, and economic sustainability [4]. By considering previous work and related studies, MAR travel guide apps can create a positive and balanced impact on society, users, technology, the environment, and the economy. The five dimensions are discussed hereafter. Table 1 summarizes the findings for each dimension.

3.2 Step 2: Applying the Sustainability Awareness Diagram

After capturing the sustainability dimensions and corresponding issues of the MAR travel guide applications, a comprehensive overview of the current state in the field was gained. Derived from Step 1, Step 2 connects the identified sustainability issues, particularly with AudioNear. At this step, attention is exclusively on the AudioNear application. The objective is to discuss the app's sustainability issues and envision the development of the app's sustainable next version. For that purpose, a workshop with experts was organized to envision the sustainability of AudioNear within a decade and to capture as many chains of effects as possible. Workshop participants were selected based on their previous experience in mobile system development, and all five were categorized as "experts" with backgrounds in system engineering, software engineering, and programming. A second selection criterion was their previous knowledge of AudioNear since they contributed to previous versions of the application development and research. Participation was voluntary. During the workshop, the authors of the paper, together with the experts, worked on a mapping exercise where a modified radar chart was employed called Sustainability Awareness Diagram (SusAD)[14]. SusAD serves as a visualization tool where the issues of Step 1 are mapped into five interconnected sustainability dimensions, according to SusAF [4].

Table 1. Key sustainability issues per dimension identified in the literature.

Sustainability dimensions	**Key Sustainability Issues in MAR travel guide apps**
1. Social dimension explores the relationships and interactions between individuals and groups, such as inclusion, trust in the operating environment, attitudes toward others, participation in social communities, and perceptions of fairness in relation to others .	– **Responsible Tourism** [6, 31] refers to responsible and sustainable travel practices that raise awareness and minimize environmental impact, such as providing information and recommendations on sustainable travel and transportation options, eco-friendly accommodations, and responsible behavior while visiting natural and cultural sites. – **Cultural Preservation** [15, 29] concerns the preservation of local culture, heritage, and authenticity, by providing accurate information on historical sites, landmarks, and cultural practices, ensuring the content presented in the application is culturally sensitive, inclusive, and aligned with the values and aspirations of the local population, and providing storytelling for various cultural landmarks that can enhance users' understanding and appreciation of the culture. – **Local Community Engagement** [32, 19] aims to empower local communities by promoting local businesses, artisans, and service providers through recommendations, partnerships, or advertising within the application. – **Education and Cultural Exchange** [27] refers to enhancing cultural understanding and promoting educational experiences, such as in immersive and informative content, intercultural dialogue and understanding, and diverse perspectives and narratives.
2. User dimension pertains to an individual's capacity to flourish, exercise their rights, and grow autonomously. It involves examining how the utilization of a system can impact the user's physical and mental well-being, knowledge level, privacy, safety, decision-making, etc.	– **Personalized Travel Experiences** [19, 18, 3] could enhance user engagement and satisfaction through customized recommendations, suggested itineraries, and personalized content. – **User Empowerment** [20, 8] relates to user access to information, navigation tools, and resources that promote independent exploration and navigation to unfamiliar places, providing, for example, details about places of interest, transportation options, local customs, and safety guidelines. – **User Safety and Privacy** [23] should be prioritized by offering real-time updates on safety alerts, emergency contact information, health services, and potential risks for unfamiliar places. – **Usability and Universal Design** [20] should be applied to assist user interaction and navigation, broadening the range of users, including those with disabilities or diverse needs.
3. Environmental dimension focuses on the utilization and responsible management of natural resources, involving considerations of how a system can impact resource consumption, waste production, pollution, emissions, and biodiversity.	– **Minimized Carbon Footprint** [22]: contributes to reducing the carbon footprint produced by travel through efficient navigation and eco-friendly transportation options, such as public transport and walking routes. – **Sustainable Resource Management** [25, 24] refers to the information on sustainable resource management practices, such as waste reduction, water conservation, and energy-saving initiatives. – **Environmental Awareness** [25, 24] involves educating users on the importance of environmental sustainability, raising awareness about local ecosystems, biodiversity, and conservation efforts through information on local ecosystems, wildlife conservation, and environmental challenges. – **Virtual Exploration** [25, 24] contributes to a more sustainable approach to travel, allowing users to learn and engage with destinations without the environmental impact of physical presence through virtual tours, 360-degree images, and immersive cultural AR experiences.

Sustainability dimensions	Key Sustainability Issues in MAR travel guide apps
4. Economic dimension encompasses the financial aspects and business value associated with a system. It explores how it generates or diminishes value, its impact on the relationship between businesses and customers, and whether it modifies a business's supply chain, governance, processes, or research and development (R&D).	– **Sustainable Business Model** [30, 11] involves generating revenue through various channels, such as app sales, in-app purchases, advertising, partnerships, and premium content or features. – **Tourism Industry Innovation** [13] could be leveraged by cutting-edge technologies and interactive features in MAR apps. This innovation fosters competitiveness, stimulates economic growth, and attracts more visitors, benefiting the entire travel ecosystem. – **Cost Efficiency for Travelers** [19, 18, 3] refers to the cost-efficient alternatives to traditional guidebooks or guided tours that can be provided through MAR apps. By providing comprehensive information, interactive features, and personalized recommendations, the application helps travelers make informed choices, optimize their travel, and, ultimately, save costs. – **Economic Impact and Data Analysis** [19, 18, 3] refer to the potential positive impact on the economy through job creation and collaborations with key stakeholders, such as tourism boards, local businesses, and travel service providers. Additionally, MAR travel guide applications could collect data, after user consent, that can be analyzed to gain insights into travel patterns, preferences, and market trends and could be used to tailor offerings, improve user experiences, and make informed business decisions.
5. Technical dimension focuses on the software system's capacity to evolve while delivering the necessary features and capabilities. The objective is to determine how the system is maintained and utilized over time, assess its ability to adapt to environmental changes, and evaluate whether it prioritizes security and user privacy.	– **Technical Safety, Security and Privacy** [16, 20] issues should be prioritised in MAR travel guide applications. Users' personal information, location data, and preferences should be handled securely, following best practices for data encryption, secure authentication, and secure data transmission. Privacy settings and permissions can be clearly communicated to users and provide control over the data shared with the application. – **Device Compatibility and Optimization** [9] issues could be improved to ensure accessibility for a wide range of mobile devices, processing capabilities, operating systems, and screen sizes. – **Scalability and Adaptability** [2] issues for MAR travel guide applications could be designed to accommodate a growing user base, increased data traffic, and new features or content additions. Scalability can be achieved, for example, through scalable cloud infrastructure, efficient data management, and modular architecture that supports future updates and expansions. – **Connectivity and Accessibility** [21] issues rely heavily on network connectivity to deliver real-time information and updates. Technical sustainability involves ensuring seamless or intermittent connectivity or providing offline access to certain features or content.

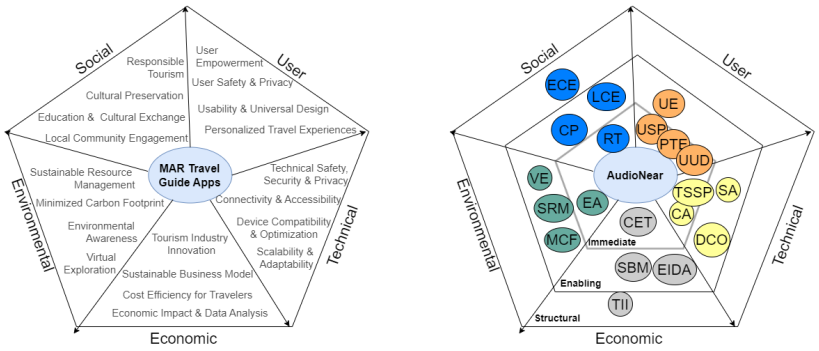

Fig. 1. The SusA Diagram with identified sustainability issues for MAR travel guide apps (left), and classified into three levels of effects for the AudioNear app (right).

Each dimension is further subdivided into three levels of effects, indicating the impact a software system can have on the short and long term. Similarly with previous works (cf. [17] and [7]), these effects are subdivided into [14]:

- **Immediate effects** refer to the direct consequences resulting from the system's function or development.
- **Enabling effects** include effects on the surroundings that arise from using a system.
- **Structural effects** refer to the enduring changes that can be observed at the macro level.

The purpose of this exercise is to identify issues that could affect the future impact of AudioNear on the sustainability of its socio-technical environment (Fig. 1). The participants were informed beforehand of the workshop's process and became familiar with the diagram. In the first phase, after discussing the sustainability issues in five dimensions, connections among the issues in each dimension were first negotiated. Then, relations across dimensions were drawn, highlighting overlaps among issues and dimensions in the radar chart. To manage both the process and discussions efficiently, a combination of driving questions and questions from the existing literature was applied during decision-making into levels of effects. Supplementary material, such as printouts of the SusAD, templates for taking notes, colorful pens, and sticky notes, were used. The workshop lasted two hours, followed by additional discussions and clarifications on the findings. Hereafter, examples of driving questions per dimension are presented:

- **Driving questions on social issues:** How might the app affect people's trust in their surroundings and perception of others? How could the app encourage responsible and sustainable travel practices and user participation in social communities for cultural preservation?
- **Driving questions on user issues:** How might using the app affect an individual's travel experience and satisfaction/level of knowledge in navigation

and travel independence/physical and overall well-being/safety and ability to act on their surroundings, as well as the inclusion of people with different backgrounds, age groups, education levels, or other differences?
- **Driving questions on environmental issues:** How might the app affect the consumption of resources, waste production, pollution, emissions, and biodiversity toward more sustainable tourism practices and resource management? How can the app affect the environmental education and awareness of users?
- **Driving questions on economic issues:** How does the app create or diminish (e.g., monetary) value? What are the related types of business value, and for whom? How might the app affect the relationship between (e.g., local) businesses and travelers?
- **Driving questions on technical issues:** Have the app's security and its users' privacy been considered? What are the risks associated with using the app? How can someone use the app with poor network connectivity?

By mapping sustainability issues into three levels of effects, the short-, mid-, and long-term effects of the application were realized. Additionally, levels of effects can be considered in the system development phase, where functional issues in the "immediate effects" are essential to creating a sustainable MAR travel guide experience. Accordingly, the issues in "enabling effects" enable the long-term sustainability of the application, although they should be embedded and considered together with functional issues. Lastly, issues in "structural effects" could be considered in subsequent development phases in the long run of the application since they could create a secondary type of experience complementary to the primary MAR travel guide experience.

- **Immediate effects** include eight sustainability issues: 1. Responsible Tourism, 2. Personalized Travel Experiences, 3. User Safety & Privacy, 4. Usability & Universal Design, 5. Environmental Awareness, 6. Cost Efficiency for Travelers, 7. Technical Safety, Security & Privacy, 8. Connectivity & Accessibility.
- **Enabling effects** include ten sustainability issues: 1. Cultural Preservation, 2. Local Community Engagement, 3. User Empowerment, 4. Minimized Carbon Footprint, 5. Sustainable Resource Management, 6. Virtual Exploration, 7. Sustainable Business Model, 8. Economic Impact & Data Analysis, 9. Device Compatibility & Optimization, 10. Scalability & Adaptability.
- **Structural effects** include two sustainability issues: 1. Education & Cultural Exchange, 2. Tourism Industry Innovation.

To exemplify the relations and overlaps among sustainability issues, the connections of Responsible Tourism (RT) with all three levels of effects will be explained. RT represents a vital part of sustainability in the tourism sector that should be adopted in MAR [6, 31]. On the immediate effects, RT could significantly impact Environmental Awareness through the MAR technology by raising awareness about environmentally conscious travel practices and encouraging users to make sustainable consumption choices during travel. Additionally, RT could play a significant role in educating users about sustainability practices and

inspire environmentally responsible actions, such as reducing waste, conserving resources, and supporting eco-friendly transportation options. MAR apps have the potential to inspire users to become more environmentally conscious travelers and make a positive impact on the environment. On the enabling effects, RT impacts User Empowerment by providing personalized experiences through the MAR app, access to accurate and reliable information about destinations, and responsible travel choices aligned with users' values that could have a positive social, cultural, and environmental impact. Furthermore, RT could foster a sense of ownership and empowerment among travelers by providing opportunities for engagement with local communities through community-led initiatives, cultural events, opportunities for authentic cultural exchanges, and by providing a platform for user feedback to empower users to have a voice and influence the tourism industry by sharing their opinions and promoting responsible travel practices. On the structural effects, RT could significantly impact Tourism Industry Innovation, specifically through the development and implementation of MAR travel guide apps that enhance the overall travel experience. Responsible tourism could stimulate innovation activities through collaborations with local communities, cultural preservation and educational experiences.

3.3 Step 3: Design Suggestions for Sustainability in AudioNear

According to the identified sustainability issues (Step 1) and their mapping into levels of effects (Step 2), we select issues with immediate effects for further development at this initial design phase. These issues constitute the most vital part of the app's sustainability, while future work will focus on the remaining

Table 2. Design suggestions for AudioNear v2.0 categorized into sustainability dimensions (SD), i.e., S: Social, U: User, En: Environmental, Ec: Economic, T: Technical.

SD	Design suggestions
S	**DS2.1:** *The MAR travel guide application should provide information and recommendations on responsible tourism practices.*
U	**DS2.2:** *The MAR travel guide application should offer a personalized travel experience.*
U	**DS2.3:** *The MAR travel guide application should provide and prioritize information related to user safety and privacy on travel.*
U	**DS2.4:** *The MAR travel guide application should provide a user-friendly interface that follows Universal Design principles.*
En	**DS2.5:** *The MAR travel guide application should provide information on environmental awareness during travel.*
Ec	**DS2.6:** *The MAR travel guide application should offer cost-efficient alternatives to travelers.*
T	**DS2.7:** *The MAR travel guide application should follow best practices for technical safety, security, and data privacy.*
T	**DS2.8:** *The MAR travel guide application should offer alternatives to connectivity and accessibility issues.*

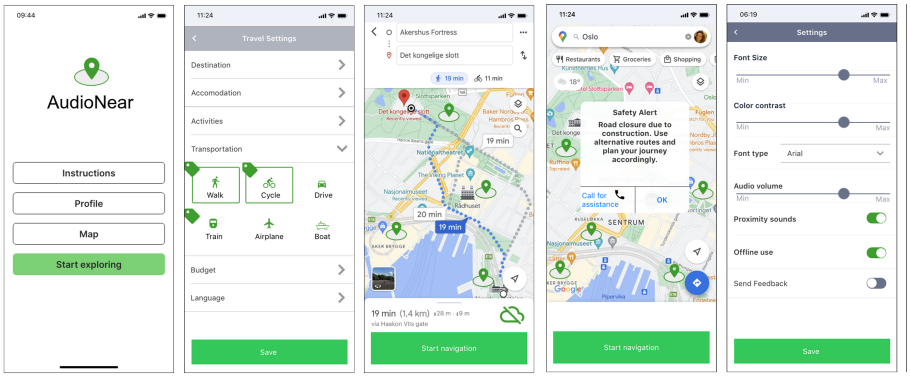

Fig. 2. From the left to the right (a): The main menu of AudioNear v2.0. (b): Implementation of transportation options (DS2.1). (c): Implementation of travel preferences (DS2.2). (d): Implementation of emergency assistance (DS2.3). (e): Implementation of customized settings (DS2.4).

issues. Design suggestions of AudioNear v1.0 (Section 2.1), previous work in the field (Section 3.1), interrelations of sustainability issues (Section 3.2), and feedback from workshop participants were combined into a list of design suggestions (Table 2). Although suggestions are self-evident, they are formulated into a higher level of abstraction for various reasons, such as to allow the production of multiple designs according to various app-specific needs, to reflect and summarize best the ongoing research in a field, and to serve as a list of alternatives when designing for MAR apps. Likewise, suggestions are not self-excluding as they reflect interrelations among overlapping sustainability issues. In this work, discussions with experts were influential in translating the design suggestions into mock-ups. Both the rationale of the design suggestions (DS) and their implementation in mock-ups are presented below. Note that DS2.X stands for the design suggestions developed for AudioNear v2.0 (Table 2).

On the Social dimension, DS2.1 refers to Responsible Tourism practices, and the implementation for AudioNear is to promote sustainable transportation options through the MAR travel guide app, such as public transportation, biking, or walking routes to reduce carbon footprint and promote environmentally friendly travel (Fig. 2, b). By selecting transportation preferences, the users' travel could be designed accordingly (Fig. 2, c), while sustainable choices in transportation could activate cost-saving strategies (Fig. 3, b). Therefore, sustainable transportation is also relevant for Environmental Awareness (DS2.5), Cost Efficiency for Travelers (DS2.6), and maybe other sustainability issues, such as Cultural Preservation and Local Community Engagement.

On the User Dimension, DS2.2 corresponds to the Personalized Travel Experiences, and the implementation in AudioNear will utilize user profiles where users can specify their travel preferences, interests, and needs (Fig. 2, c). The personalized travel experience could be useful for many other issues, such as Cost

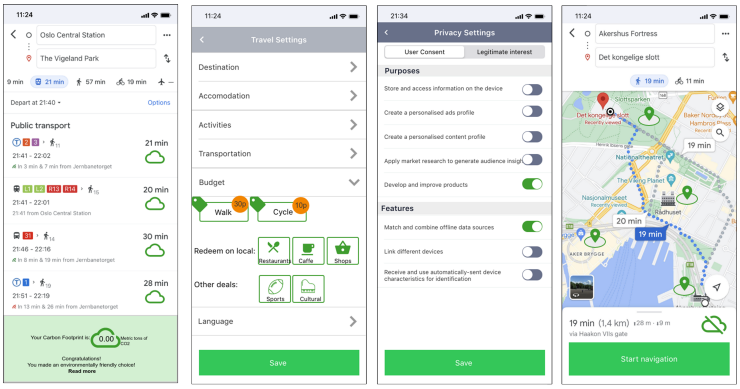

Fig. 3. From the left to the right: (a): Implementation of carbon footprint calculator for travels (DS2.5). (b): Implementation of cost-saving strategies (DS2.6). (c): Implementation of privacy settings (DS2.7). (d): Implementation of offline mode (DS2.8).

Efficiency for Travelers (DS2.6), User Safety and Privacy (DS2.3), and Usability and Universal Design (DS2.4).

Additionally, DS2.3 refers to User Safety and Privacy, which aims to enhance user confidence and provide a secure environment for users' travel experiences. Prioritization of this issue over other functionalities is recommended in MAR travel guide applications. Implementation in AudioNear will be through emergency assistance features within the app, such as an emergency line or a direct link to local authorities (Fig. 3, d). Users can easily access these features in case of any safety or security issue. This feature could be applicable to satisfying other sustainability issues, like User Empowerment.

Furthermore, DS2.4 corresponds to Usability and Universal Design and suggests a user-friendly and universally accessible app design. This will improve the overall user experience and make the app more enjoyable and functional for all users. Implementing DS2.4 with customized settings will allow users to customize app settings according to their preferences and adjust font sizes, color contrast, language and audio preferences, and other accessibility features (Fig. 3, e). Customized settings will correspond to other issues' implementation, especially the Personalized Travel Experiences (DS2.2).

On the Environmental Dimension, DS2.5 refers to Environmental Awareness and is implemented through the calculation of the travel carbon footprint (Fig. 3, a). This feature will allow users to track and monitor their carbon footprint while traveling and provide recommendations for reducing carbon emissions based on their travel preferences. This implementation is also relevant for Responsible Tourism (DS2.1) and future implemented issues, such as Minimized Carbon Footprint.

On the Economic Dimension, DS2.6 refers to the Cost Efficiency for travelers (Fig. 3, b). Implementing DS2.6 in AudioNear will embed cost-saving strategies with local tips and special offers from locals or experienced travelers.

Again, this suggestion is connected with DS2.1 and sustainable transportation. This can include tips on local markets, exclusive deals, and discounts that could provide unique experiences at a lower cost. Cost-saving strategies could support future implemented issues like Local Community Engagement and Sustainable Business Model.

On the Technical Dimension, DS2.7 refers to Technical Safety, Security, and Privacy that raise confidence in users, protect their personal information, and ensure a secure and trusted app experience. In AudioNear, DS2.7 will be implemented by embedding privacy settings, giving users control over their privacy settings and allowing them to choose what personal information is collected, stored, and shared within the app (Fig. 3, c). DS2.7 will clearly inform users about the data collection practices, while user consent will be obtained in the case of data processing activities. Implementation of privacy settings could be relevant to User Safety and Privacy (DS2.3) and Personalized Travel Experiences (DS2.2), among other sustainability issues.

Lastly, DS2.8 refers to the Connectivity and Accessibility issues. The aim is to enhance the user experience and mitigate the impact of network connectivity issues in MAR travel guide apps. In AudioNear, DS2.8 will be implemented through the offline mode of navigation maps (Fig. 3, d). Providing an offline mode or caching functionality will allow users to access essential information, such as maps, audio guides, and points of interest, when there is limited or no network coverage, ensuring accessibility in those areas. Offline mode could be extended, particularly for the audio guide feature, and is compatible with Usability and Universal Design (DS2.4).

3.4 Step 4: Synthesis and Future Steps

Sustainability issues addressed by design suggestions and solutions cannot be universally applied across all technological areas; thus, they need to be tailored to domain-specific sustainability challenges and goals. In MAR travel guide apps and the sustainability design context, the suggestions are focused on promoting responsible and sustainable tourism practices, preserving the environment and local cultures, supporting local economies, and enhancing the overall travel experience while minimizing negative impacts. Furthermore, a balanced consideration among different sustainability dimensions should be considered for a well-rounded and equitable approach to sustainability.

The design suggestions for MAR travel guide apps aim to enhance users' overall sustainability performance, create value for users and stakeholders, and contribute to a more sustainable and responsible travel experience. The use of SusAF supported this direction. Overall, the step-wise process of SusAF provides a systematic and holistic approach to developing sustainable applications. It allows the team of developers, designers, and/or other disciplines to follow a clear sequence of steps, ensuring that all relevant aspects and dimensions of sustainability are addressed. Nonetheless, during the application of the SusAF, we dealt with several challenges. First, identifying sustainability issues and their classification to dimensions is not an easy and straightforward task when applying

SusaF. It requires conducting research and benchmarking existing MAR apps or similar technologies to identify common sustainability challenges and best practices. Second, applying design frameworks demands a deep understanding of the framework and its application, which may require specialized knowledge or training. Third, translating sustainability issues into design suggestions is an iterative and ongoing process, where a deep understanding of sustainability issues, user needs, and the application context are needed.

For sustainable MAR applications, implementation of the design suggestions (Table 2) during development is recommended. This is the first step in creating sustainable MAR apps. However, it remains unexplored the development of design suggestions for all three levels of effects, their evaluation against sustainability-related objectives and how SusAF could better support the development of sustainable MAR applications. Future work should focus on evaluating the SusAF and assessing the usability and effectiveness of the SusAF on the application design. It is also part of the future work to fully develop the AudioNear v2.0 according to mock-ups. Future implementation will try to embed sustainable development, such as using open-source and lightweight library AR.js (*https://github.com/AR-js-org/AR.js*) for web-based AR and using a cloud server, among others.

Acknowledgements

This research was funded by the Norwegian University of Science and Technology (NTNU) under the Center for Sustainable ICT (CESICT, no. 2575079) for D. Chasanidou and J. Krogstie, and by the Research Council of Norway under the Gaia Vesterålen project (no. 321550) for C. Boletsis.

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