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Augmented reality situated visualization in decision-making

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Abstract Decision-making processes and decision support systems (DSS) have been improved by a variety of methods originated from several scientific fields, such as information science and artificial intelligence (AI). Situated visualization (SV) allows presenting visual data representations in context and may support better DSS. Its main characteristic is to display data representations near the data referent. As augmented reality (AR) is becoming more mature, affordable, and widespread, using it as a tool for SV becomes viable in several situations. Moreover, it may provide a positive contribution to more effective and efficient decision-making, as the users have contextual, relevant, and appropriate information that fosters more informed choices. As new challenges and opportunities arise, it is important to understand the relevance of intertwining these fields. Based on literature analysis, this paper introduces the main concepts involved, and, through practical examples, addresses and discusses current areas of application, benefits, challenges, and opportunities of using SV through AR to visualize data in context to support better decision-making processes. In the end, a set of guidelines for the design and implementation of DSS based on situated augmented reality are proposed.

Keywords Decision-making · augmented reality · situated visualization

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1 Introduction

Over the past years, technology has been enhancing the way we perceive and act in the world around us. An example of this is the use of Decision Support Systems (DSS) to aid in the process of decision-making in numerous scenarios. These systems have been an active subject of scientific research and are at a crossroad of various areas such as information science, cognitive psychology, and Artificial Intelligence (AI). The process of decision-making has been a major focus of several scientific fields, as it develops methods for making rational choices. "Good decision-making" means users are informed and have relevant and appropriate information on which to base their choices, among multiple alternatives [1].

Methods enhanced by a variety of approaches have been developed using computer programs to help in the complex process of decision-making. Such methods are often given the common name of Decision Support Systems [2]. The DSS area, as a matter of study and practice, continues to expand horizons, often combined with other major information system expansions, such as pervasive computing [3]. It is noteworthy that more than a decade ago, the DSS community was already aware of the importance of supporting decision-makers "anytime anywhere", which AR (in general) and situated visualization (more specifically) may facilitate.

DSS is a wide area of research [4]. Various researchers have approached the field from various vantage points and report different accounts of what was important [5] [6]. While there have been several definitions of DSS, the one that seems generally accepted is a computer-based system that in some way assists in decision-making [7]. In contrast, a decision can be viewed as "a non-random activity ending in the selection of one from among multiple alternative courses of action" [8].

Some common and accepted characteristics of a DSS, found in the literature long ago [9] [10], rather than automate decision-making, support decision-makers at any level in an organization in semi-controlled and unstructured problems (less structured problems frequently need the participation of individuals from different departments and organization levels). More specifically, these characteristics are support for interdependent or sequential decisions, support for intelligence, design, choice, and implementation, support for a variety of decision processes and styles, and adaptive over time (to deal with changing conditions). It is also possible to list several other attributes, which allow a broader perspective on the DSS concept [11] [12] [13], such as adaptability and flexibility, high level of interactivity, ease of use, efficiency and effectiveness, complete control by decision-makers, ease of development, extensibility, support for modelling and analysis, support for data access, standalone, integrated, and web-based, facilitate specific decision-making activities and/or decision processes, be used routinely or as needed for ad hoc decision support tasks, execute sensitivity analysis and improve accuracy, timeliness, quality as well as the overall effectiveness of independent and/or sequential decisions.

It is possible to classify DSS concerning the mode of assistance provided [14] [15] [16] according to the following five categories: model-driven (emphasizing access to and manipulation of statistical, optimization, or simulation models), communication-driven (aiding more than one person working on a shared task), data-driven (emphasizing the access to and manipulation of data), document-driven (managing free information in a variety of electronic formats), and knowledge-driven (providing specialized problem-solving expertise stored as facts, rules and procedures).

The main components of a DSS are database management (the required data may come from internal or external databases), model management (to store and access models that help the decision-making), and support tools, like, for instance, online help and graphic presentation. The typical types of DSS are the status inquiry system (to help to make decisions at an operational level, executive level, or middle-level executive - for example, everyday schedules of posts to machines or machines to operators), the data analysis system (requires comparative analysis, based in formulas or algorithms - for example, cash flow analysis and inventory analysis), the information analysis system (data is analysed to produce a report - for example, sales and market analysis), the accounting system (to keep track of the main characteristics of the business - for example, final receivables and payables accounts), and the model-based system (simulation or optimization models utilized for decision-making, establishing standards for operation or management).

Another area that gains from the boost of the technology is Situated Visualization (SV), the presentation of data in their spatial and semantic context, that can aid in complex decision-making processes. Similarly, the evolution of Augmented Reality (AR), made solutions that were unpractical until recently possible [17].

Whereas visualization may leverage the capacity of virtually all types of DSS and decision tasks to support the decision process, SV may extend this applicability beyond the desktop through AR, paving the way to the pervasive computing paradigm, which envisions support to decision-makers "anytime, anywhere" [3][18].

As AR is becoming more affordable, mature, and widespread, using it as a tool for SV in DSS is becoming viable. The growing interest in these fields and their combined potential highlights the importance to address and understand the current contributions provided by SV using AR in the decision-making process.

This paper addresses the mentioned topics based on literature analysis and introduces the main concepts involved, and, through examples, addresses and discusses current areas of application, benefits, and challenges of using AR to visualize data in context to support better decision-making processes. It also identifies research opportunities where the combination of SV and DSS make sense. This work is an extension of a previous one [19], where generally the paper revision was extended and a new set of guidelines, regarding the design and implementation of decision support systems based on situated augmented reality, is proposed.

All the concepts and examples resulted from a literature review, performed as inclusive as possible using the following methodology based on three phases: parameter calibration, the search process itself and the analysis of the outcomes. Electronic databases were defined ensuring coverage of books, journals, conference, and workshop proceeding articles, between 1980 and 2020. The used databases were Web of Science (Clarivate Analytics), Google Scholar and Scopus. Specific keywords ("Augmented Reality" AND "Situated Visualization" AND "Decision-Making") were selected for the search and Boolean logic was applied to further refine initial search results and obtain a more manageable number of publications to analyse. Only publications in the English language were considered as this is the current "lingua franca" of the academic research.

The article is organized as follows. Section 2 introduce concepts of AR and SV based on illustrative examples. Then, section 3 presents cases of usage for situated AR DSS, identifies its areas of application, and discusses benefits, challenges, and research opportunities. Finally, concluding remarks and the future of situated augmented reality DSS are discussed in section 4.

2 Augmented reality, AR-based visualization and situated visualization

Next, fundamental concepts regarding the augmented reality, AR-based and situated visualizations are presented to provide a better understanding of this paper.

2.1 Augmented reality

The concept of augmented reality can be described as a ”human-machine interaction tool that overlays computer-generated information in the real-world environment” [20] [21]. The processes of exhibition and overlay of information are context-sensitive, which means that they depend on the observed objects [20]. This definition is not limited to a specific sense. AR has the potential to be applied to other senses as well [22], displaying information not directly available or detectable by the human senses [23] [24]. The term ”augmented reality” appears for the first time in [25], although it is commonly accepted that the first AR system has been presented in [26]. However, it was Azuma, in [23], that defined the three main characteristics necessary for an AR experience: the combination of real and virtual content, interaction in real-time, and registration in 3D (the virtual elements must be aligned, or registered, with real-world structures).

AR may be viewed as an intermediate step between Virtual Reality (VR) presenting a virtual world and the unmodified real-world in the ”reality-virtuality continuum”, proposed by Milgram and Kishino [27]. Both VR and AR have the goal of immersing the user, although these two different paradigms use different approaches to accomplish this goal. While VR offers a digital recreation of a real-life environment, AR uses computer-generated technology to blend virtual reality and real life, displaying virtual elements as an overlay to the real world, making it more meaningful through the ability to interact with existing virtual elements. Interaction with these elements may provide a different perception of the real world and thus a richer experience [27]. AR, unlike VR, does not aim to fully replace the physical environment, but to present virtual stimuli, while keeping the sense of presence from the individual experiencing it, trying to improve reality, instead of replacing it [21] [28]. Depending on the context, AR may take advantage of two different references. The first is visual clues/labels to provide additional information regarding real-world elements (Fig. 1), to know when and where to present the virtual content, which is currently the most used. The second, location-based, places content according to the real-world geographic location and an estimation of the user’s viewpoint (e.g., using GPS and other sensors). This last reference is used to show information not aligned in 3D with objects (and although it is not AR according to Azuma’s definition, it is called AR, e.g., in the media).

AR applications have been growing significantly in different fields with the development of easy-to-use frameworks and the reduction of hardware costs [30] [31]. The most common application domains of AR are education (e.g., a real-time cosmic scanner), architecture, games, entertainment, medical, art, industry/military maintenance (supporting equipment or appliances maintenance procedures), business, tourism (e.g., maps that use AR tips to show information regarding places of interest), indoor navigation, marketing (e.g., Rayban© virtual mirror to try on glasses[1]), and telecommunications/broadcasting [17] [21] [31] [32] [33] [34] and it is expected that AR will soon spread to daily tasks [35] [36].

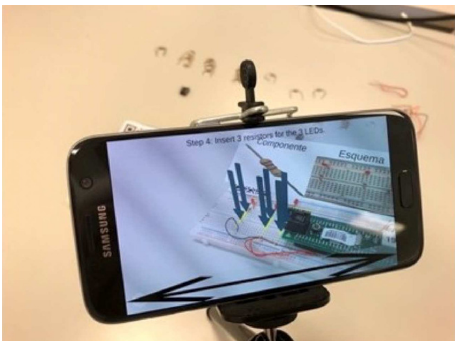

Fig. 1: Example of visualization in context using augmented reality to provide visual cues to assist in the assembly of electronic circuits [29].

Regarding AR device types, not bound to any specific technology [31] [32], Nizam et al., in [33], show that most systems rely on mobile devices, also known as handheld displays (possible to use with a single hand and equipped with both a display and a camera [17] [20]), typically using the device's camera to detect markers and deploy an enhanced version of the environment by blending digital components into the real world (camera's image). Although they are spread worldwide, cheaper, and less intrusive, handheld devices are not appropriate for immersive experiences [17] [37]. As an answer to the lack of immersivity and the need to have hands free AR systems, see-through-based devices are gaining ground (nevertheless they are not without issues and challenges). In this equipment the user sees the real-world in a natural form, the device only provides the digital content and the user's brain merges all the real and virtual information together. These devices are an evolution of the famous head-mounted displays (HMD), commonly used in VR. The HMD used in AR, that merges both real-world images and virtual content and feeds them to the user's eyes simultaneously, belongs to the see-through-based device group. Other categories of AR devices are the desktop computer-based (not mobile) and projection-based groups [38]. The latter uses video projection techniques, lasers, LCD/LED projectors, holographic technology or radio-frequency and is also known as the spatial display because the display of visual information on real-world objects is usually not connected to the user [17] [37]. It is suitable for multiple users without the need for them to wear any kind of device, which is particularly relevant for task performance and collaborative settings. When the virtual content needs to be overlaid directly on the surface of a real object, the use of projection-based devices brings more benefits as it provides the natural coincidence of vergence and accommodation of the human

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[1] http://www.heritagemalta.org/ray-ban-virtual-mirror-app.html

visual system (an issue with the other types of solutions) [39]. Nee et al., in [20], introduce other AR devices with haptic, and force feedback capabilities (wearable devices that provide feedback to the user without distractions from the task to be performed).

To easily perform decision-making tasks using AR, it should be used handheld or see-through-based devices with a specific AR-based visualization (the situated visualization). This occurs because not all these tasks are confined to a single place and the need for interaction, in the field, must consider the user's context.

2.2 AR-based visualization

Visualization could be defined as the communication of data, a process of interpreting data that is not immediately seen and representing it in a visual form to produce readable and understandable images [40]. Munzner, in [41], explains that "computer-based visualization systems provide visual representations of data sets designed to help people carry out tasks more effectively" and that "visualization is suitable when there is a need to augment human capabilities rather than replace people with computational decision-making methods". According to Card et al., in [42], visualization can also be defined as the use of computer-based, interactive, visual representations of data to amplify cognition, linking the visualization definition with the AR (the augmentation of the perception of conventional reality).

AR visualizations can be divided into two types: visual augmented reality (VAR) and spatial augmented reality (SAR). In VAR, the computer-generated content is overlaid into the user's visual field, as can be seen in Fig. 2(a). In SAR, the digital content is overlaid on the physical space [43], as can be seen in Fig. 2(b).

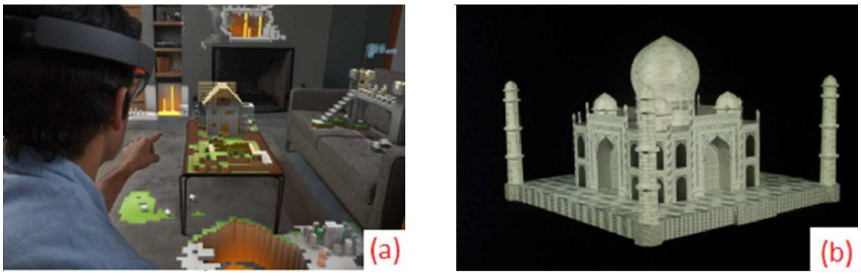

Fig. 2: Examples of augmented reality visualizations, from [43]. (a) Visual augmented reality. (b) Spatial augmented reality, where a one-meter square physical model of the Taj Mahal is augmented with a shader lamps technique.

Also, Kalkofen et al., in [44], organized visualization techniques based on AR in three main categories: data integration, scene manipulation and context-driven visualization. Concentrating only on the last category, given the scope of this paper, the visualization techniques can be congregated in different groups, such as situated visualization, the object as context, the sensor data as context, and the scene as context. In SV, the visualization of the virtual information is intrinsically related to its environment. As can be seen in Fig. 3 the virtual information is related to the street walk (the real environment). Since SV is a more open concept, it can deal with issues that are characteristic of the other groups. The visualization techniques in the object as context are used when the digital information is presented according to the real-world object in the scene, which is recognised by the AR system. The techniques from sensor data as context deal with virtual information that represents invisible aspects of a scene, specifically the data that comes from the sensor and wherein the scenario it is coming from. An example of this is the visualization presenting the level of concentration and position of carbon dioxide on a street, acquired from an environmental sensor, as can be seen in Fig. 3. Regarding the scene as context, the visualization techniques are applied when the depiction of the digital information considers the scenario that is seen (for example, avoiding placing information over relevant aspects of the scene or ensuring that the visualization itself is legible). Fig. 3 presents an example of the visualization technique scene as context, where the virtual information is meticulously fused in the street walk.

Fig. 3: Example of a context-driven visualization (simultaneously considered situated visualization, sensor data as context and scene as context), from [44].

2.3 Situated visualization

The concepts of mobile and outdoor solutions adapt perfectly to the paradigm of AR, not being confined to a single place, allowing interaction in the field using different types of tracking (e.g., markers, sensors, GPS) and interface (e.g., handheld devices, headgear, etc.) [45]. This serves as a basis to the concept of situated visualization, referring to a visualization related to its environment. Besides this, one of the main advantages that AR systems offer is that additional digital information of the process can be visualized and explored directly overlaid on the images of that world. Situated visualization (SV), introduced in [46] [47] [48], is exactly about that advantage. It encompasses all the visualizations that change their appearance based on context, by considering visualizations that are relevant to the physical context in which they are displayed [44]. In other words, SV occurs when the visualization of the virtual information is intrinsically related to its environment, giving meaning to White's words "through the combination of the visualization and the relationship between the visualization and the environment" [47] [48].

Examples of SV based on AR can be seen in applications that present the underground infrastructure of the place where the user is [49] [52], as can be seen in Fig. 4(a), the level of concentration and position of carbon dioxide on a street, acquired from an environmental sensor [48], as can be seen in Fig. 3, the identification of points of interest in scenarios of a city [50], as can be seen in Fig. 4(b), the presentation of information depending on the viewer's distance (in a library) [53], or that guide a user through assembly tasks. It should be noted, however, that using AR technology to display visualizations does not imply that the visualizations are situated, as it is the case when the displayed virtual elements are not physically related to the viewed real-world entity (and might as well be presented by a VR system) [54]. Examples of this visualization type can be found, for example, in [51] (presenting a way to investigate common properties of dynamical systems on a personal interaction panel), as can be seen in Fig. 4(c), in [20] (showing an AR tool for industrial assembly of parts), and in [55] (a prototype which allows users to perform tasks such as data dynamic filters, attribute selection, semantic zoom and details on demand, in a desktop information visualization tool).

Fig. 4: Examples of: (a) Situated visualization (SV) of physically-based data type, from [49], (b) SV of abstract data type, from [50], (c) Non-SV, from [51].

According to the SV definition, it is not the type of data to be displayed that defines the visualization as situated. Data is a purely logical entity. Thus, it is possible to have SV with both abstract data type (ADT) and physically-based data type (PBDT) [54]. Both can be situated with the advantage of being displayed and explored directly in the spatial reference frame of the real world [54]. In the PBDT, the behaviour of real-world elements is defined by the physical laws that rule the 3D world. Examples of physically-based data are addressed in [48], as can be seen in the example of Fig. 3, in [49], as can be seen in the example of Fig. 4(a), and in [56], while abstract data are visualized in [53] and in [50], as can be seen in the example of Fig. 4(b).

Regarding technology, SV systems are not dependent on any specific system. SV systems do not even have to require the use of AR technology as they can be created with simple methods, for example, printing information about an object on a paper and taking it near the object itself. However, emerging technologies make it possible to create elaborate forms of SV based on AR [43]. These technologies must assist users in swiftly building visualizations that combine real information with the digital one. Yet, Merino et al., in [57], observe that existing SV toolkits generally lack such responsiveness.

The characterization of SV must start with the understanding of what it means for data visualization to be spatially situated. According to [43], a "visualization is spatially situated if its physical presentation is close to the data's physical referent". A physical referent is "a physical object or physical space to which the data refers" [58]. The term "close", used in this definition, is left vague on purpose because situatedness is lying on a continuum with different levels. For example, a visualization projected on a physical object (the referent) is spatially more situated than a visualization viewed on a mobile device near the referent.

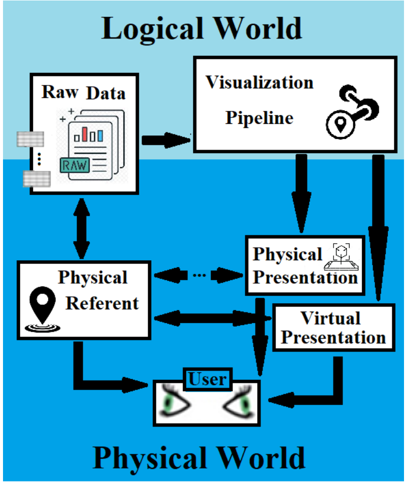

Fig. 5: Conceptual model of situated visualization, adapted from [58].

For a better explanation, Thomas et al., in [43], present a theoretical model of a spatially SV, mainly based on the model from [58], which covers both logical and physical worlds, as can be seen in Fig. 5. The visualization pipeline only requires the logical world, but the existence of a physical world is necessary for SV since data visualizations are intertwined with the physical environment. Fig. 5 only represents the information path between the raw data and the user, ranging from the transformation of the raw data, the visualization pipeline (composed of a sequence of geometric transformation matrices), to a comprehensible visual representation (the rendered images). One of the existing connections between the logical and the physical world links the visualization pipeline with the physical presentation module, as can be seen in Fig. 5. A physical presentation is "the physical object or apparatus that makes the visualization observable" [59]. Only with physical presentation can the user see the information created from the transformed raw data [59]. Another way to connect the logical and the physical worlds is through the dashed connection between the raw data and the data's physical referent -

shown in Fig. 5 - meaning that the raw data can have several referents and that sometimes some referents may not be seen by the user [43]. The dashed arrow between the physical referent and the physical presentation represents the distance among them. If the physical referent and the physical presentation share the same space, both can be seen by the user, at the same time. When this happens, the visualization is called spatially situated.

It is common knowledge that distance is perceived in a relative way. This divergence in the perception of the distance between physical referent and the physical presentation is common in AR [21]. So, to avoid the vagueness of the definition of spatially SV, Thomas et al., in [43], suggest the following definitions: "A visualization is physically situated in space if its physical presentation is physically close to the data's physical referent" and "A visualization is perceptually situated in space if its percept (physical or virtual presentation) appears to be close to the percept of the data's physical referent". Thus, perceptually SV can be related to virtual presentations and that is the reason to include the component of virtual presentation in Fig. 5.

Another important physical property in the characterization of SV is embedded visualization. According to [58], embedded visualization "is the use of visual and physical representations of data that are deeply integrated with the physical spaces, objects, and entities to which the data refers". So, this differentiates the SV situations, in which the data is displayed close to data referents, from embedded visualization, which displays data so that it spatially coincides with data referents (i.e., physical spaces, objects and entities to which the data refers). The concept of embedded visualization has a more limited scope and introduces more challenges. SV and embedded visualization are connected to newly defined research areas, namely immersive analytics [60] [61] and situated analytics [62] [64], which imply the "use of data representations organized in relation to relevant objects, places and persons for the purpose of understanding, sense-making and decision-making" [43]. Analytical reasoning is facilitated by visual interactive interfaces [63]. Situated analytics aims to support analytical reasoning using SV. Due to the growing concern in understanding situated information directly related to their current situation, there are many areas in which situated analytics might apply to. A good example is retail applications because the grocery shopper has a wealth of information directly and indirectly available about products on the shelf: price, ingredients, nutritional information, information about the manufacturer, origins of ingredients, the sustainability of the manufacturing processes, expiry date, and comments about the product in social media [64].

According to [43], SV may also be related to another physical dimension when the data changes over time. In their definition "a visualization is temporally situated if the data's temporal referent is close to the moment in time the physical presentation is observed". An example of temporally SV could be the user's water consumption, which can be estimated and visualized at different moments. A spatially and temporally situated example is presented in Fig. 3, showing in real-time a representation of the polluted air, measured within the place where the user is.

Fig. 6 presents the theoretical model for interaction with situated visualization proposed in [43] and constructed from the embedded visualization [58] and the beyond-desktop [59] visualization models. This conceptual model represents all the possible interactions between a user and a spatially SV system, showing the interaction with the visualization pipeline (pertaining to all interactive visualizations), as well as interaction with the physical referent and the physical representation, specific to SV. This allows physical action to follow analytical reasoning and decision-making, more promptly than when visualizations are not situated. Also, if the system is real-time and the physical referent is the data source, analysis and action can be interweaved, including altering the data [43].

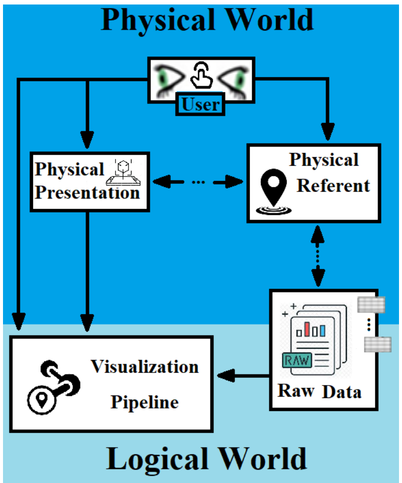

Fig. 6: Theoretical model for interaction with SV, adapted from [43].

Since all the interactions are originated from the user, the information flows - black and dashed arrows in Fig. 6 - have opposite directions regarding the model presented in Fig. 5. Both the user interactions that need the visualization pipeline (passing or not by the physical presentation) could belong to any kind of interactive visualization system (situated or not). The flow that comes from the user to the physical referent is specific to SV. The first mode of interaction with the visualization system happens when the user performs operations that modify the visualization pipeline. Examples of such operations are selecting, filtering, or highlighting data, changing the visual representations, or changing the camera parameters [59]. These operations allow a greater concentration of the user in the information related to the decision to be made. To accomplish these modifications in the visualization pipeline through interactions, information from sensors must be collected and combined with software to understand the user's actions. Changing the physical representation is the second mode of interaction the user can perform. According to [59], the reorganisation of the physical elements (by moving them or by moving around) can give the user new perceptions of the physical presentation and extend the possibilities of interactions, overcoming the limitations of the interaction's first mode. This second mode allows the user to have a more global view on the decision situation. The reason for having a black arrow linking the physical presentation to the visualization pipeline, in Fig. 6, is because some of the user's physical interactions affect the visualization pipeline as well. When the information that flows from the user passes through the physical referent, as mentioned, the visualization system is situated, and the third way of interaction appears. It also makes the physical referent visible and, usually, accessible, and manageable [58]. If the user interacts with SV, analysis and actions can be interlaced and actions could be taken forthwith, including modifying the raw data if the system is in real-time and the physical referent is the data source - dashed link between the raw data and the data's physical referent in Fig. 6. For example, a visualization of traffic lights could dynamically update itself according to traffic accumulation. Classical visualization usually does not support this type of interaction [43].

3 Situated visualization in decision-making

The fact that visualization enhances human memory in distinct manners has been long recognized since humans can process visual cues in parallel. In this vein, working memory, long-term memory, and visual cognition [65] can be augmented through visualization, saving space in working memory, as well as facilitating internal computation and comprehension of domain knowledge, fundamental in making future decisions. Equally important, using visualizations can aid users in finding and understanding existing patterns in large amounts of data. It may also help in the process of information acquisition during decision-making, not only to help reach a decision but also to explain the process and the decision more clearly [66].

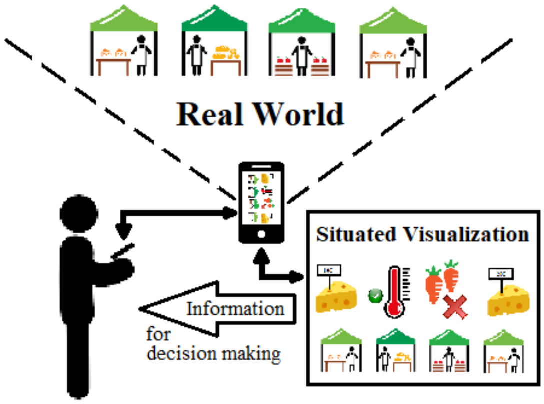

Fig. 7: Illustrative example of a simple decision of selection based on a situated visualization of data corresponding to each alternative item.

Figure 7 illustrates an example of situated visualization in the decision-making process. In this example, a user goes to his usual market to buy fresh bread, cheese, and carrots. The visualization system, using the context information, presents two prices for his favourite cheese (one from each sales stand). Also, it provides the bread temperature with a notification indicating whether it is freshly baked or not. The system also perceives and informs the user that there are no carrots for sale in that market. With all the information given by the situated visualization, the user makes simpler decisions of what to buy. Regarding this example, the SV can show abundant information to ease the decision process, like nutritional values of the displayed food, harvest details, smells, known allergens, if kept in a proper environment, etc.

Visualizations can be used to support the analytical, subjective, and judgmental approaches to assess alternatives in a decision-making process between several individuals [66]. It may also support individual decisions in scenarios where information is obtained from numerous sources. According to Zhu and Chen, in [66], several approaches may be supported through visualization, allowing decision-makers to comprehend patterns from large amounts of information, increasing knowledge and awareness. In analytical approaches, the use of visualization refers to the use of mathematical models. Regarding subjective approaches, decision-makers can draw subjective conclusions based on data and opinions they collect from visualizations. Finally, when using judgmental approaches, decision-makers base their decisions on intuitions rooted in their domain knowledge, previous experience, and awareness of the situation. These authors also explored the impact of information visualization in the decision-making process and the role it might play while supporting different tasks. In this context, they recognize no universal visualization exists able to address all possible decision-making tasks. Therefore, specific visualizations and decision-makers must take into consideration the characteristics of the tasks, to ease the decision-making effort. This is in-line with the now widely accepted user-centered methodology for designing effective visualization systems [41].

As the applicability of visualization is extended beyond the traditional desktop environment thanks to the concept of situated visualization (allowing its use and viability in more scenarios of application), this concept improves sense-making by presenting data more understandably through its association with the pertinent physical objects. Besides, it delivers a more natural interaction, since the decision-makers can touch and manipulate physical objects, thus facilitating information analysis based on contextual data, as well as the decision-making process [43]. Notwithstanding the clear benefits that SV can bring to the decision-making process, its combined usage with DSS is still rare, possibly caused by the novelty of such concepts. Nevertheless, we argue that it will soon become more common due to its supporting technology and advances in theory. Next, some examples of AR usage that assist in the decision-making process are presented as SV, even though they were not qualified as such by their authors.

3.1 Examples of current usage

In the literature, only a few applications that utilize AR with DSS were uncovered. Be that as it may, it is possible to present some fascinating and exploratory examples that make use of AR to support decisions.

The SARDE (Spatial Augmented Reality Design Environment) project, proposed by Chen and Chang [67] to assist students in interior design decisions, is one of the prior examples. As can be seen in Fig. 8, it uses an AR projection-based device. A frequent challenge faced by novice designers is the gap between what they aim to do and what they have drawn on paper. Specific problems are scale, textures, and how they are represented in distinct circumstances. SARDE projects virtual images onto the physical environment, adapting the student's drawings on-site with visual feedback. This system educates novice designers in making decisions, giving them more confidence in presenting their future projects. The application's evaluation, with novice and experienced designers, concluded that it must offer more contextual data to help novice designers. This ease of adaptation and potential learning, in real-time, are important benefits of the AR-supported DSS systems. The evaluation's conclusion reinforces the challenge and the opportunity of using situated visualization and exemplifies why some tasks, when the user's context matters, are better done with situated AR.

Fig. 8: Manipulation of an interactive augmented reality surface to obtain a design decision, from [67].

Another example is the utilization of augmented reality to assist in training and decision-making to improve the capacities of the maintenance professionals in the embedded electronics field [68]. This European Union funded project starts to provide a unified platform (composed by a baseboard with field-programmable gate array and extension boards with microprocessors) which covered a complete process for embedded system learning. It was validated within the universities, institutes, and research centres to allow the initial system to be in the market. In the final product, AR provides an interactive, natural, and efficient learning tool. The AR mobile-based device is used to assist in maintenance procedures, simplifying the access to specifications and the path leading to the explicit execution of the assignments, and helping specialists and operators in decision-making (upheld by the related DSS which operates dependent on information provided accordingly to each specific task). These characteristics allow situated AR-supported DSS users to a swifter understanding of the tasks and systems, as well as more effective interventions, all the benefits of using this kind of system.

The work of Caricato et al., in [69], aims to propose a model integrating technical and organizational metrics for DSS by analysing the application of AR technologies in manufacturing scenarios. The main objective of this DSS is to assess the feasibility of applying AR devices in different manufacturing contexts. The authors performed an analysis of the current fields of applications of AR systems and concluded that this technology could be used in different phases relevant to the maintenance process, ranging from the design phase to production process control phase. The authors employed a multi-criteria approach based on an analytic hierarchy process, deriving the criteria of the supply chain operations reference model (SCOR model), to build an integrative model. This study aimed to select the most effective AR system for supporting performance improvement in a specific manufacturing process, involving the use of mobile-based, video-see-through-based

(HMD), projection-based, user tracking and haptic, and force feedback devices. A test case was done to validate the proposed method. The decision goal considers the assessment of the most efficient AR systems employed to enhance information sharing performance during on-site maintenance. This example highlights the challenge of selecting the best AR device to the right task, which, when poorly chosen, can jeopardize the entire DSS.

Another pertinent example is a system that utilizes AR and DSS for lodging health and security [70]. This mobile-based application creates value in the following vital ways: search for dwelling options, find out alternatives and make an initial negotiation table, provide augmented reality services, complete a multiple criteria analysis of choices, make negotiations based on real calculations, determine the most rational dwelling purchase variant, statistical analysis, decision-making cluster, and complete analysis of the loan alternatives offered by certain banks. CO2, NO2, as well as other indicators, are also detected and the DSS gives customized recommendations for enhancing living conditions, while AR presents real-time data about specific places. The authors argue that because of these upgrades it is conceivable to produce conditions for a superior quality of life, lower disease levels and raise the residents' labour productivity, important benefits of DSS based in situated AR.

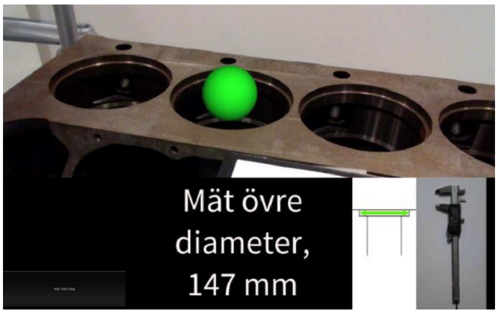

Fig. 9: Example of AR instructions for a quality control decision task [71].

Combining AR and DSS techniques can also be applied to shop-floor operations. The perspective of a shop-floor operator using AR with DSS is described by Syberfeldt et al. [71], where they state that these systems must operate in real-time and with the right information, time, and place, as can be seen in Fig. 9. The operator using these systems will have improved skills compared to the actual ones, as the technology impact will change these operations. They also point out directions for the future of shop-floor operations citing location awareness and user-tailored interactions with AR. The four prototypes, built for industrial shop-floor scenarios (considered different objectives), used see-through-based, video-see-through-based, and projection-based devices. Seven manufacturing companies were associated with the evaluation process, participating in workshops and interviews. Two main benefits/challenges were behind this study, the high work productivity, and the cost reduction.

Another example is seen in the work of Milovanovic et al. [72], who made an overview of systems that use VR and SAR to support the collaborative design and decision-making in architectural education. All the presented examples can be understood as an opportunity of being able to offer SV to their users whether they view illustrations of architectural constructions on physical 2D plans, information about contaminants on an estate location, or component specifications on a circuit panel, supporting the user's choices, even when there is no conventional DSS. We claim that these examples are indications of a sort of system that incorporates AR-based SV and decision support, which may have multiple application areas and become more common and accessible as technologies and theory advance (as predicted to happen shortly), possibly posing tough challenges, while providing possible benefits and research opportunities.

More recent examples of applications using AR with DSS can be found in scenarios of industry 4.0. The work of Fraga et al., in [73], presents a review of industrial augmented reality (IAR) systems applied to help in shipbuilding and maintenance. In shipbuilding, production and construction can overlap, and an AR interface can help in the manipulation of CAD data in real-time. In the face of the many steps of a maintenance process, an AR device, based on SV, can be used to indicate a step-by-step process of a task and to locate elements necessary to its completion. It also proposes an architecture for future shipbuilding mobile-based IAR application, the Shipyards 4.0, which allows the remote operator to combine the physical experience with the display of information to support their decision-making (see Fig. 10). The big challenge/opportunity is how to deepen the DSS.

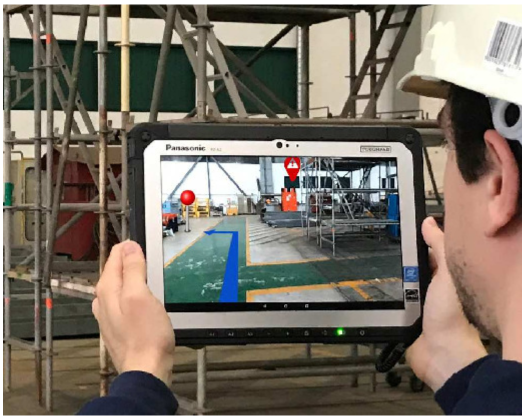

Fig. 10: Example of an AR application, based on situated visualization to be applied with DSS in shipbuilding and maintenance [73].

As explained in previous sections, the AR maintenance area can have a lot to gain from using SV and DSS. So, it is important to mention that Lorenz et al., in [74], present requirements for an AR maintenance support system, divided into several domains: user, technical, environmental, and regulative. The requirements regarding users are about information availability and presentation, as well as ergonomics. The technical support requirements aim to allow the previous ones to be fulfilled. The environmental and regulative concerns exposure to external factors, taking also into account the necessity of safety gear usage. The authors point out different challenges and conclude that currently there are no devices suitable to work in harsh conditions which allow different user perspectives and free hands.

The most recent example of a decision-making application based on situated augmented reality can be found in [75]. The proposed video-see-through-based application was designed for assisting decision-making in electromagnetic compatibility (EMC) testing context. This application was meant for aiding skilled users to investigate electromagnetic fields and EMC information in general, as can be seen in Fig. 11. The suggested solutions were compared among each other in similar 2D and 3D interactive visualizations of the same information in a sequence of data-extraction evaluations with users to prove the approaches.

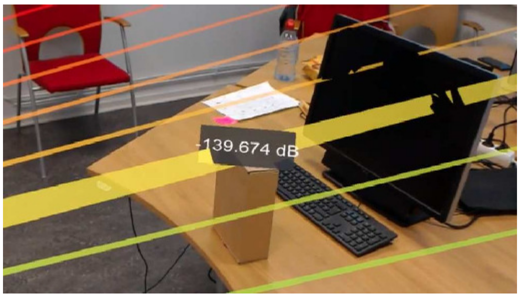

Fig. 11: Example of a situated AR application for DSS (user quantifying the signal intensity reaching a target cardboard box) [75].

A summary of the main results and insights are presented in Table 1.

Table 1: Summary of the main results and insights.

Pub	Year	Area	AR Type	DSS	Evaluation	Main outcomes
[67]	2006	Interior design	projection-based	✓	Experienced designers could complete the design decisions with only a small sketch. No novices could do that. The application must offer more contextual data to help novice designers.	A decision making training tool on-site for novice designers.
[68]	2013	Maintenance in the embedded electronics (training and assistance)	Mobile-based (handheld display)	✓	Validated within universities, institutes, and research centres to allow the initial system to be on the market.	A system to assist in training and decision making to improve the capacities of the future and present professionals in the embedded electronics.

Pub	Year	Area	AR Type	DSS	Evaluation	Main outcomes
[69]	2014	Manufacturing	Mobile-based (handheld display), video-see-through-based (HMD), projection-based, user tracking and haptic, and force feedback	✓	A test case was done to validate the method. The decision goal considers the assessment of the most efficient AR systems employed to enhance information sharing performance during on-site maintenance.	A multi-criteria model, integrating technical and organizational metrics, to offer reliable DSS for analysing the application of AR technologies in manufacturing (assess different AR systems).
[70]	2016	Real estate	Mobile-based (handheld display)	✓	—	An application that creates value in the following important ways: search for dwelling alternatives, find out alternatives and make an initial negotiation table, provide augmented reality services, complete a multiple criteria analysis of alternatives, make negotiations based on real calculations, determine the most rational dwelling purchase variant, statistical analysis, groupware decision making and complete an analysis of the loan alternatives offered by certain banks.
[71]	2016	Industrial Shop-floor operations	See-through-based, video-see-through-based, and projection-based	✓	Four prototypes were built for industrial scenarios (taken into account different objectives). For assessment, workshops, and interviews were done with seven companies.	A study, in collaboration with industrial manufacturers, to apply augmented reality in its operations (present advantages and disadvantages of different solutions from a shop-floor operator's perspective)
[72]	2017	Education	—	—	—	Overview of applications of virtual reality and augmented reality in the field of architectural design, showing a variety of possible uses of systems to accompany decision-makers in their architectural design process

Pub	Year	Area	AR Type	DSS	Evaluation	Main outcomes
[73]	2018	Industry 4.0 shipyard	Mobile-based (handheld display)	—	—	A revision of the different aspects that influence the design of an industrial augmented reality (IAR) system for the Industry 4.0 shipyard, considering diverse scenarios like workshops and a ship. It also proposes an architecture for future shipbuilding IAR applications.
[74]	2018	Maintenance	—	—	—	Lists the user, technical, environmental, and regulatory requirements for an AR maintenance support system, collected by studying three different production places.
[75]	2020	Electrical engineering	Video-see-through-based (HMD)	✓	The suggested solutions were compared among each other in similar 2D and 3D interactive visualizations of the same information in a sequence of data-extraction evaluations with users to prove the approaches. Extra feedback was asked from the participants, after each test condition, for a broader evaluation.	An application designed to assist in decision-making in an electromagnetic compatibility (EMC) testing context. The exemplary case of application was meant to aid skilled users to investigate electromagnetic fields and EMC information in general.

3.2 Benefits, challenges, and opportunities

According to the literature analyzed, the main advantages of DSS, potentially providing competitive benefits are [2] [11] [68] [70] [72] [76] better interpersonal communication, significant decision-maker fulfilment, time, and cost reductions, as well as higher productivity and improvement in efficiency and effectiveness. By using DSS, decision-makers are encouraged to explore and discover using new methods to brainstorm the task at hand and generate new evidence to support their decisions.

In the same way, supporting DSS through situated AR may present the following advantages: enable the design and development of memorable sensory experiences, able to enhance interconnection and captivate decision-makers' awareness. Also, eliciting more natural data exploration, leading to quicker learning of new skills, facilitating flaw detection and high work productivity. Hence, fostering a better comprehension of the available course of actions, making faster, more informed decisions, with greater satisfaction. As such, it seems reasonable to assume that applying SV solutions can lead to further enhancement of the characteristics of DSS.

Using AR as a tool for SV in decision-making implies challenges that impact its applicability and usefulness. Willet et al., in [58], discuss these trade-offs and point-out research challenges. In addition to the traditional challenges inherent to visualizing data, SV for AR in decision-making presents additional difficulties since the visual representations are presented through AR, namely the dynamic and distracting nature of the real world. These specific challenges are, according to [54], visual coherence (to deliver data that makes sense to the decision process), temporal coherence (the data must be given in the exact time or else becomes pointless), visual interference (to distinguish crucial information from the irrelevant one, avoiding the occlusion of vital data by the virtual content), egocentric viewpoint (to see/collect data outside of the current viewpoint, avoiding or mitigating alterations of the user's position), data overload (to provide the needed information, avoiding confusion and lack of clarity), dynamics of the situation (to keep track of the changes done in the scenario or the user's viewpoint when digital content is merged, avoiding confusing outcomes), and registration with the real world (to overlay the digital content at the exact position).

Analytics is an important tool in decision-making. According to Thomas et al., in [43], analytics moving into the "real world" raises challenges at technical, methodological, and conceptual levels. Situated analytics fosters a more "casual" approach to analytics than the traditional data analysis, which uses a desktop, and this will involve rethinking how to design, implement and evaluate situated tools, entailing new methods, guidelines, and frameworks. The creation of immersive visualizations in SV for DSS is still a challenging task. Sicat et al., in [77], present a new framework that tries to expedite it, offering developers an efficient way to specify visualization designs by using a concise declarative visualization grammar.

As suggested by previous examples, DSS enhanced by situated AR can act as solutions to enhance construction scenarios, architectural design, as well as industrial maintenance, training, and safety management, easing cooperation and dialogue between decision-makers by augmenting selected data with interactive interfaces, providing methods for rapid and intuitive exploration of information. Likewise, it is possible to envisage other use cases, like marketing, shopping, or natural sciences, which may take advantage of the characteristics offered by SV through AR, unable to be recreated by traditional methods. The use of these technologies can facilitate understanding of phenomena and promote more informed decisions, if properly designed, considering the users, their tasks and context.

An escalation in the adoption of SV solutions in DSS is expected soon. Meanwhile, future research efforts will continue to explore new developments by resorting to fields like simulation, optimization, AI, machine learning, human-computer interaction, data mining, software engineering. Equally important, is taking advantage of organizational decision-making, planning and organizational behaviour [16]. Advances in these fields will contribute to increasing the effectiveness of individual and group decisions.

Considering all the revised work and the experience with design and implementation of AR applications, a set of guidelines for the design and implementation of DSS based on situated AR are proposed in the following:

- Always involve professionals as consultants and communities of practice in the sector in which the DSS based on situated AR is being created;
- Match the capabilities of the DSS based on situated AR to its potential users (one size does not fit all), ensuring its relevance when released (more complex ones could take 3 to 4 years to complete);
- Produce comparative studies and make an independent evaluation to understand whether the DSS based on situated AR are accomplishing their purpose and if they can be improved;
- Deliver comprehensible and clear directives (whenever possible, through real-world objects), appropriate contextual information, and informative feedback while balancing its amount, so that the user does not lose focus of the real-world and is more aware of the surroundings. The world must be enhanced, not replaced (do not overload the user, but be explicit with the relevant and indispensable). Use visual exogenous cues for simple tasks (for example, picking and locating an object) and employ endogenous visual indications for more complex tasks (such as assembling a machine);
- Support redundant interaction mechanisms, inspired by the natural interactions performed by humans. Use quick micro-interactions, with limited input (one input per interaction) and limited tasks per interaction to reduce its time and have the same usability and interest from the users. Any task should be interruptible at any time and the user should control the pace of task interactions;
- Make the interface not just for the user but also for the people around the user (for instance, a mobile AR application is typically used pointing to the real-world and, sometimes, unintentionally directed at someone. This situation is not taken lightly by some people because it suggests an intrusion).

4 Concluding remarks and future work

Since the beginning, mankind has always needed to make decisions. Nevertheless, systems that support decision-making have only been around for a short time, brought forth by the increase of scientific research in the field and the advances in computer programs. Likewise, the evolution of situated visualization systems is now able to present more and better data in context, and therefore give more assistance in complex decision-making. Evidence of this can be seen in applications in the last decade. So, since AR is now more mature, and affordable, the use of augmented reality as a tool for SV in DSS has become viable.

The main concepts along with the benefits, challenges, and opportunities of using augmented reality for situated visualization in the process of decision-making and DSS were examined based on literature analysis. Moreover, considering all the revised work, a set of guidelines for the design and implementation of DSS based on situated augmented reality was proposed.

As these fields and their combined usage grow in popularity, the integration of situated visualization through AR is presented as a logical step for the further enhancement of DSS characteristics (e.g., permitting rapid and intuitive exploration of data, earlier detection of possible flaws, high work productivity, among others). This keeps users more informed and gives them more precise data to support an effective and efficient decision. Although not a lot of studies and applications were found, there were interesting exploratory examples identified in architectural design, construction, as well as industrial maintenance, training, and safety management.

Similarly, all the mentioned enhancements create additional challenges and opportunities. The continual exploration of new theory and technology developments associated with AR and SV is of the utmost importance in the process of decision-making and DSS. Natural and interactive interfaces and environments should be considered, which may speed the process of understanding the available options, facilitating design collaboration and discussion, allowing more efficient and effective support of individual and group decisions.

The relatively recent incorporation of AI into the traditional DSS has produced new advanced intelligent decision-support systems (IDSS). With it, it is possible to understand a broad variety of inputs and choose the finest course of action. Using machine learning, IDSS could learn from former instances and enhance with time, delivering more efficient decisions, permitting its users to concentrate more on their soft skills and quality of the interaction.

The main vulnerability of an IDSS is counting on the user's input, subjective and susceptible to error. To avoid that, the future of the situated augmented reality IDSS should be based on computer vision and deep learning. Computer vision will reduce the necessity for user input, by allowing the IDSS to automatically gather information inside of the user's field of view, and will improve the precision of identification and decision-making, delivering better results according to the IDSS' objectives.

Situated AR-based IDSS will be a valuable instrument to give a large variety of benefits to daily tasks when eliminating the dependency on human input, allowing users to focus on the bigger picture. So, the future will pass through merging cognitive understanding and cognitive vision to produce substantially superior decision-making capabilities.

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