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Usability Heuristics for Applications in the Context of Resilient Cities

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Abstract. This research establishes a set of usability heuristics for designers and developers of interactive software systems that are used in the context of resilient cities, and thus contributes to the specification of a tool for the evaluation and design of solutions for this context. The article describes the research process carried out to identify a set of 15 usability heuristics, which are grouped into five families: (1) design and aesthetics, (2) flexibility and navigation, (3) errors and help, (4) information use and display, and (5) community. The heuristics were validated through various mechanisms, such as the application of the heuristics, expert judgment, and evaluation, to ensure their clarity and effectiveness. The implementation of these heuristics is expected to contribute to the ease of use of interactive software systems in resilient city contexts, so that citizens can enjoy a user experience that is satisfactory to stakeholders.

Keywords: Resilient Cities, Usability, User Experience, Usability Heuristics.

1 Introduction

Godschalk [1] mentions two reasons for resilience being an important goal. The first arises from the vulnerability of socio-technical systems [2], as these cannot be fully predicted, and it therefore becomes evident that resilience (the ability to adapt to change gracefully, without catastrophic failure) should receive greater emphasis in decision-making [3]. Secondly, people and property are likely to be more successful in resilient cities (RCs) affected by disasters than in less flexible and adaptable places that are faced with unusual stresses [4, 5]. As a result, many cities have now made the decision to transition to the RC model.

Although there are projects around the world that have contributed to resilience, many of these have scientific objectives. For this reason, this article focuses on the development of interactive software systems for the context of RCs from a user-centred approach, since there is a need to establish general design rules or usability heuristics that can lead to applications with a high level of usability.

Usability has been a well-known concept for decades, while user experience (UX) is a broader concept that encompasses usability. Evaluation of usability and UX is an important task that should be performed when developing any kind of website [6]. It is necessary to assess whether a website meets the needs of its users and whether it fits properly into the physical, social and organisational context in which it will be used. In this regard, it is important to evaluate whether an application for the context of RCs is intuitive, easy to use, and allows users to achieve their objectives. UX should be explicitly considered, since the information, content, presentation and structure of the application should contribute to a user-friendly experience, and should motivate people to learn about the characteristics of these applications in the context of RCs.

In general terms, methods of evaluating usability/UX can be classified into two types: (1) inspections, in which expert evaluators inspect a product to detect potential usability/UX problems; and (2) tests, where real or representative users interact and complete tasks using a product, system, or service. Heuristic evaluation is probably the most common method of usability inspection. This is a method that stands out in regard to its great ability to find usability problems; it is also inexpensive and easy to perform. In this process, experts use empirical rules to measure the usability of user interfaces in independent runs, and report any problems detected [6]. However, domain-specific problems can be missed, and for this reason, the use of appropriate heuristics is very important [7]. Evaluators may have experience in this type of evaluation, but if they do not know the business rules, several usability problems are unlikely to be identified. In view of this, there is a need to generate a set of usability heuristics to facilitate the design and evaluation of applications with a high level of usability for the context of the RC.

Nielsen's heuristics for the web [8] have been used as a basis for specifying usability heuristics with a focus on various contexts [9], such as mobile applications, grid computing, online shopping systems, and social networks, among others. However, recent reviews of the state of the art in usability heuristics defined for different domains [10] show that there are few proposals for heuristics specific to the context of RCs.

This research contributes to the work of designers and developers of interactive software systems by offering a set of 15 heuristics for applications in the context of RCs, which can facilitate the process of design and implementation of future systems in this context. The heuristics were developed using the methodology proposed by Quiñones et al. [7]. Using these heuristics, designers and developers will be able to define specific requirements and restrictions for this type of system, which will optimise resources and facilitate their development. In addition, systems in this context can be evaluated using these heuristics to determine whether they comply with the requirements for usability, UX attributes, and context-specific characteristics.

This article is organised as follows: Section 2 reviews a set of previous works that are taken as references for this research. Section 3 explains each of the stages of the methodology, as well as its application. Section 4 presents the results achieved for each stage of the methodology. Section 5 introduces the usability heuristics proposed for applications in the context of RCs. Finally, Section 6 presents a discussion of this research and the results obtained.

2 Background

2.1 Usability

According to ISO 9241-210 [11], usability is defined as "the extent to which a product, system, or service can be used by specific users to achieve specific goals with effectiveness, efficiency and satisfaction in a specific context of use". This definition focuses on the concept of quality and the use of a certain product, system or service. Usability relates to how the user achieves their specified goals, the resources used to achieve the goals, and the degree to which the user's needs are met. Jakob Nielsen indicates that the nature of usability is multidimensional [12], while Nielsen states that usability has the following five attributes [12]:

1. Learnability: This relates to the ease of learning the operation and behaviour of the system by inexperienced users.
2. Efficiency: This is the level of productivity attainable once the expert user has already learned the system. The greater the usability of a system, the faster the user can use it, and thus the more rapidly work can be done.
3. Memorability: This is the ease of remembering the functionality of the system, so that the occasional user, when returning to the system after an inactive period, does not need to learn how to use it again.
4. Errors: The system must have a low error rate; that is, users should make few mistakes while using the system, and when they make them, the system should help them recover easily.
5. Satisfaction: This is the most subjective attribute, and represents the extent to which the user finds the system pleasant to use.

To develop our heuristics for applications in the context of RCs, all of Nielsen's usability attributes were considered.

2.2 User Experience

UX extends the concept of usability beyond effectiveness, efficiency and satisfaction. According to the ISO 9241-210 standard, UX can be defined as a person's "perceptions and responses resulting from the use and/or anticipated use of a product, system or service" [11]. It states that UX "includes all the users' emotions, beliefs, preferences, perceptions, physical and psychological responses, behaviors and accomplishments that occur before, during and after use". In addition, the ISO 9241-210 standard remarks that UX "is a consequence of brand image, presentation, functionality, system performance, interactive behavior and assistive capabilities of the interactive system, the user's internal and physical state resulting from prior experiences, attitudes, skills and personality, and the context of use" [11].

Peter Morville has proposed a model based on seven factors that explain UX [13] as follows:

1. Useful: The content must be original and satisfy a need.
2. Usable: The product or system must be easy to use.
3. Desirable: Image, identity, brand and other design elements are used to evoke emotion and gratitude.
4. Valuable: The product or system must add value for the interested user.
5. Findable: The product or system must have a good navigation scheme and its content must be easily found, so that the user always finds what he/she needs.
6. Accessible: The content must be accessible to various types of people, including those with disabilities.
7. Credible: Users must trust and believe what is presented to them.

2.3 Heuristic Evaluation

A heuristic evaluation is an expert inspection method that identifies the usability/UX problems that users may encounter when using a product or an interface [14]. This is one of the most widely used evaluation methods, as it has a low cost and allows for the rapid identification of usability errors on a website, application or any system that interacts with the user.

Between three and five expert evaluators evaluate the interface by detecting usability/UX using heuristics. These usability heuristics, which may be generic (as for Nielsen's heuristics [8]) or specific (applied to evaluate usability, UX and specific application domains). According to the chosen set of heuristics, the evaluators are responsible for detecting potential usability/UX problems that a user might encounter when interacting with the system interface under evaluation.

Initially, evaluators work independently to find and document problems. The previous experience that each evaluator has with the system may influence the number of problems encountered. Subsequently, work is carried out in a group, where the evaluators compile a single list of the problems that have been identified. Individual work then continues, in which each evaluator independently qualifies the severity, frequency and criticality of each of the problems on the common list. Finally, they return to work in a group to consolidate and interpret the results. A ranking of usability/UX problems is established that indicates which problems are more serious, and therefore more urgent in terms of being corrected.

2.4 Resilient Cities

According to the United Nations Strategy for Disaster Reduction, an RC is one with the capacity to resist, absorb, adapt, and recover from the effects of danger in a timely and efficient way, including the preservation and restoration of basic structures and functions [15]. Meerow and Stults [16] have found that RCs have 16 characteristics, which are summarised in Table 1 and are taken as a reference for the development of this research.

Table 1. Characteristics of resilient cities (source: Meerow and Stults [16])

Characteristics	Description
Robustness	Ensure that municipal infrastructure and organisations can withstand external shocks and quickly return to their previous operational state.
Redundancy	Ensure that backup systems, infrastructure, institutions, and agents are in place.
Diversity	Ensure a diverse resource base, infrastructure, and economics (do not rely on a single mode of operation, solution, or agent/institution).
Integration	Ensure that plans and actions are integrated across multiple departments and external organisations.
Inclusiveness	Ensure that all users have access to municipal infrastructure and services, including the opportunity for all people to participate in decision-making processes.
Equity	Ensure that the benefits and impacts associated with the actions are felt equitably throughout the municipality.
Iterative process	Create a process whereby feedback and lessons learned are used to inform future actions.
Decentralisation	Decentralise services, resources, and governance (solar or wind energy; stronger local governance).
Feedback	Build mechanisms for rapid feedback of information to decision-makers or system operators.
Environment	Protect natural systems and assets.
Transparency	Ensure that all municipal processes and operations are open and transparent.
Flexibility	Make municipal operations and plans more flexible and open to change when necessary.
Forward-looking	Use information on future conditions (population, economy, and climate) in community planning and decision-making.
Capacity to adapt	Ensure that all users have the capacity to adapt to climate change.
Predictability	Ensure that systems are designed to fail predictably and safely.
Efficiency	Improve the efficiency of government and external operations.

2.5 Usability and UX in the Context of Resilient Cities

Jacob Nielsen [8] has identified 10 essential heuristics that any software system must at least contain in order to ensure a good UX and to guarantee the usability of the system. This work is of vital importance, as these heuristics are a reference and can be adapted to other applications that will be used in the context of resilience.

Bayrak [17] sought to identify and define the factors on which any type of natural disaster depends, in order to prevent it or to respond appropriately in the shortest possible time. These factors were intended to improve disaster prevention and monitoring systems. This project provides specific characteristics that an application must comply with in the context of resilience in order to function correctly, and it is necessary to ensure that these characteristics are supported and tested. This allows for the detection of important aspects when proposing specific heuristics and new items in the checklists associated with each heuristic.

A study conducted by Delgado et al. [18] found that natural park websites have their own characteristics (providing updated information, virtual experiences, and multimedia resources, among others), and that it was necessary to establish a set of usability heuristics specific to this type of website. Based on some of the characteristics to be taken as a reference (asynchronous interaction, credibility of information, and multimedia resources), it was possible to identify a series of heuristics to adapt to the context of RCs.

Dowding and Merrill [19] proposed a set of heuristics for evaluating dashboard visualisations, which were rated by 10 experts and corroborated based on 49 usability factors. In addition, since dashboards are typically used to represent information, it is important to have a set of well-tested and documented heuristics to ensure that the checklist items that can be applied in the context of RCs are the appropriate ones.

The above review of the state of the art allowed us to detect a few works related to the definition of specific usability heuristics in the context of RCs. However, there are also several existing heuristics that could potentially be adapted to the context under study, such as heuristics for grid computing [20], information visualisation [21], dashboard visualisations [19], and a set of requirements for a disaster monitoring system [13]. These related heuristics consider issues related to large amounts of data and visualisation of these data, to enable a team of people/experts to make decisions. In our case, the data generated in the context of resilience (natural disasters and citizen security, among others) will be used by government entities for data visualisation and strategic decision making in the face of various incidents that may occur in the city. In view of this, a set of relevant heuristics can be used as a basis for developing specific heuristics according to the characteristics of applications used in the context of an RC.

Against this background, this research aims to provide designers and developers with a series of heuristics that are specifically for use with applications in the context of RCs, to facilitate the process of design and implementation of future systems that may be developed in this context. Based on these heuristics, designers and developers will be able to address the specific requirements and constraints on this type of system, which will allow for optimisation of resources and will facilitate their development. In addition, systems in this context can be evaluated with these heuristics to determine if they meet usability, UX, and context-specific requirements.

3 Methodology

To develop a set of usability heuristics for applications in the context of RCs, we used the methodology for developing UX heuristics proposed by Quiñones et al. [7]. This methodology has already been applied to develop several new sets of heuristics for other application domains, such as online travel agency applications, websites, social networks, and video games. The process is divided into eight stages (see Table 2), which can be performed iteratively. In certain situations, some stages may be optional, some may overlap, and/or a stage may be stopped with the possibility of returning to a previous stage.

Table 2. Stages in the methodology (source: Quiñones et al. [7])

No.	Name	Definition
1	Exploratory	Conduct a literature review to gather information on the specific domain, its characteristics, usability/UX attributes and existing sets of heuristics (and/or other relevant elements).
2	Experimental	Analyse the data obtained through various experiments to gather additional information that has not been identified in the previous step.
3	Descriptive	Select and prioritise the most important topics from all the information gathered in the previous stages.
4	Correlation	Match specific characteristics of the application domain with existing usability/UX attributes and heuristics (and/or other relevant elements).
5	Selection	Maintain, adapt, and/or discard the existing usability/heuristics/UX sets that were selected in Step 3 (and/or other relevant elements).
6	Specification	Formally specify the new set of usability/UX heuristics using a standard template.
7	Validation	Validate the set of heuristics through various experiments (heuristic evaluations, expert judgments, user testing) in terms of their effectiveness and efficiency in evaluating the specific application.
8	Refinement	Refine and improve the new set of heuristics based on the feedback obtained in Step 7.

Based on the steps set out above, the following aspects are considered here in association with each of the stages.

Stage 1: Exploratory. This stage involves obtaining the definition and characteristics of an RC, as well as establishing the usability and UX attributes. It is important to highlight that the characteristics of an RC, as well as the usability and UX attributes, formed the main input when performing a search for existing heuristics related to the context under study.

Stage 2: Experimental. From the literature review conducted in Stage 1, it was possible to determine in detail the 16 characteristics of an RC, five usability attributes, seven UX attributes, and several research works in which usability heuristics had been proposed. It was therefore considered unnecessary to carry out Stage 2, since there was sufficient information to move on to the following stages. It should be clarified that this stage is optional, according to the authors of the methodology.

Stage 3: Descriptive. In order to prioritise the most important elements to consider when specifying the heuristics, a value should be assigned to reflect the relevance of the characteristics of a RC, and the usability and UX attributes.

Data obtained from different sources (sensors, social networks, user reports, and government databases, among others) must be visualised and processed to extract relevant information to support decision making. For this reason, characteristics such as feedback, a forward-looking outlook, predictability, an iterative process, and efficiency were considered important.

In addition, community participation (users, governmental organisations, and third-party organisations) is an important factor in the resilience of a city, as this allows the community to be informed about the events that happen and to contribute.

Features such as inclusiveness and transparency were also given priority. The features of redundancy, adaptability, flexibility, and integration were considered important because they are mostly included in and/or are a consequence of the important features.

The characteristics of environment, decentralisation, robustness, diversity, and equity were considered unimportant, since they cannot be addressed through usability heuristics as they depend on the management and administration of governmental entities.

The five usability attributes used here were those proposed by Nielsen [22]. They were considered somewhat important, as they satisfy the minimum needs related to usability.

The UX attributes we considered were those proposed by Morville [13]. Attributes such as usefulness, usability, findability, and credibility were considered important in view of the characteristics of the RC context. The attribute of accessibility was considered somewhat important, but due to its complexity it could not be covered in a broad way. The attribute of desirability was considered to be a result of the usability attributes as much as the UX attributes.

Stage 4: Correlational. This objective at this stage is to identify possible heuristics. The usability heuristics identified in this process were grouped into related RC features and assigned a family of heuristics. The characteristics of an iterative process, a forward-looking outlook, redundancy, transparency, efficiency, and feedback belong to the first family of heuristics (information processing and visualisation), since they are related to the management of information and its use in the best possible way, including its storage, visualisation, and use. The second family of heuristics (community) was formed of the characteristics of inclusiveness and adaptability, since these are related to the participation of users and organisations, and are necessary in order to have a community where everyone can contribute and be informed. In addition, systems are required to possess the attributes of usability and UX [13, 22], which is how the third, fourth, and fifth families of heuristics (design and aesthetics, flexibility and navigation, and errors and help) were proposed.

Stage 5: Selection of heuristics. When the existing heuristics had been selected in Stage 3 and grouped in Stage 4, a selection of useful heuristics was made based on the characteristics of the RC context. The possible actions that could be performed on each heuristic at this stage were to maintain, adapt, or discard them.

Stage 6: Specification. At this stage, two iterations were applied. In the first, a preliminary version of the heuristics for applications in the context of RCs (HRC) was obtained, which included 15 heuristics grouped into five families. In the second iteration, after the validation process, it was possible to refine the proposed heuristics (HRCU).

Stage 7: Validation. Two iterations were applied at this stage. In each iteration, different validation mechanisms were applied to refine the proposed heuristics and to determine the clarity and effectiveness of each of them.

First iteration

a) Application of heuristics

For the application of preliminary heuristics (HRC) in the design process, we worked with the Telematics and Applied Informatics Research Group (acronym GITI in Spanish) of the Universidad Autónoma de Occidente (UAO), Cali, Colombia, which oversees the ResCity project. A platform based on the Internet of Things (IoT) was developed to improve resilience, and to allow social entities to participate in addressing emergency events and systemic conditions that affect the city of Santiago de Cali. It also considers two types of resilience: sporadic events (such as earthquakes, floods, and fires), and daily situations (such as unemployment, insecurity, and lack of access to education) [23].

Two software applications were developed in this project, one of which focused on the context of flooding and the other on biosecurity protocols. In the rainy season, the city of Cali is subject to serious flooding problems in areas close to the city's rivers, such as Cauca, Cali, Pance and Lili. Flooding affects homes, inhabitants, mobility, crops, frequent tree falls, suspension of the energy supply, and the provision of drinking water. A report entitled "Santiago de Cali Emergency Response Strategy", published by the Cali mayor's office, identified the communities with the most flood events between 1949 and 2018 [24]. Those with more than 100 flood events were surrounded by rivers, and included Cauca, Cañaveralejo and Cali. Floods in Cali are recurrent, as much of the territory is flat and the eastern neighbourhoods of the city are below the level of the canals and the Cauca River. In addition to this, the sewage system becomes inoperable in the rainy season due to the presence of garbage. In view of this problem, a software application was developed for the acquisition, transmission and processing of data on floods that occur in the city of Cali for integration with the ResCity platform.

In addition, in the period 2020 to 2021, the world was faced with a pandemic caused by the COVID-19 virus. This led to the creation and application of biosafety mechanisms across the globe, in a bid to reduce the spread of the virus. In the city of Cali, several measures were taken to control the disease, such as minimum distancing and mandatory use of face masks, among others. However, there was evidence of a lack of compliance with the regulations imposed by the city. Valle del Cauca became the department with the third highest number of people infected by the virus in the country [25]. The lack of citizen awareness forced the local government to take new measures to improve the monitoring and control of citizens who did not comply with the provisions, such as an increase in the period of confinement and limitations on the use of trade premises. Taking these situations into account, a software application was developed for the acquisition, transmission and processing of data on the different biosafety controls in the city of Cali.

During the design of the two software applications mentioned above, the heuristics were socialised among four designers who were multimedia engineering students with knowledge in the area of human-computer interaction. They applied the heuristics to the design of the systems, and an interview was then carried out in order to gather their perceptions regarding the use of the heuristics in the early stages of design.

b) Expert judgment

To validate the quality of the preliminary set of heuristics (HRC), a survey was conducted to obtain the opinion of expert evaluators of each of the heuristics in the set. This survey was adapted from the one proposed by Quiñones et al. [7], and included three dimensions: D1: "Usefulness", D2: "Clarity", and D3: "Need to add items to the checklist". The "Ease of use" dimension was not included, as the evaluators were not using the heuristics. The survey response form made use of a five-point Likert scale (where five was the best rating and one the worst) for each of the heuristics in the three dimensions. Evaluators could also add comments on each heuristic.

A total of 11 experts responded to the survey, from various countries (Colombia, Chile, Mexico, Peru, and Spain), with an average of 10 years of experience in usability evaluation. Dimension D3: "Need to add items to the checklist" was not considered in this analysis, as it was stated in an ambiguous way; some of the evaluators were confused about which was the best or worst rating, meaning that the results were not completely reliable. In order to evaluate this dimension, we considered the comments made by the experts.

Once the first iteration of validation was complete, the team adjusted the heuristics, resulting in an updated set of heuristics that were submitted again to the validation process.

Second Iteration

a) Heuristic evaluation

To validate the updated set of heuristics (HRCU), a heuristic evaluation was carried out based on the Colombian Geological Survey web application [26]. The web application was evaluated by two groups of evaluators, each consisting of three practitioners from the Multimedia Engineering program of the UAO, with knowledge in the discipline of human-computer interaction and experience of performing heuristic evaluations. The control group used Nielsen's set of heuristics [8], while the experimental group used the set of heuristics proposed for applications in the context of HRCU resilient cities. The usability/UX issues identified were compared in order to assess the effectiveness of the HRCU suite, based on the five criteria proposed in [7, 9].

Stage 8: Refinement. Based on the feedback received from the two validation mechanisms used in the first iteration of the validation stage (application of heuristics and expert judgment), the preliminary set of heuristics (HRC) was refined, resulting in an updated set of heuristics (HRCU). This set contained 15 heuristics grouped into five families.

4 Results

Stage 1: Exploratory. Table 3 summarises the most relevant issues identified from the literature review as being necessary for the conception of usability heuristics for applications in the context of RCs. At this stage, the specific characteristics of the software systems used in the context of RCs were determined, and the usability and UX attributes were included to allow us to start defining the heuristics. These elements were of vital importance, as they served as a starting point for the development of the following stages of the methodology.

Table 3. Relevant elements of the literature review (source: own elaboration)

Subject	Selected information
Information about RCs	Definition, types, and characteristics of an RC
Characteristics of an RC	All of the characteristics proposed by [16] were selected: (1) robustness, (2) redundancy, (3) diversity, (4) integration, (5) inclusiveness, (6) equity, (7) iterative process, (8) decentralisation, (9) feedback, (10) environment, (11) transparency, (12) flexibility, 13) forward-looking outlook, (14) adaptability, (15) predictability, and (16) efficiency. In Stage 3, they were prioritised based on their level of relevance.
Usability attributes	All of the usability attributes proposed in [22] were selected: (1) ease of learning, (2) recall over time, (3) efficiency, (4) errors, and (5) satisfaction. In Stage 3, they were prioritised based on their level of relevance.
User experience attributes	All of the user experience attributes proposed in [13] were selected: (1) useful, (2) usable, (3) findable, (4) trustworthy, (5) desirable, (6) accessible, (7) valuable. In Stage 3, they were prioritised based on their level of relevance.

Stage 3: Descriptive. Table 4 summarises the values assigned based on the relevance of the characteristics of an RC, the usability, and the UX attributes.

Table 4. Relevance of RC features, usability attributes, and UX (source: own elaboration)

	Value indicating relevance (3: highly important, 2: somewhat important, 1: not important)		
Subject	3	2	1
Resilient city feature	Feedback, inclusiveness, forward-looking outlook, predictability, iterative process, efficiency, transparency	Flexibility, redundancy, integration, adaptability	Environment, decentralisation, robustness, diversity, equity
Usability attributes	Efficiency, ease of learning, recall over time, error rate, satisfaction		
UX attributes	Useful, usable, findable, credible	Accessible, desirable	Valuable

Interactive software systems used in RC contexts typically include web and mobile applications. Web applications are used by administrators and analysts of computer control institutions, as they require optimal visualisation and performance [17, 27], whereas mobile applications are typically used by city residents, due to the large number of people who own smartphones and the portability of these devices [28, 29]. Thus, according to related case studies, the proposed heuristics for smartphone applications [30] and the traditional heuristics defined by Jakob Nielsen [8] are useful for this study. Similarly, due to the need to handle of significant amounts of data, usability heuristics for grid computing applications [20] are also considered in this work. Other relevant heuristics and documents are summarised in Table 5.

Table 5. Existing sets of related heuristics and relevant documents (source: own elaboration)

Set/documents	Justification
Ten usability heuristics for user interface design [8]	Defines the basic principles for interaction design
EUHSA: Extension of usability heuristics for smartphone applications [30]	Based on the characteristics of smartphones (small screen size, mobility and variable context, single window, etc.), an extended set of heuristics for smartphone applications were proposed
Usability heuristics for grid computing applications [20]	Since grid computing is based on the sharing of different types of computational resources that are geographically distributed, these heuristics are useful
Theoretical analysis of uncertainty visualisations [31]	Describes the application of perceptual and cognitive theories to the analysis of uncertainty visualisations; useful for the visualisation of collected data
A set of heuristics for evaluation in information visualisation [21]	An investigation was carried out to synthesise a set of heuristics focused on information visualisation
A taxonomy of tasks by data type for information visualisation [32]	Considers seven tasks (overview, zoom, filter, details on demand, relation, history and extracts); useful for the visualisation of data collected by the system
Four data visualisation heuristics to facilitate thinking in personal informatics [33]	Four heuristics were identified for the design and evaluation of personal computing systems by analysing self-tracking devices and applications
UX heuristics on national park websites [18]	Usability heuristics for national park websites; useful for visualising city locations
Development of heuristics to evaluate dashboard visualisations [19]	Heuristic evaluation checklist that can be used to evaluate systems that produce information for visualisation; it was combined with heuristic principles previously developed by researchers specifically for evaluating information visualisation
Design and evaluation of online communities: The research speaks about emerging practice [34]	Describes heuristics for community-centred participatory development; useful for creating community among city users
Data visualization in the Internet of Things: Tools, methodologies and challenges [35]	Comprehensive survey of visualisation methods, tools and techniques for the IoT; useful for the visualisation of data collected by the system.
Identifying requirements for a	Defines three sets of factors for designing a disaster

Set/documents	Justification
disaster monitoring system [17]	monitoring and response system; useful for monitoring data;
SNUXH: A set of UX heuristics for social networks [36]	offers a set of heuristics focused on social networks that are useful when considering resident participation

Stage 4: Correlational. Table 6 presents the relationships between the characteristics of the RCs, usability and UX attributes with the proposed families of heuristics and the existing sets of heuristics.

Table 6. Relationships between RC characteristics, usability and UX attributes and the proposed families of heuristics (source: own elaboration)

RC features, usability and UX attributes	Proposed family of heuristics	Existing heuristics
Iterative process (RC), forward-looking outlook (RC), redundancy (RC), transparency (RC), efficiency (RC), feedback (RC)	Information processing and visualisation	IVH1: "Codification of information" [21] IVH10: "Data set reduction" [21]
Inclusivity (RC), Adaptability (RC), Accessible (UX), Credible (UX)	Community	HS: "Heuristics of sociability" [37].
Desirable (usability)	Design and aesthetics	NH1: "System visibility" [8] NH2: "Relationship between the system and the real world" [8] NH8: "Aesthetics and minimalist design" [8] NH4: "Consistency and standards" [8]
Usable (UX), findable (UX), efficient (usability)	Flexibility and navigation	NH3: "User control and freedom" [8], NH6: "Recognise rather than remember" [8] NH7: "Flexibility and efficiency of use" [8]
Predictable (RC), desirable (UX), errors (usability), satisfaction (usability)	Errors and help	NH5: "Error prevention" [8] NH9: "Helping users to recognise, diagnose, and recover from errors" [8] NH10: "Help and documentation" [8]

Stage 5: Selection of heuristics. In the process of selecting useful heuristics according to the characteristics of the RC context, no heuristic remained unchanged; that is, 38 heuristics were adapted, where similar heuristics were integrated, some were separated to create new ones, and others were joined to the proposed heuristics. Sixty-five were discarded, as they were either not related to the context or had already been selected for another set. In addition, four heuristics (HRCU 7, 12, 13, 14) were created for the evaluation of specific characteristics, such as inclusiveness, forward-looking outlook, transparency, iterative process, feedback, efficiency, and adaptability.

Stage 6: Specification. In the first iteration of this stage, the first version of the heuristics for applications in the context of resilient cities (HRC) was obtained. This version included 15 heuristics grouped into five families (see the first column of Table 7).

In the second iteration, refinement of the set of heuristics (HRC) was performed, resulting in an updated set of heuristics (HRCU). This set contained 15 heuristics grouped into five families (see the second column of Table 7), which were defined after the first iteration of validation (in stage 7) and refinement (in stage 8).

Table 7. Set of heuristics for RC applications developed in each iteration (source: own elaboration)

First iteration (HRC)	Second iteration (HRCU)
HRC1 - Relationship between the system and the real world	HRCU1 - Relationship between the system and the real world
HRC 2 - Simplicity	HRCU 2 - Simplicity
HRC 3 - Consistency	HRCU 3 - Consistency
HRC 4 - Feedback	HRCU 4 - Feedback
HRC 5 - Extraordinary users	HRCU 5 - Browsing
HRC 6 - Browsing	HRCU 6 - Recognising rather than remembering
HRC 7 - Recognising rather than remembering	HRCU 7 - Flexibility and efficiency of use
HRC 8 - Flexibility and efficiency of use	HRCU 8 - User control and freedom
HRC 9 - User control and freedom	HRCU 9 - Error prevention
HRC 10 - Error prevention	HRCU 10 - Recovering from error
HRC 11 - Recovering from error	HRCU 11 - Support and documentation
HRC 12 - Support and documentation	HRCU 12 - Display of information
HRC 13 - Display of information	HRCU 13 - Use of information
HRC 14 - Processing of information	HRCU 14 - Informed community

Stage 7: Validation

First iteration

a) Application of the heuristics

The qualitative feedback obtained from the interviews with the designers who participated in the two case studies related to flooding and biosafety protocols was considered positive, but it was insufficient to determine the clarity and ease of application of the heuristics proposed for the design stage of interactive software systems. The designers found the proposed heuristics useful and easy to remember, and were familiar with them as they were related to the Nielsen heuristics. Moreover, they were adapted to the RC context, and could therefore contribute to the evaluation and detection of specific usability problems in systems used in this context.

b) Judgment by experts

Table 8 shows the average results of the experts' evaluation for the dimensions of usefulness (D1) and clarity (D2) of each heuristic, as well as the population standard deviation for each dimension. For dimension D1, the lowest average was 3.9 (HRC15 - Community), although the standard deviation was 0.79, since seven of the experts' evaluation scores were between four and five.

For dimension D2, the lowest average was 3.6 (HRC15 - Community) and the associated standard deviation was 0.88, since eight of the experts' ratings scores were between three and four, and only one rating was below these values. In view of this, it can be inferred that the heuristic was perceived as being clear; however, it should be reviewed and adjusted to make it specific to the RC context. Regarding the clarity of the heuristics, the highest standard deviation was 1.21 (HCR12 - Help and documentation), where 10 of the ratings were between three and five, and one rating was the lowest value on the scale.

Table 8 shows that there were some other high values with respect to the standard deviation. It was considered that heuristics HRC2, HRC5, HRC6, HRC9, HRC13 and HRC14 should be reviewed and adjusted with high priority, and subsequently submitted to another validation mechanism.

Table 8. Average values and population standard deviation of the experts' evaluations (source: own elaboration)

Heuristic	D1 - Usefulness	Standard deviation D1	D2 - Clarity	Standard deviation D2
HRC1- Relationship between the system and the real world	4.4	0.65	4	0.79
HRC 2- Simplicity	4.2	0.86	3.8	1.02
HRC 3- Consistency	4.6	0.64	4.5	0.65
HRC 4- Feedback	4.6	0.77	4.6	0.64
HRC 5- Extraordinary users	4.3	0.97	4	0.95
HRC 6- Browsing	4.1	0.93	3.7	1.05
HRC 7- Recognising rather than remembering	4.4	0.65	4.1	0.71
HRC 8- Flexibility and efficiency of use	4.6	0.64	4.2	0.74
HRC 9- User control and freedom	4.7	0.61	4.0	1.04
HRC 10- Error prevention	4.6	0.64	4.0	0.84
HRC 11- Recovering from errors	4.4	0.65	3.9	0.66
HRC 12- Support and documentation	4.5	0.78	3.7	1.21
HRC 13- Display of information	4.5	0.65	3.7	1.13
HRC 14- Processing of information	4.2	0.71	3.8	0.93

HRC 15- Community	3.9	0.79	3.6	0.88

The experts also expressed their views on whether the HRC set was correctly specified, whether it was useful, and which elements they would add or remove. The experts made the following statements:

It is recommended that the concepts should be homogenised as far as possible, if the heuristics are proposed cross-culturally, i.e., to think of generic concepts with respect to the mental models of different types of users (countries).

Certain elements of the checklists may be subjective and complicated for an individual/evaluator to answer.

It is recommended that the items on the checklist should be individual and unique, so as not to generate conflicts.

Being consistent in the way heuristics are specified.

Some heuristics refer more to the scope of a system's functionality for resilience contexts.

There are some checklist items and definitions that are more related to other heuristics.

Second Iteration

a) Heuristic evaluation

Once the evaluations of the heuristics had been performed by the control and experimental groups, the identified usability/UX issues were compared to evaluate the effectiveness of the HRCU suite based on five criteria [7, 9]. As indicated in the methodology, HRCU performed well and was an effective instrument, as it performed better than the heuristics used by the control group based on criteria (1), (2), (3), (4) and (5). Table 9 presents a description and formula of each criterion.

Table 9. Five criteria for evaluating the effectiveness of a new set of heuristics (adapted from [9])

Criterion description	Formula
(1) Number of correct and incorrect associations of problems with heuristics	$CA = \frac{\sum_{n=1}^{T} CAHn}{TP} \times 100$ $IA = \frac{\sum_{n=1}^{T} IAHn}{TP} \times 100$ where: • CA: correct associations • IA: incorrect associations • T: total number of heuristics in the set • CAHn: number of correct associations of problems with heuristic *n*. • IAHn: number of incorrect associations of problems with heuristic *n*. • TP: total usability/UX issues identified

Criterion description	Formula
(2) Number of usability/UX issues identified	P1 = Problems identified by both groups of evaluators (common problems identified by both groups) P2 = Problems identified only by the group that used the new set of heuristics (without considering common problems) P3 = Problems identified only by the group that used the control heuristics (without considering common problems)
(3) Number of specific usability/UX issues identified	$ESS = \frac{NSP}{TP} \times 100$ where: ESS: efficiency NSP: number of specific usability/UX issues identified TP: total usability/UX issues identified
(4) Number of usability/UX problems identified that are rated as most severe (i.e., how catastrophic the detected usability/UX problem is)	$ESV = \frac{NPV}{TP} \times 100$ where: ESV: efficiency NPV: number of usability/UX issues identified and rated with a severity greater than two TP: total usability/UX issues identified
(5) Number of usability/UX problems identified that are rated as most critical (i.e., the severity and frequency of the detected problem, where frequency is understood as the number of times a problem occurs, and criticality is the sum of frequency and severity)	$ESC = \frac{NPC}{TP} \times 100$ Where: ESC: efficiency NPC: number of usability/UX issues identified and rated with a criticality greater than four TP: total usability/UX issues identified

Table 10 presents a comparison of the results obtained from the control and experimental groups in the heuristic evaluation, with respect to the five criteria.

Table 10. Comparison of results from the heuristic evaluations (adapted from [9])

	Experimental group	Control group	Observations
Number of evaluators	3	3	Both groups with the same experience
Set of heuristics used	RC Heuristics (HRCU)	Nielsen Heuristics (NH)	Not applicable
Number of heuristics (T)	15	10	Not applicable
Total problems identified (TP)	32	11	Not applicable

	Experimental group	**Control group**	**Observations**
Number of specific problems identified (NSP)	8	0	Not applicable
Number of problems identified and rated with a severity greater than two (NPV)	15	10	Not applicable
Number of problems identified and rated with a criticality greater than four (NPC)	15	10	Not applicable
Problems identified by both groups (P1)	2	Since (P2) includes the largest number of problems, it is concluded that HRCU performs better than NH	
Problems identified by the experimental group (P2)	30	-	
Problems identified by the control group (P3)	-	9	
Total number of correct associations ($\sum_{n=1}^{T} CAHn$) Total incorrect associations ($\sum_{n=1}^{T} IAHn$)	26	6	Not applicable
Total incorrect associations ($\sum_{n=1}^{T} IAHn$)	6	5	Not applicable
Percentage of correct associations (CA)	CA1 = 81.25%	CA2 = 54.55%	Given that CA1 > CA2, it is concluded that HRCU performs better than NH (HRCU has a higher percentage of correct associations)
Percentage of incorrect associations (IA)	IA1 = 18.75%	IA2 = 45.45%	Since IA1 < IA2, it is concluded that HRCU works better than NH (HRCU has a lower percentage of incorrect associations)
Effectiveness in terms of number of specific problems identified (ESS)	ESS1 = 25%	ESS2 = 0%	Given that ESS1 > ESS2, it is concluded that HRCU performs better than NH (HRCU encounters more specific usability/UX problems than NH)
Effectiveness in terms of the number of	ESV1 = 46.87%	ESV2 = 90.90%	Since ESV2 > ESV1, it is concluded that HRCU

	Experimental group	Control group	Observations
problems identified and rated with a severity greater than two (ESV).			performs worse than NH in terms of finding usability/UX problems more severe than NH
Effectiveness in terms of the number of problems identified and rated with a criticality higher than four (ESC).	ESC1 = 46,87%	ESC2 = 90,90%	Since ESC2 > ESC1, it is concluded that HRCU performs worse than NH for finding usability/UX problems more critical than NH

The results show that HRCU performs better than NH on criteria such as the numbers of correct and incorrect associations of issues, the number of usability/UX issues identified, and the number of specific usability/UX issues identified. However, on criteria such as the number of usability/UX issues identified that are rated as more critical and the number of identified usability/UX issues identified that are rated as more severe, there is scope for improvement regarding their effectiveness. Further refinement of the specifications of the HRCU set is therefore needed to increase its efficiency based on these criteria.

Stage 8: Refining. At this stage, changes were made to all the heuristics in the HRC set. Table 11 shows the most relevant changes.

Table 11. Refinement of the HRC set (source: own elaboration)

Heuristics	Problem	Action
The entire HRC set	The examples given and the checklist items are mostly the same	Refine: Add visual examples showing compliance or non-compliance with the heuristics.
HRC5 (Extraordinary users)	It is difficult to evaluate the accessibility of a system with a single heuristic (there are other techniques, methods, etc. to do this, for example those proposed by the W3C)	Eliminate: The heuristic is removed because: (1) it covers too many elements and (2) there are already existing methods such as W3C and WCAG that can be used for evaluating accessibility. Hence, some elements will be moved to other heuristics.
HRC14 (Information processing)	The name of the heuristic may be confusing	Refine: Change name to 'Use of information'.
HRC15 (Community)	This covers too many elements	Eliminate: Create heuristics that cover specific elements.
HRC15 (Community)	There are items in the checklist that are related to other heuristics.	Refine: Reposition the items to the corresponding heuristic.
HRC15 (Community)	There are items in the checklist that are functionalities rather than usability items.	Refine: Adjust items to contribute to usability and user experience.
HRCU14	HRC15 has many elements.	Create: Review elements of HRC15 that

(Participatory community)		correspond to resident participation.
HRCU15 (Informed community)	HRC15 has many elements.	Create: Review elements of HRC15 that correspond to residents being informed.

5 Usability heuristics for applications in the context of resilient cities

From the application of each stage of the methodology, a set of 15 usability heuristics was proposed for applications in the context of RCs. The heuristics were grouped into five families, as follows:

1. Design and aesthetics heuristics
   - (HRCU1) Relationship between the system and the real world
   - (HRCU2) Simplicity
   - (HRCU3) Consistency
   - (HRCU4) Feedback
2. Flexibility and navigation heuristics
   - (HRCU5) Browsing
   - (HRCU6) Recognising rather than remembering
   - (HRCU7) Flexibility and efficiency of use
   - (HRCU8) User control and freedom
3. Error heuristics and support
   - (HRCU9) Error prevention
   - (HRCU10) Recovering from mistakes
   - (HRCU11) Help and documentation
4. Heuristics for use and visualisation of information
   - (HRCU12) Display of information
   - (HRCU13) Use of information
5. Community heuristics
   - (HRCU14) Informed community
   - (HRCU15) Participatory community

Due to length restrictions on this article, we will describe in detail only four relevant heuristics in the context of RC. Tables 12 to 15 present the heuristics HRCU12 - Display of information, HRCU13 - Use of information, HRCU14 - Informed community, and HUCR15 - Participatory community, respectively.

Table 12. ‘Display of information’ heuristic (source: own elaboration)

Display of information	
ID	HRCU12
Definition	The visualisation of information from a software system used in resilience contexts must be optimally displayed to improve users' understanding, perception

Display of information	
	of the data and subsequent decision making.
Explanation	The data should be presented in an optimal way to improve the visualisation and understanding of the information. With this in mind, appropriate graphics should be used depending on the context, and options should be provided to facilitate the interpretation of the information.
Example	Figure 1 shows compliance with the heuristics for the Google COVID-19 system. A line histogram is used to represent the behaviour, patterns, and evolution of the number of cases in Colombia.
Checklist	• Related information is grouped together. • Information is organised in a hierarchical order. • The system presents an overview of relevant information. • A map graph is used to represent the relative differences in the data at different locations. • A map graph is used to represent the behaviour of the data at different locations. • A map graphic is used when the data include geographic information. • A heat map is used to represent the spatial distribution of a variable. • A column histogram is used to represent the behaviour, patterns, and evolution of a variable over time for a few data points. • A line histogram is used to represent the behaviour, patterns, and evolution of a variable over time for many data points. • A scatter plot is used to represent the behaviour, patterns, and evolution of two variables over time. • A 3D area graph is used to represent the behaviour, patterns, and evolution of more than two variables over time. • A simple bar chart is used to compare different groups of data corresponding to the same period for a single variable. • A variable width bar chart is used to compare different groups of data corresponding to the same period for data with two variables. • A pie chart is used to compare the same set of data for different time periods.

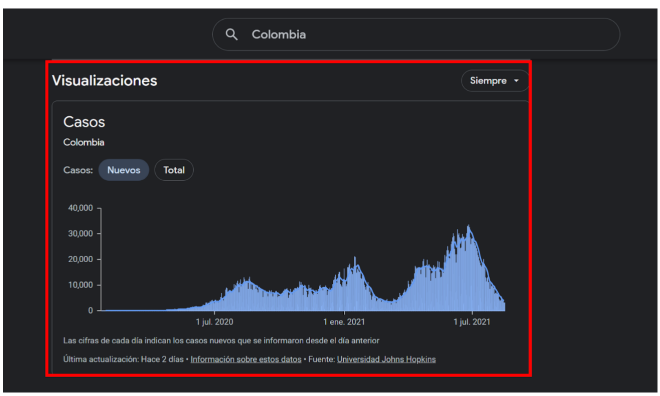

Fig. 1. Example showing the ‘Display of Information’ heuristic (source: [38]).

Table 13. 'Use of information' heuristic (source: own elaboration)

Use of information	
ID	HRCU13
Definition	A software system used in resilience contexts should foster an informed community in which residents can receive alerts and notifications of events.
Explanation	This heuristic aims to foster an informed community. It is important that residents are informed about events and alerts that occur and make inquiries.
Example	Figure 2 shows how the Disaster Alert system complies with the heuristics. The system uses the data to perform a descriptive analysis of an event.
Checklist	• The system displays the date of publication and/or updates to the information. • The system displays the source of the information. • The system includes contacts (phone, e-mail or other) for emergency services. • The system has a dissemination mechanism so that residents can receive notifications. • The system presents information of interest to residents (services, recommendations, and restrictions). • The system has a news section for residents to keep them informed.

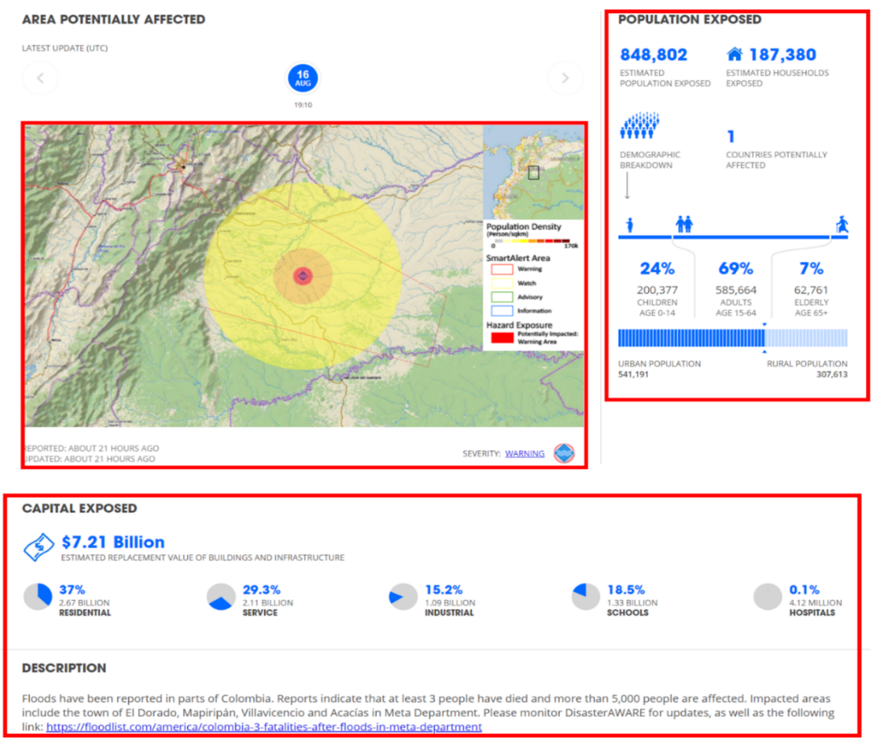

Fig. 2.. Example showing the 'Use of information' heuristic (source: [39]).

Table 14. ‘Informed community’ heuristic (source: own elaboration)

	Informed community
ID	HRCU 14
Definition	A software system used in resilience contexts should foster an informed community in which residents can receive alerts and notifications of events.
Explanation	This heuristic aims to foster an informed community. It is important that residents are informed about events and alerts that occur and make inquiries.
Example	Figure 3 presents an example of how the prototype included in the ResCity project complies with the heuristics. The system has a form via which residents can subscribe to river status notifications.
Checklist	• The system displays the date of publication and/or updates to the information. • The system displays the source of the information. • The system includes contacts (phone, e-mail or other) for emergency services. • The system has a dissemination mechanism so that residents can receive notifications. • The system presents information of interest to residents (services, recommendations, and restrictions). • The system has a news section allowing residents to stay informed.

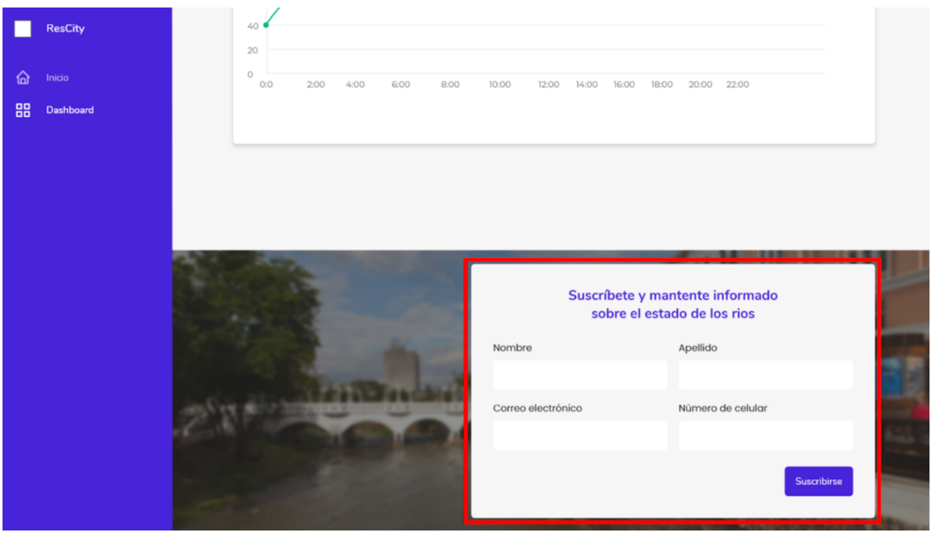

Fig. 3.. Example showing the ‘Informed community’ heuristic (source: [40]).

Table 15. The 'Participatory community' heuristic (source: own elaboration)

Participatory community	
ID	HRCU15
Definition	A software system used in resilience contexts should foster a participatory community where residents can make contributions.
Explanation	This heuristic aims to encourage the participation of system users to create community. It is important for residents to actively participate in decision making and to be able to make contributions to the system, so the system must also ensure the inclusion of all members of the community.
Example	Figure 4 includes an example of how the Streetwyze system complies with the heuristics. The system has a mechanism via which residents can share about a story at a specific point, as well as interact with it.
Checklist	• System information can be shared. • The system has a mechanism through which residents can make contributions. • The system allows residents to interact with each other (e.g. via chat, comment boxes, reactions). • The system is compliant with the Web Content Accessibility Guidelines (WCAG).

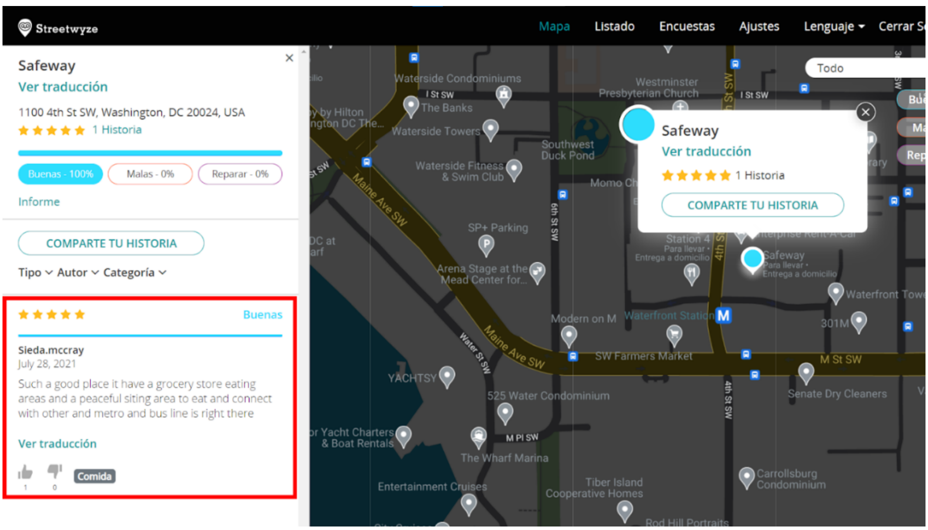

Fig. 4. Example showing the 'Participatory community' heuristic (source: [41]).

6 Discussion

The UX is an essential element that must be considered when designing products, systems, and services. In view of this, we believe that the heuristics proposed in this paper can help in detecting problems that generate frustration, thus improving the interaction with and the overall UX of applications in the context of RCs.

In this research, a set of 15 usability heuristics were specified by means of a template that included elements such as a definition, an explanation, examples, and a checklist, among others. This facilitates the description of the heuristics, and allows them to be used by designers or developers. However, the way is open for further validation of these heuristics by people working in the field of RCs, so that their specification can be more precise, useful, and clear, in order to increase their efficiency.

The validation mechanisms were applied iteratively, which allowed us to obtain promising results in terms of the perceived usefulness and clarity of the proposed heuristics. Feedback was used for the refinement of the heuristics where there was the opportunity to correct confusing and redundant elements, as well as to complement the specification of the heuristics to ensure their contribution to the usability of interactive software systems in the context of RCs. In this sense, it is convenient to continue refining the heuristics and their respective checklist, considering dynamics and other work approaches that evolve in the context of RCs.

During the development of the third stage of the methodology, in which the relevance of the characteristics of an RC, usability and UX attributes were defined, some UX attributes were valued as “somewhat important”, including the attribute of accessibility. This research did not explore aspects of accessibility due to the wide scope of this topic and difficulties with implementation. In the future, heuristics of this nature could be proposed to expand the characteristics that can be covered by the heuristics, and to develop new ones that respond to the accessibility of a system in a RC context, based on metrics and other specific documentation on this topic.

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