Proceedings of the 54th Hawaii International Conference on System Sciences | 2021

Designing Chemical Emergency Response Systems Based on Open Data

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Abstract

Emergency situations call for reliable information to allow for an effective and timely response. While digitalization penetrates industry sectors at an increasing rate, advances in information technology are not fully leveraged in emergency situations today. Building upon the paradigm of openness in form of open data, we propose a solution that connects government-provided emergency services with private sector expertise and resources. We apply a design science research approach to design an artifact that provides information in real-time to fire departments and medical staff in case of chemical substance incidents. We showcase that by providing open data, private sector organizations acknowledge their responsibility to share critical data while creating value in the process. Our contribution with this paper is threefold: First, we derive design requirements for artifacts to address chemical substance incidents. Second, we design and evaluate an artifact to showcase its suitability. Third, we showcase value creation through open data.

1. Introduction

Across the globe, we observe the emergence of crisis situations. Driven by climate change, natural disasters and armed conflicts, emergency response services are searching for new ways to combat the information deficit challenges arising from this new status quo.

The process of digitalization across the public and private domains drives changes in crisis management and enables disaster management to be more efficient. For decades, coordination relied on paper-based processes, voice communication and analog radios. While these methods are robust, they do not reflect the advances in information technology. Timely access to information is critical in emergency situations [1]. Providing real-time information while linking (open) data from multiple sources is a requirement to advise and coordinate emergency response services in the field [2]. Contemporary trends towards openness of organizations foster a sharing culture and enable new forms of value creation [3].

Opening up organizational boundaries by sharing information in form of open data leads to social and economical value creation [4, 5]. In recent years, we observe that organizations in the private sector have started engaging in open data—i.e. releasing data to the general public. While providing company assets free of charge may contradict profit maximization objectives [6], it serves as a key ingredient to spark innovation and to capture internal efficiency gains [7, 8]. The phenomenon of open data itself is not new: The public sector has been a role model driven by open government data initiatives such as the one in the United States [9] and the European Union [10].

The interconnectedness between academia, private and public sector organizations and their data resources is a key driver to create situational awareness in emergency scenarios [11]. The availability of interconnected interdisciplinary open data allows for disaster preparedness and mitigation activities to be executed in a timely manner [12]. Depending on the nature of the emergency, different kinds of open data sources create value. In geographically wide-spread situations such as earthquakes, crowdsourced linked open data enables timely reaction for disaster management [13], while locally concentrated emergencies such as the fire or spillage of a chemical substance calls for specialized open data from the manufacturer of the substance. Hence, providing the right kind of information is critical to enable emergency response services to take mitigating actions.

Driven by the need to better leverage advances in information technology in emergency situations, we frame our research objective as follows: We aim to derive design requirements for an artifact for emergency scenarios that involve chemical substances. By basing the artifact on an open data standard, organizations are enabled to integrate their data in an effort of contributing

URI: https://hdl.handle.net/10125/70889
978-0-9981331-4-0

to societal value. Hence, this paper makes three distinct contributions. First, we contribute to design theory by deriving five design requirements based on expert interviews and extant literature. Second, we develop an artifact and show its suitability in two evaluation cycles. Third, we contribute to the understanding of value creation through open data.

In the next section, we describe our Design Science Research (DSR) approach in detail, including the choices we made for our initial setup. In line with the proposed approach of Hevner and Chatterjee [14], we derive initial requirements for the proposed artifact as part of an interview study in the *relevance cycle*. In Section 4, we elaborate on the body-of-knowledge as part of the *rigor cycle* while deriving additional design requirements. Sections 5 and 6 are devoted to our two design cycles where we discuss design and evaluation of the artifact [15], before concluding in Section 7 with a summary, limitations and research outlook.

2. Research Design

We select DSR as our research paradigm. DSR has proven to be an important and legitimate paradigm in information systems research [16]. Moreover, it fits our specific research well since it allows considering both the theoretical and practical tasks necessary when designing and evaluating IT artifacts [17]. To approach our research problem, we conduct a relevance cycle, a rigor cycle and multiple design cycles [14, 18]. The design cycles are an adapted version of the FEDS framework [15, 19] to ensure a thorough and holistic evaluation. Figure 1 shows an overview of our concrete DSR approach.

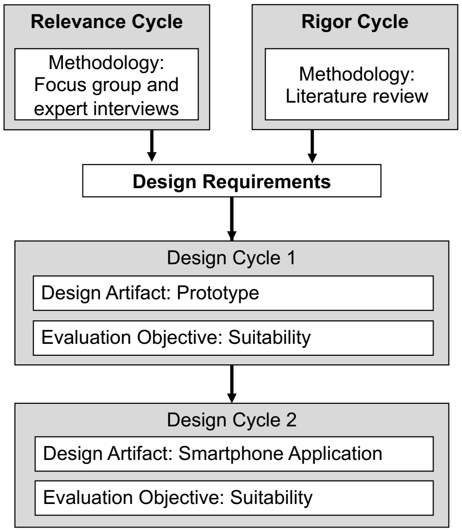


Figure 1. Overview of DSR approach.

3. Relevance Cycle: Refining the Problem

The aim of the relevance cycle is to develop a better understanding of the problem being addressed. For that, we apply a two-step approach: First, a designated focus group discusses potential use cases and stakeholder groups that may be exposed to emergency situations involving chemical substances. Second, we conduct a series of expert interviews to better understand the needs of each stakeholder group. To underscore the practical relevance of this research study, the implementation of the artifact is done in collaboration with BASF. With an annual revenue of more than 66 billion USD (2019), BASF is the world's largest chemical company, employing more than 110,000 people worldwide. Its diverse product portfolio ranges from performance chemicals for plastics and automotive to crop protection solutions for farmers [20].

Through the discussion of a focus group, four stakeholder groups are identified that may be exposed to critical situations involving chemical substances: fire departments, medical assistance, logistics firms and product end users.

Initially, it is decided to select the fire department and medical assistance as primary stakeholder groups while aiming for generalizability of the artifact. These use cases shall showcase the collaboration between a private organization (BASF) and publicly provided emergency services. To better understand the processes and procedures in emergency response situations involving chemical substances, we conduct a series of semi-structured interviews since this method combines structure with flexibility [21]. A purposeful sampling approach is applied [22]; the roles of the six experts are summarized in Table 1.

Table 1. Overview of interviewees

Interviewee	Focus	Role
Alpha	Medical	Head of Emergency Medicine
Beta	Medical	Doctor
Gamma	Medical	Emergency Assistant
Delta	Fire	Head of Education
Epsilon	Fire	Station Officer
Zeta	Fire	Head of Preventive Measures

Based on six interviews, we identify challenges in obtaining critical information in emergency situations involving chemical substances. We also develop a first understanding of the type of information that is needed.

First, channels that the information is made available through vary broadly across countries and

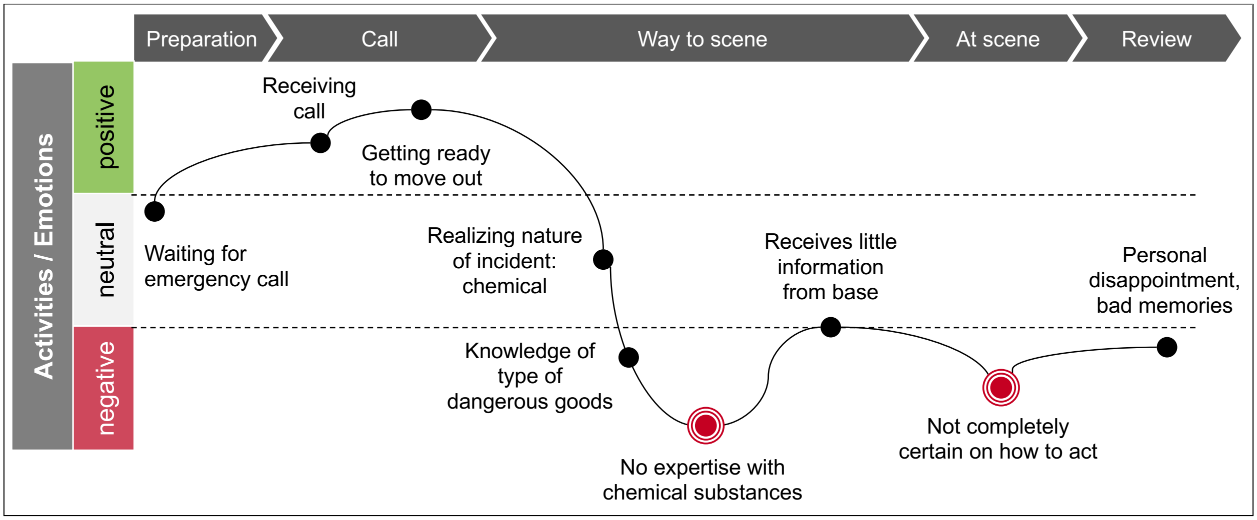


Figure 2. Emotional journey of a fire fighter during chemical incidents.

regions. While some regions can rely upon web-based information sources, others have to rely on paper-based documentation. Both sources have turned out to be outdated in many cases and paper-based documentation sometimes disappears, making it difficult for emergency response services to react in a timely manner. Second, even if web-based information is available, the databases are not optimized for mobile (i.e. smartphone or tablet) usage. Hence, search queries are difficult to submit and results are displayed in a format that is difficult to read. Third, given different levels of education and training of emergency response services around the globe, each individual has a different need in terms of the depth and breadth of information needed. Hence, information needs must be tailored to the situation where a person experiences negative emotions. The Design Thinking-inspired visualization of this emotional journey (cf. Figure 2) is based on interviews and has been validated with the experts as outlined in Table 1. Fourth, knowledge about the substance involved in the incident may be sparse, making it difficult to submit valid search strings to enquire more information on how to act.

Based upon these challenges, we derive the requirements that an artifact must fulfil. For that, we rely on the input provided by the experts during the interviews. Additionally, we derive design requirements (DR) from literature in Section 4 and combine both inputs in Section 4.4. First, the artifact must allow to search for different identifiers since the information at hand may vary depending on the location and emergency scenario (DR 1). Second, to account for changing product portfolios of manufacturers and time constraints in emergency situations, it must be ensured that the information is up-to-date and available in real-time (DR 2). Third, while the search process is standardized, search results must account for country-specific regulations (DR 3). Fourth, ensure good usability on mobile devices for information access whenever and wherever needed (DR 4).

4. Rigor Cycle: Fundamentals and Related Work

In the following, we briefly introduce open data as the foundation of the artifact to-be-built, provide an overview of digitalization in crisis management and elaborate on information sources available in the case of chemical substance incidents.

4.1. Open Data

Open data as a resource enables value creation in digital ecosystems. Data provider (supply side) and data integrator (demand side) expect open data to have certain features to facilitate resource integration. While the demand side asks for unrestricted availability combined with accessibility and technical interoperability [23], the supply side describes the value of open data as a function of format, license, accessibility and availability [24]. Despite receiving a growing amount of attention both in academic and practice over the past years, no commonly accepted definition of open data has emerged. A widely accepted concept, combining the requirements of the demand and supply side, describes open data as a form of content that can be freely used, modified, and shared by anyone and for any purpose [25]. Being an open resource, open data shows a proximity to other open initiatives such as open API and open source while drawing a clear line toward open processes such as open innovation [3].

The phenomenon of open data as such is not new: open government data, primarily driven by policy changes in the United States [9] and the European Union [10], has started to gain traction almost two decades ago. This form of open data in the public domain has since drawn a considerable amount of attention in academia [26].

The use of open data in disaster management has proven to be beneficial in a number of scenarios. For instance, by combining multiple data sources across the public, private and academic domain, situational awareness in emergency situations can be improved [11]. Furthermore, interconnected interdisciplinary open data enables better disaster preparedness and mitigation actions to be executed more quickly [12]. The ability to rapidly acquire and serve data (e.g. through crowd-sourcing) as open data allows for timely reaction in disaster management [13]. Hence, combining data from various sources through an open standard aids rapid gathering of knowledge to be passed on to the appropriate emergency response services (DR 5).

Despite open data initiatives leading to benefits such as the de-silofication of organizations, its wide-spread adoption in the private sector remains in its infancy [8]. This may in part be owed to the difficult decision companies face when deciding which datasets to reveal to the public without harming business operations [27]. Furthermore, a low level of visible innovation and the struggle to turn data into a monetary benefit fuels the open data value paradox: Data integrators hesitate to build services and business models on open data given the uncertainty of data perpetuity while data providers hesitate to increase their investments due to a lack of evidence of its concrete value-in-use [28]. Hence, additional use cases are needed to showcase the value contribution of open data across the public and private domain.

4.2. Digitalization in Crisis Management

In emergency and disaster situations, having timely access to accurate information is crucial [1, 29], digital tools are well suited to meet this demand.

There are various methods and digital tools available that provide timely information to first responders. An established approach is the extraction of relevant information from user-generated content from social media platforms. This information is not only available almost in real-time but has also been shown to be valuable in addition to other data sources [30]. For instance, Ashktorab et al. [31] and Imran et al. [32] leverage machine learning to automatically extract actionable information from Twitter data. Johnson et al. [33] extend the applicability of this approach by leveraging transfer machine learning. This significantly reduces the necessary amount of training data and thus facilitates a quick adaptability to novel problems. Using unmanned aerial vehicles is a relatively new way to leverage digital technology to provide timely information to first responders in a crisis or emergency situation [34]. Furthermore, the Internet of Things (IoT) has been shown to benefit emergency response scenarios since it can provide essential sensor-based information in real-time [35]. For example Hernández et al. [36] developed a sensor to measure water levels in rivers to enable an early warning against floods.

In emergency situations, not only first responders but also citizens require timely and accurate information. Leveraging the wide spread of smartphones and mobile network coverage to send warning messages about crisis and emergency situations is an established approach driven by digitalization [37].

In parallel to the need for timeliness of information, trustworthiness is of equal importance. Recently, Blockchain has been discussed as an emerging digital technology that may enable trustworthy communication in emergency situations [38].

In summary, we learn from extant literature that having timely access to information is crucial (DR 2) and that mobile devices aid the rapid spread of that information in emergency situations (DR 4).

4.3. Information Sources for Chemical Incidents

Independent of the nature an emergency situation, having access to information is critical for emergency response (ER) services to guide decision-making processes [2, 39]. With focus on the chemical industry, several information systems have emerged over the years. Different levels of maturity of the systems across the globe are a representation of its fragmentation and call for a more standardized approach.

Today, emergency response services draw their information from various sources. Globally harmonized safety data sheets (SDS), for instance, are documents that summarize various information on a chemical substance, including information on how to react in case of an emergency [40]. Given its length and complex structure, extracting the most relevant information may be time consuming and hence defies the purpose of aiding in emergency situations. As a further source, Emergency Response Intervention (ERI)

Table 2. Design requirements.

DR	Description	Interview Source	Literature Source
DR 1	The artifact shall allow various identifiers for the substance search.	Alpha, Gamma, Epsilon, Zeta	
DR 2	The artifact shall provide information in real-time.	(all)	[2]
DR 3	The artifact shall take local regulations into account.	Delta, Zeta	
DR 4	The artifact shall be tailored for use on mobile devices.	(all)	[29]
DR 5	The artifact shall be based upon open data.		[11, 12, 13]

cards are available either in a paper-based format or through a web-based search [41] and primarily used by ER services in Europe. It contains information on basic chemicals in a condensed form, however, neglects manufacturer-specific product data. Apart from solely supplying information to ER services, countries worldwide have created systems where a combination of education material, phone support and chemical substance documentation form an integrated system. For instance, CANUTEC (Canadian Transport Emergency Center) is a national advisory service operating in Canada to provide 24/7 support [42]. In the United States, Chemtec (Chemical Transportation Emergency Center) supplies relevant information to ER services [43]. Similar services exist in Brazil (Pró-Química) and New Zealand (Hazard Substance Toolbox) with minor adjustments to local legislation [44, 45]. Each of these services supplies information on hazardous goods and dangerous materials. Given a lack of open interfaces of each system, redundant manual data maintenance is required to keep information current and calls for a solution that standardizes data formats along with supplying manufacturer-specific product information.

4.4. Design Requirements

Based on expert interviews described in the relevance cycle (Section 3) and the presented extant literature, we derive a set of design requirements (DR) for the artifact to-be-built. A summary of those requirements is shown in Table 2. These requirements are of general nature and are supported by both, interviews and literature. They can be referred to for the design of any chemical emergency response system—or even emergency response systems where quick, real-time reactions are required and open data is available. In the remainder of our work, we will design an artifact based on these DRs to instantiate precise design decisions in order to meet them. While this is a specific implementation to match our precise use case, the resulting design knowledge is applicable to other use cases as well.

5. Design Cycle 1: Prototyping

We perform two distinct design cycles to develop the artifact in an iterative manner. As part of the first design cycle, we describe the design and evaluation process of the artifact in form of an initial prototype. The second design cycle elaborates on the process for designing and evaluating a smartphone application as our final artifact.

5.1. Design

To give potential users a better understanding of the artifact, we first design and build a clickable prototype. The prototype contains all features that could also be included in a deployable native smartphone application. An early prototype allows the users to quickly interact with the artifact and, therefore, enables short iterations. Based upon the design requirements as outlined in Section 4.4, we design a prototype that tailors to two stakeholder groups: fire department and medical assistance.

In order to ease usability, we keep the number of buttons to a minimum and ensure flat hierarchies [46]. The prototype is designed in such a way that users select one of two roles as can be seen in Figure 3. Wherever possible, images are used to minimize reading time and ensure an intuitive usage. Upon selecting a role, the user is shown a screen to search for a particular substance name. To account for DR 1, the search allows for both, a product name as well as a product number query.

Once the user submits the search, a BASF provided open data-based API is called to retrieve the results in real-time (DR 2 & DR 5). The proprietary BASF product data is made available in a structured format to enable this artifact in addition to other use cases such as generating safety data sheets (cf. Section 4.3). In case multiple substances contain the text that has been entered, the user is presented a list to select from. Upon selecting a substance, detailed substance information is displayed. Following the information collected during the first set of expert interviews, the user is shown the following general information categories: *at-a-glance*, *protective gear*, and *additional information*. To

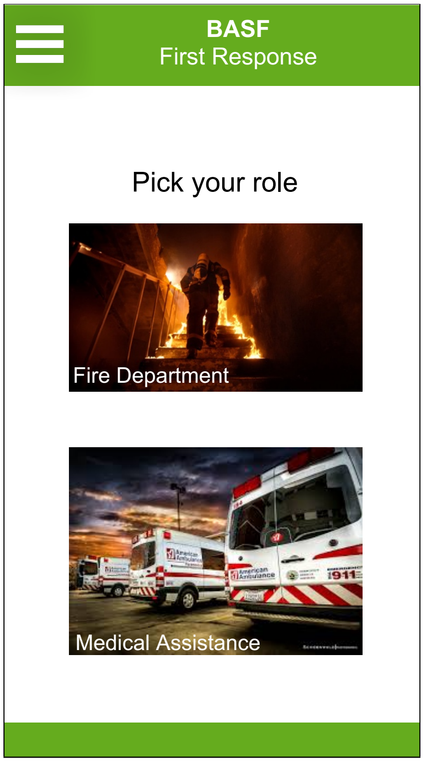
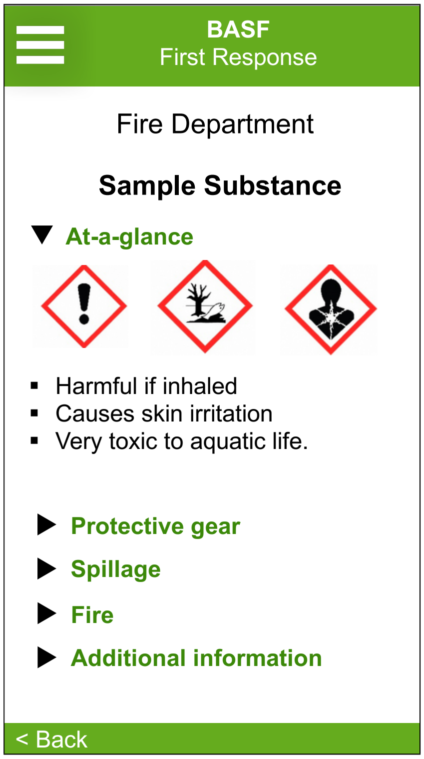


Figure 3. Prototypical role selection.



- Harmful if inhaled
- Causes skin irritation
- Very toxic to aquatic life.

Figure 4. Prototype information sections.

account for specifics of each stakeholder group, the fire department role also includes the *fire* and *spillage* categories, while the medical assistance role contains *first aid* and *symptoms/treatment* sections. Each section contains additional information retrieved through the open data interface. To ensure that most relevant information for self-protection is visible at first sight, the upper section *(at-a-glance)* is expanded by default while all others are collapsed as shown in Figure 4.

5.2. Evaluation

The designed prototype represents an instantiation of the artifact towards our research objective [47]. To evaluate the current artifact and gain knowledge for the next design cycle, we follow the evaluation approach according to FEDS [15]. In this evaluation cycle, we evaluate the artifact towards *suitability* for use by emergency response services, namely fire departments and medical assistance, in the context of incidents with chemical substances.

Methodology. To evaluate the suitability of the prototype, we conduct semi-structured interviews [21]. A subset of the experts that provided input for the initial design of the artifact participate in the evaluation. In particular, experts Alpha, Beta, Delta and Epsilon volunteer to take part in the in-person interview process (cf. Table 1). To prepare for the interview questions, experts are given a brief explanation of the artifact. Afterwards, the experts respond to a series of semi-structured questions. The questions are separated into two clusters: (1) Does the artifact cover all information that is needed in emergency situations with chemical substances? (2) Does the usability of the artifact enable the user to find the desired information quickly? The researchers took notes to capture the experts' responses and discussed those afterwards.

Findings. While in general all experts agree that the prototype is suitable for quickly retrieving information on chemical substances in emergency situations, they provided helpful comments for the next design cycle. The initial design is based on the design requirements as outlined in Section 4.4. By confirming that the prototype is suitable for the intended use, the experts refer to the information that is provided as well as the overall usability. The remarks for further improvement can be separated into three groups: adjustments to content, improvement to usability, and layout/formatting.

Regarding the content displayed, the experts from the fire department note that the information sections (*spillage* and *fire*) go into too much detail, which may lead to cognitive overload given the short time to process the information. Hence, individual items in these sections need to be eliminated based upon the experts' feedback. The medical assistance experts make a similar observation and ask individual items to be removed from the *first aid* section. On a different note, the fire department experts ask more chemical parameters to be added to the *additional information* section of the prototype. In particular, information about the pH value, oxidizing characteristics, vapor pressure, density, water solubility, flash point, and ignition temperature of a substance should be added. These parameters do not belong to the core information needed by first responders, however, provide additional detail to better understand the behavior of a substance.

While the experts perceive the usability of the prototype to be an improvement compared to current information sources used to obtain substance information, they also provide insights on what can be improved in the next iteration. For once, experts Alpha and Delta point out that it would not be necessary to ask for the role of the user during each search process. It can be assumed that the role remains the same over the duration of usage. Furthermore, all experts raise concerns that the substance search by name and number may not be sufficient since information available to emergency response services is oftentimes sparse. They suggest to also include additional identifiers such as a CAS number and EAN code into the search.

The third group of remarks revolves around the layout of the prototype. For instance, expert Beta suggests the font size to be increased to allow for better readability while in a moving vehicle on the way to the scene. Expert Epsilon suggests to put additional space in-between the sections of information to enable sections to be expanded or collapsed more easily.

In summary, the experts confirmed that the prototype shown is suitable for intended purpose. They provide valuable feedback to be taken into account in the next iteration. In addition to the feedback presented, the experts Alpha and Delta asked for an additional screen that shows the emergency phone numbers of the country where the user is located (DR 3).

6. Design Cycle 2: Smartphone Application

Based upon the knowledge gained through the first evaluation cycle, we design an updated artifact and perform a second evaluation cycle. This design cycle consists, analogous to the first one, of a design and evaluation cycle.

6.1. Design

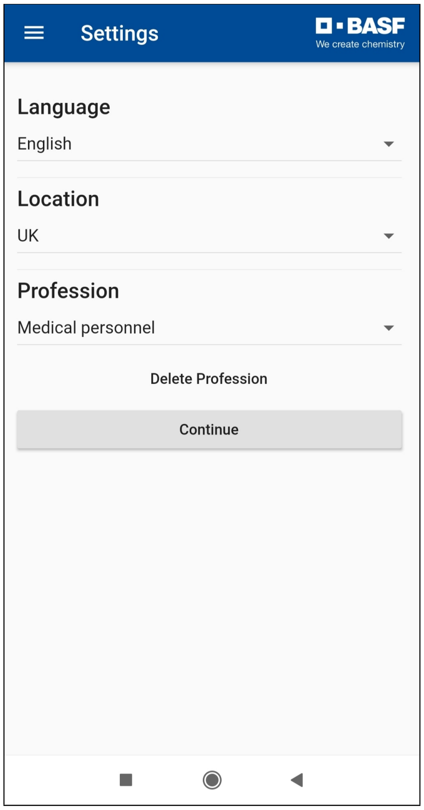
For the second design cycle, we design the instantiation of the artifact in form of a smartphone application (DR 4). The information collected during the first evaluation cycle shapes the foundation of the second design cycle. The changes made can be separated into three groups: content, usability, and front-end customization.

Following the experts' feedback, we remove individual entries of the *fire*, *spillage*, and *first aid* sections to ease readability and to narrow it down to the most relevant information. Furthermore, we add chemical parameters (pH value, oxidizing characteristics, vapor pressure, density, water solubility, flash point, and ignition temperature) to the *additional information* section of the fire department role.

Based upon the experts' recommendation to remove the role selection for each search process, we introduce a settings page that consolidates user preferences. The user is once guided to this page during the initial start of the application. While the artifact stores the preferences for future search queries, the user may go back to the settings page and change it at any time. In addition to selecting a role, the user must select a preferred language and current location as is shown in Figure 5. The location information is used to retrieve location-specific information through the open data interface, which aligns with DR 3. For instance, certain countries require ER services to report an incident with chemical substances to the appropriate authorities. The location feature is also used to show local emergency phone numbers as requested during the first evaluation cycle. A single tap on the phone number initiates a call.

The search for substance was raised as a concern during the initial evaluation cycle as being too narrow. Following the recommendations of the experts, we add the possibility to search for additional identifiers, which also responds to DR 1. Besides product name and product number (UPC), the user may also enter a CAS number or the EAN code. To ease the input of the EAN code into the search field, we add a feature where the smartphone camera can be used to scan the bar code of a shipping label. By tapping the camera icon as shown in Figure 6, the user enables this feature.

Finally, a number of small adjustments to the front-end of the artifact are made. For instance, we increase the font size for improved readability and added space in-between the information sections. Furthermore, we added the opportunity to change the language of the artifact to either English, Spanish, German or French to tailor it to local market needs.



Language: English

Location: UK

Profession: Medical personnel

Figure 5. Smartphone app settings page.

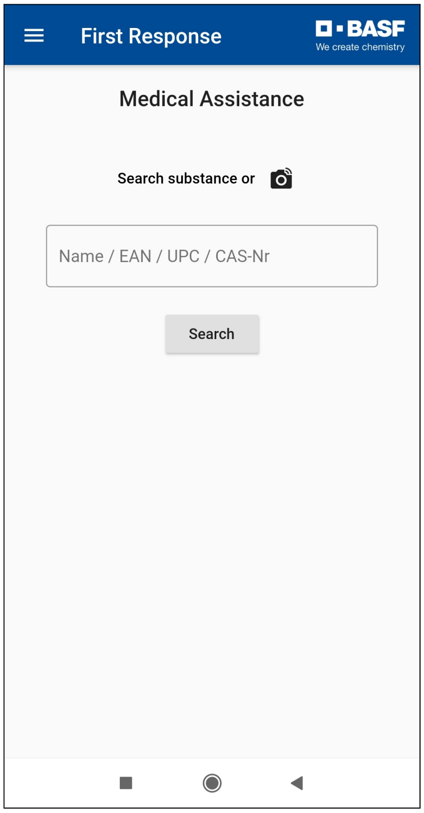


Figure 6. Smartphone app search page.

6.2. Evaluation

We conduct a second evaluation cycle of the artifact to gain knowledge for the next design cycle. As our research objective remains the same, we once again evaluate the artifact towards *suitability* [47].

Methodology. Similar to the first cycle evaluation, we conduct semi-structured interviews [21]. The experts participating in the second evaluation cycle are the same that participated in the first cycle. To prepare for the interview questions, the experts receive an explanation of the artifact and have the opportunity to interact with it. Afterwards, the experts respond to a series of semi-structured questions, which are summarized for further analysis.

Findings. After being able to interact with the artifact, the fire department and medical assistance experts are in agreement that the application would allow to quickly retrieve necessary information in emergency situations. They stress the benefit of being able to use a wide range of identifiers to search for substances and especially highlighted the possibility to scan EAN codes using the smartphone camera. Furthermore, the experts confirm that the information on the substance shown represents a good balance between enough information to act and not too much information to overload the user.

Still, the experts provide valuable feedback for future design iterations of the artifact. As such, the medical experts ask to have links added to the *additional information* page, which provide more detailed knowledge on how to treat patients after the first aid measures. Furthermore, the fire fighters note that it would be helpful to add a feature, which would allow communication between fire fighters at the scene of the incident and the station chief to coordinate next steps.

7. Conclusion

In this paper, we address shortcomings in leveraging information technology in emergency situations that involve chemical substances. Driven by the need for improved collaboration between government-regulated emergency response services and private sector organizations, we propose an artifact that provides information in real-time based on an open data interface.

Based on a design science research (DSR) approach, we derive five design requirements by combining insights from a set of expert interviews and extant literature. By building upon research on mobile devices enablement for the rapid spread of information in emergency situations, we design an artifact in form of a smartphone application and evaluate it towards suitability. While the evaluation takes place in an artificial rather than a naturalistic setting, experts confirm that the artifact is suitable to aid in a real-world emergency situation. A beta test phase of the artifact with fire departments and medical services will provide additional insights and knowledge for the next design iteration. Despite the current version of the prototype being close to operational readiness, certain prerequisites such as scalability and information security have to be reviewed ahead of a full-scale rollout. The use of open data to feed data to the artifact defines a new standard in the chemical industry. It allows multiple organizations to contribute and integrate their data with the existing artifact and thereby contribute to societal value creation in emergency situations.

Given a high maturity of the application domain and a low solution maturity, our work represents an *improvement* according to Gregor and Hevner [17]. We develop a new solution to a known problem and thereby make the following three contributions: First, we contribute to design knowledge by deriving five design requirements for artifacts targeting emergency scenarios that involve chemical substances. Second, we design an artifact and evaluate it towards its suitability. Third, we contribute to the research field of open data by showcasing a form of value creation through open data.

Evidently, our work has certain limitations that offer avenues for further research into the field. For once, we evaluated the artifact towards its general suitability in chemical substance incidents. Further research needs to be conducted to evaluate each of the design requirements derived. The results of the evaluation may be distorted given a social desirability bias of the participant due to location proximity of researchers and experts [48]. Furthermore, the artifact is tailored to the needs of fire departments and medical services. As indicated in Section 3, additional stakeholder groups may benefit from having access to this kind of information. Understanding their concrete requirements is crucial to tailor the artifact to their specific needs. Also, since the evaluation has taken place in an artificial setting, further evaluation of the artifact is needed once it has been tested in the field to provide knowledge for the next iteration of the design cycle. Finally, we acknowledge the fact that the artifact may also use proprietary data instead of an open data source. However, to enable value creation across organizational boundaries, an open standard is inevitable.

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