ARCH State-of-the-Art Report 4

Decision support systems: applications, frameworks, and technologies

Deliverable No.	**D7.1**
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This document has been prepared in the framework of the European project ARCH – Advancing Resilience of Historic Areas against Climate-related and other Hazards. This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement no. 820999.

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This project has received funding from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement no. 820999.

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List of Abbreviations

Abbreviation	Meaning
AR5	IPCC Assessment Report 5
BSotA	Beyond the State of the Art
CC	Climate Change
CCA	Climate Change Adaptation
CHC	Cultural Heritage Conservation
CHP	Cultural Heritage Preservation
CI	Critical Infrastructure
CIP	Critical Infrastructure Protection
DRR	Disaster Risk Reduction
DS	Decision Support
DSS	Decision Support System(s)
EISAC	European Infrastructure Simulation and Analysis Center
GHG	Green House Gas
GIS	Geographical Information System
IBVA	Indicator-Based Vulnerability Assessment
INSPIRE	Infrastructure for Spatial Information in Europe
IPCC	Intergovernmental Panel on Climate Change
MCDA	Multiple Criteria Decision Analysis
MCDM	Multiple Criteria Decision Making
SEIS	Shared Environmental Information System
SotA	State of the Art
TRL	Technological Readiness Level
UNDRR	UN Office for Disaster Risk Reduction
VSB	Vulnerability Sourcebook
VSBM	Vulnerability Sourcebook Method

Executive Summary

Due to complexity and variety of uncertainties, climate change adaptation for historic areas is a ‘wicked problem’, i.e. a problem that is difficult or even impossible to solve, optimally. Decision Support Systems (DSS), often defined as ‘computer technology solutions that can be used to support complex decision making and problem solving’, can help to reduce uncertainties by evaluating quantitative data and supporting the process of prioritising actions and solutions, and thus give guidance to decision makers and authorities with the goal of improving decision quality.

This State-of-the-Art report provides an overview of DSS, especially in the context of management and response risks, physical damage and economic impacts to cultural heritage objects and areas caused by climate change effects, natural and man-made incidents and other large-scale events. The report begins with a short summary of the development and history of DSS in the last 50 years. Much of the early research was dedicated to understanding what DSS could be, what support they could provide, and what limitations they have. Several different methodologies for designing DSS have been developed, including model-driven, data-driven, knowledge-driven, and communication-driven DSS. All these systems share a common worldview: While the DSS recommends actions, the decision ultimately is left to a human decision maker, who is thus responsible for its outcome. For this reason, the decision maker, the DSS user, needs to understand the way the recommendation has been generated and what the limitations of the DSS are.

The report then goes on to present an overview of computer-based DSS for ARCH’s core application domains, namely climate change adaptation and cultural heritage preservation. All decision-making in these domains relies on data and information derived from that. Therefore, the overview also covers the range of available and necessary technology for eliciting required data, like environmental monitoring and 3D object/areas scanning, and information and knowledge management systems for processing the elicited data and information derived thereof.

The report introduced the DSS already in use or developed by ARCH partners, examines existing functionality, and discusses first ideas of missing features and potential ways to deliver them.

1. Introduction

The late 20th century marked a rapid growth in public concerns about the future of the Earth's environment due to severe climate change impacts, leading to a demand of evidence-based actions to reduce those impacts and to adapt to them. Understanding the processes of climate change and determining actions for climate change adaptation however is a wicked problem with high complexity and many uncertainties. Methods and tools are needed to support decision makers and authorities for identifying effective solutions and making appropriate decisions.

Decision Support Systems (DSS) are part of the comprehensive management and response to critical situations. Situational awareness is raised by sensing and monitoring given circumstances, which are processed into quantifiable information thus allowing easier understanding of the acquired data. Data from various sources are correlated into a comprehensive view of the situation leading to new insights on the situation. This can be set into a framework that identifies and displays e.g. the given and occurring risks and problematic conditions, and give guidance and support for deciding for an effective solution.

This report offers an overview of DSS with a special emphasis on DSS in the field of climate change adaptation and cultural heritage preservation and common methods and technology used for DSS. This includes sensing, monitoring and surveillance systems, developing approaches that offer ways of processing such sensed data into e.g. models (e.g. when it comes to objects), propagation maps (e.g. when it comes to areas), simulation and scenario forecast (e.g. for determination of future evolutions), planning systems (e.g. corresponding to city planning).

1.1. Background information and aim of the report

This report reviews the state of the art in computer-based DSS for ARCH's core application domains, namely climate change adaptation and cultural heritage preservation. The aim is to identify areas of possible innovation that bear the potential of producing useful DSS with added value for ARCH's stakeholders. All decision-making in these core domains relies on data and information derived from that. Therefore, the state of the art review also covers the range of available and necessary technology for eliciting required data, like environmental monitoring and 3D object/areas scanning, and information and knowledge management systems for processing the elicited data and information derived thereof.

1.2. Relation to other SotA reports and deliverables

The Deliverable D7.1 consists of six SotA Reports that inform several tasks in the ARCH work packages 2, 5, 6, and 7. DSS as described in this report relate to the other SotA Reports of this deliverable as follows:

- **SotA Report 1** handles conservation practices and relevant regulations/policies that are relevant information needed as input data for the DSS.
- **SotA Report 2** handles Disaster Risk Management, emergency protocols, and post-disaster response that are relevant information needed as input data for the DSS.

- **SotA Report 3** handles the framework and processes of Building Back Better that need to be integrated in the DSS.
- **SotA Report 5** handles gender aspects in conservation, regulation, and disaster risk management of historic areas that have to be considered when designing a DSS.
- **SotA Report 6** handles standards and regulatory frameworks that are important information when designing and using a DSS.

1.3. Structure of this report

The report is structured into the following main sections:

- **Section 2**: Decision Support System: Brief history of DSS and an overview of DSS for the application domains of ARCH.
- **Section 3**: Environmental Monitoring and 3D Object/Areas Scanning: Detailing concepts and most applicable technologies to be used for acquiring data for DSS in ARCH
- **Section 4:** Information and Knowledge Management: Outlining main approaches to process existing and acquired data and for producing actual knowledge for end users.
- **Section 5:** Progress Beyond the State of Art (BSotA): Discussion of outcomes and conclusions indicating expected progress BSotA.

2. Overview of Decision Support Systems

2.1. Introduction

In this report, we understand a Decision Support System (DSS) [68]-[70] as a computer-based information system that supports organisational decision-making activities [29]. DSS can be particularly useful when a problem has characteristics of a ‘wicked problem’, a term coined in the domain of social policy planning [35]. According to Wijnmalen et al. ([37] p. 8 (p. 250)),

> *“‘Wicked’ problems are categorised by a great number of uncertainties relating to issues including stakeholders involved, the boundaries of the problem, the effects of long-term developments, organisation and responsibilities. In such contexts, decision making is rather based on subjective, judgement-based assessments.”*

Generally, the objective of a DSS is to produce information for a problem by analysing the data, in an intelligent and fast way a human cannot in reasonable time. Decision-making can be supported by a wide array of tools and methods. Decision support tools include statistical figures, maps with special information layers, or simple Excel sheets. Historically, a number of different understandings, definitions, and research approaches on DSS exist, with the specific meaning of the term shifting over time and depending on the community, from being firmly rooted in operations research to a visual interface giving access to data warehouses [25].

A common view is that a computer-based solution to be classified as a DSS has to support governmental, business, or organisational decision makers with at least four functions [33]:

- Provide a *unified view* on data or information stored in one or more databases or documents;
- offer functions to customise that view, and use visualization to *improve the understanding* of the existing data and its interdependencies;
- provide access to models and/or analysis tools to *explore potential improvements*; and
- provide these functions in an interactive fashion to *support non-expert users*.

Wijnmalen et al. ([37] p. 11 (p. 253)) characterise two fundamental types of methods and techniques for decision support, namely ‘hard’ and ‘soft’ ones:

> *- ‘hard’ methods and techniques are predominantly based on quantitative analysis (characterized by mathematical models, algorithms, factual and objective information; value proven by theory). These are well-suited to puzzles;*
>
> *- 'soft' methods are based on human judgement in a qualitative analysis (governed by guidelines and non-mathematical reasoning principles or interpretative logic; value proven by experience). These are likely to be used for addressing wicked problems.*

2.2. Historical developments

A number of historical overviews on the field of DSS exist [2][8][18][24][25]; the next few paragraphs roughly follow the introduction to the field by Power [25].

While the roots of DSS can be traced back to the works of Vannevar Bush [4] and Douglas Engelbart [8], the first DSS in a modern sense were researched and implemented in the second half of the 1960s, when the advent of time-shared mini-computers led to an explosion of computing applications beyond centralised number crunching. As a first systematic study in 1966-1967, an early researcher in the field, Michael S. Scott Morton, developed and evaluated a ‘Management Decision System’ allowing marketing and production managers to coordinate production planning for laundry machinery [26]. In a further research step, Gorry and Scott Morton argued in 1971 that such a “Management Decision System” would primarily help to take structured decisions in a well-understood environment, while a computer system focussing on semi-structured and unstructured decisions should be named “Decision Support System” [9]. To be useful, such a system would have to be, it was found, robust, easy to control, simple, and complete in all details relevant for the decision [15].

Most early DSS were *model-driven*: they used limited access to data and input provided by the decision makers to parameterise and execute financial, optimisation, or simulation models [25]. While they had the potential to help analysing a given situation and decision options, they generally did not offer access to large databases, especially not to real-time ones [23]. Following the first 15 years of research, development, and evaluation of model-driven DSS, one verdict was “encouraging but certainly not uniformly positive” [25][28].

In the late 1970s, the first *data-driven* DSS combined model-driven systems and relational databases, beginning with offering real-time information screens for senior executives [12]. These systems, providing access and first visualisations of historic and real-time company data grew into data warehouses with additional real-time analytical processing [5]. In the 1990s, a popular category of data-driven DSS was Business Intelligence (BI) products, providing “concepts and methods to improve business decision making by using fact-based support systems” [25].

Knowledge-driven DSS added specific problem-solving capabilities to the availability of models and data, which allows them to recommend potential actions to decision makers [25]. While some systems have their roots in research conducted in the 1960s, their application flourished in the 1990s [14][23]. While classic knowledge-driven DSS often utilizes expert system technology [11], recent technological advances have brought into focus DSS applying Machine Learning methods [25].

In addition to model-driven, data-driven, and knowledge-driven DSS there were a number of technological side arms that evolved from being (part of) DSS into their own categories of software tools. *Communication-driven* DSS included tools to facilitate communication and collaboration, e.g. groupware and video conferencing [23]; *document-driven* or text-oriented DSS provided easy access to a multitude of documents, including “policies and procedures, product specifications, catalogues, and corporate historical documents” [25]; and *web-based* DSS provided DSS functionality not through software to be installed on a decision-maker’s computer, but via a web-browser on a PC or thin client [22].

2.3. Current developments and trends

During 50 years of research and implementation, DSS developed from simple model-based tools available via time-shared mini computers to web-based portals to corporate data resources unlocked by major artificial intelligence breakthroughs. On that way, the decision makers using DSS have pawned or facilitated classes of tools like groupware and video conferencing.

Corresponding to the competitive environments DSS usually exist in, adoption, utilisation, and success of their implementation are still regularly analysed. Current surveys and meta-studies [17][31] show the still increasing research interest, with the majority of the studies (56 percent) using quantitative methods, and a large minority (40 percent) examining and comparing DSS from multiple sectors such as government services, transportation, insurance, communications, health care, banking, agriculture, construction, and professional services [31].

A main research field currently is the *adoption of DSS by end-users* and the identification of the factors that impact that adoption, the motivating factors determining the behaviour of end-users towards the systems, as well as the overall success of the usage and its impact on the organisation itself. That impact is often measured as decision quality and performance [32] or in the dimensions of information quality, service quality, system quality and use, user satisfaction and net benefits [6][7]. While significant gains realised by DSS adoption are noted, many researchers see a need for further research caused by the prospective users' lack of motivation, capabilities, and ability to explore the system [31][32].

A fast-growing branch of *end-user DSS* research is the development and evaluation of *Recommender Systems*, i.e. systems that personalise online product, service, or news article recommendations [17]. With first systems being developed in the 1990s the field has seen, being part of the ever-increasing importance of e-commerce, a significant research attention for decades. Following the general trend, in the last few years the applications of machine learning technologies does see a lot of research interest, with first systematic surveys and meta-analyses [13][20]. Here, supervised machine learning approaches seem to be most popular by far (156 studies examined them), with unsupervised learning approaches following as second (46 studies were found). Only very few authors examined semi-supervised or reinforcement learning approaches [20]. Regarding types of machine learning algorithms used, ensemble learning, K-means and Support Vector Machines lead in the DSS field.

Other current research fields include the design of *interactive visualization* elements based on evaluating users' cognitive style and spatial ability [16], the utilization of *crowd-sourced and social media data* [21][30][34], as well as the potential advantages by utilizing *machine learning technologies* beyond simple input classification [20].

2.4. DSS in the context of Protection of Cultural Heritage

The use of DSS has been suggested in the field of cultural heritage for recommending restoration actions [69] and restoration materials [71], estimating the restoration budget [72], identifying ideal room ventilation conditions for preventive conservation purposes [73], ranking heritage buildings intended for renovations [62] and prioritizing preservation actions [74][75]. The ranking and prioritisation of preservation actions is important for the efficient restoration of cultural heritage objects under limited budget. The main challenges of decision support in Cultural Heritage Conservation (CHC) and Cultural Heritage Preservation (CHP) and the abovementioned methods are described more analytically in the following.

2.4.1. Main challenges of decision support in Cultural Heritage Conservation and Preservation

Cultural heritage serves as an important factor in the fields of sociocultural capital, education and economic development [56][59]. In 2008, UNESCO defined in the ‘Policy Document on the Impacts of Climate Change on World Heritage Properties’ the following research areas concerning the preservation of cultural heritage [55]:

- “Understanding the vulnerability of materials (indoor, outdoor, buried) to climate variables (for example, particularly too much or little moisture effects).
- Understanding how traditional materials and practices need to adapt to extreme weather events and a changing climate.
- Development of fail-safe methods and technologies for monitoring the impact of climate change at properties.
- Understanding climate change impacts causing changes in society i.e. movement of peoples, displacement of communities, their practices, livelihoods, and their relation with their heritage.”

According to [62] the main challenge in heritage preservation is the identification of the main purpose for the preservation. This can be the preservation and/or increase of the heritage’s item’s value for either research, and/or social and symbolic status, and/or sentimental value. Decision on adaption actions are based on economic factors, the variety of stakeholder demands and values and the environmental impacts on the building [59]. DSS frameworks are designed to identify the main proposes for preservation and prioritize and rank preservation actions under consideration of the costs.

2.4.2. Methods and tools

Decision making in cultural heritage is highly limited by the data available about the heritage site. Data compilation, exploitation and management is a key factor for DSS. In [57] and [58] Kioussi et al. provide methods for improved and integrated documentation strategies that are built on already existing documentation procedures. They propose an integrated documentation protocol developed in three stages. These are the identification of the state-of-the-art in the field, the advancement of the current data level and documentation procedure and finally the development of appropriate indices for the correlation of the updated and standardised data, which then are used in the decision making process.

Facing the economic factor in decision making processes, the study conducted in [72] presents a cost estimation concept based on the case-based reasoning (CBR) approach instead of a traditionally intuitive estimation method. In CBR model, two retrieval techniques, ‘Inductive Indexing’ and ‘Nearest Neighbour’, are applied to retrieve relevant cases from the knowledge-based database. Two of the most common types of Taiwan historical buildings are tested to explore the restoration cost implications. The result reveals that the CBR solution can effectively predict the actual restoration cost (since the retrieval result, based on past project's experiences, has taken work order changes and modifications of the budget into account), solve order change problems, and reduce the budget review time, to avoid a lengthy and complicated procedure delaying the restoration implementation.

In a more recent work regarding CBR [69], it appears that, as a problem-solving approach that uses specific knowledge of previous experiences for solving new problems, in a very similar way to how humans rely on their previous experience, it is a very promising approach. A CBR-based problem diagnostics application, proposed there, is intended to support Construction Industry workers on the restoration site in problem solving in the specific area of the built stock restoration in a fashion resembling the experienced workers' approach. The solution presented and results obtained in its current testing, provide a good basis for identification of the correct problem causes, i.e. are allowing for a more efficient identification of the problem and appropriate restoration actions.

Since the performance of each material on the restoration phase significantly differs with respect to its type, chemical properties and the building substrate, a decision support architecture able to face these obstacles is proposed in [71]. In that paper, a new DSS architecture suggesting the most suitable restoration actions for cultural heritage monuments is described. The architecture first includes the introduction of an aligned integrated documentation protocol acting as cultural identity card. Then, a collective intelligent DSS is proposed which is able to interoperable describe the cultural content while simultaneously suggest the most suitable restoration options as that conservation is achieved at a maximum degree, while potential negative effects on the monument status and 'cultural quality' is minimised.

In the area of preventive conservation, special climate requirements are present. Especially fluctuations in climate values should be reduced in order to avoid damages of the sensitive materials of cultural heritage. For example, in several applications, no modern ventilation systems are present, such that the only ventilation option is the opening of windows and doors by human. Therefore, serious climate fluctuations occur, if the ventilation strategy is not adapted to the climate situation. To avoid this situation, a monitoring and DSS is developed in [73]. In the face of the specials needs of reducing climate fluctuations in the area of preventive conservation, a fuzzy approach to realise a predictive monitoring and DSS considering weather forecasts, is presented. A method for adapting weather forecasts to local microclimates is analysed. The fuzzy approach allows considering the inexactness in predicted values, which increases the system robustness significantly.

Decision makers or executors often encounter with taking decisions on which heritage is prioritised to be restored within the limited budget [62]. However, very few tools are available to determine appropriately restoration priorities for the diverse historical heritages, perhaps because of a lack of systematised decision-making aids. In [74], a model for determining restoration priorities of cultural heritage under the limited budget is proposed and compared to current procedure favoured by decision makers in the Cultural Heritage Administration. To illustrate the model's efficiency, 14 cultural heritages in Korea were studied and the results were statistically analysed. Few primary contributions of this document are summarised at identifying significant criteria through three Delphi rounds and providing an alternative process for carrying out an assessment of restoration urgency of cultural heritage. It reflects the contribution effect of evaluators' expertise and knowledge on weighting the criteria and scoring restoration needs in an objective and quantitative way, as well as assisting the executors in interpreting probabilistically the ranks of restoration priorities for making a decision more rational and persuasive, comparing to the procedure depended on intuitive decisions.

A more recent work on prioritisation [75] discusses the meaning and nature of urban cultural heritage, and the available methods for its evaluation in the perspective of sustainable city development. That paper presents the multiple criteria assessment of alternatives of the cultural heritage renovation projects in Vilnius city. The model consists of the following elements: determining attributes set affecting built and human environment renovation; information collection and analysis; decision modelling and solution selection. The main purpose of the model is to improve the condition of the built and human environment through efficient decision making in renovation, supported by multiple attribute evaluation. Delphi, analytic hierarchy process (AHP) and additive ratio assessment method with grey values (ARAS-G) methods, considering different environment factors as well as stakeholders' needs, are applied to solve the problem. To illustrate the model's efficiency, it has been applied to eight cultural heritages and the results were analysed. The decision support model presented in that paper can be used for objective evaluation in a realistic consultation and a fairly advanced administration. Based on this system, heritage buildings are evaluated. The eight criteria set presented in that paper are not perfectly satisfactory for all countries. The multiple-criteria-decision-making-based grading system is of considerable use to urban planners. It provides them with a stronger basis for determining which decision should be made. This would facilitate urban regeneration through the integration of the conservation scheme into the city development plan, while minimizing conflicts between stakeholders.

Generally, decision-making problems are complicated due to various factors affecting the event evolution and the uncertainty of decision information [76][77]. Especially, the study of [76] was part of RODOS (Real-time Online Decision Support), an ongoing European Union (EU) project on developing a support system for nuclear emergency management. Decisions on countermeasures are not only driven by the need to avert the radiation dose to the population, but are based on complex and multi-attribute problems, involving, for example, monetary costs and socio-psychological factors, such as stress and anxiety. These decisions have far-reaching consequences, yet they often have to be made under severe time-pressure constraints and conditions of uncertainty. Moral and ethical values held by decision makers and stakeholders are as important as the technical issues about the consequences of radiation. Even some of the underlying assumptions in neutral risk assessments may contain value judgments. This complex situation thus places high demands on the decision-making processes. Furthermore, according to [77], there are many comparison matrices for a complicated risk assessment problem, but a decision has to be made rapidly in emergency cases. However, in the analytical network process (ANP), the reciprocal pairwise comparison matrices (RPCM) are more complicated and difficult than AHP. Concluding, the design of effective DSS is a critical step towards improving the conservation of cultural heritage objects and shall incorporate intelligent decision-making methods to cope with the aforementioned key characteristics of object conservation, requiring dynamic, real-time, effective and cost-efficient solutions.

A DSS named ArcheoRisk [78] was developed to include the safeguarding of archaeological sites within the environmental management of the Venice lagoon and to select most effective safeguarding/rehabilitation interventions, whenever needed. The DSS relies on a Geographical Information System platform (Arcview) and is composed of two modules: (1) assessment of archaeological risk, (2) selection of interventions. It can be easily applied to different case studies and environments, thus providing a promising reference of GIS-based DSS and risk analysis application for the integrated management of environmental and cultural heritage.

The exDSS software, which is described in the first part of [79] and which has been developed for the purposes of the Climate for Culture project, is another, fully functional open source software for developing decision support tools. The applicability is not only in the field of cultural heritage, but it can be used anywhere, where the know-how of the experts can be structured into a form of logic decision trees or diagrams. The decision support tool for indoor-climate risk assessment and control, which have been outlined in the second part of the report, is freely available [80]. Due to flexibility of the exDSS software, various clones of the project can be created which are then free for modification. Thus, rather than a final and closed product, a platform for creating decision support tools is provided. The authors also see a large potential in the possibility to derive the future indoor-climate risk indices from the wide set of maps, which has been provided as one of the main results of the Climate for Culture project. Finally, the given decision support module has also been used for the dissemination of the Climate for Culture project results. Particularly, the case study reports and various guideline texts are available directly on the web interface of the Conclusions or are web-linked to them as pdf files.

Recently, simulation-enabled methods [81][82] have been introduced as part of emerging DSS, addressing cognitive and team functioning modelling [82] and environmental simulation [83]. Particularly, the purpose of [81] is to report on the design and use of a gaming simulation as a means of assessing one group decision support system (GDSS) for emergency response. The paper reviews related past work and focuses on the authors' recent experience in conducting quasi-experiments to assess Emergency Management imPROViser (EMPROV), a GDSS for improvisation in emergency response operations. The authors conclude that gaming simulations have the potential for assessing a DSS and its impact on the group it is designed to support.

More recently, [82] reports ongoing work whose objective is to increase the efficiency of emergency response solutions (ERS) through iterative cycles of human in-the-loop simulation, modelling, and adaptation. Ultimately, this cycle could either be achieved offline for complex adaptation (e.g., development of a novel interface), or online to provide timely and accurate decision support during an emergency management event. The method is able to achieve a high degree of realism and experimental control through the use of an innovative emergency management simulation platform called SYnRGY. That work is focused on the identification of critical functions associated with emergency management and on the development of a 'cognitive toolbox' to support them. This is possible with the holistic and objective measurement and modelling of cognitive and team functioning during simulated scenarios involving experts.

Key research challenges [68] in supporting successfully respective actors, refer to the ability of the DSS to accommodate evolving multi-factor knowledge, stemming either from real-time information (collection of data from sensors) or even from next generation simulation engines that can effectively incorporate both domain-specific and generalized simulation models. Despite this fact, however, the use of simulation methods for DSS development in cultural heritage related information is very limited.

Furthermore, as also in the focus of the ARCH project, climate change impacts on cultural heritage are more widely discussed. Fatorić et al. [56] show in their review paper, that research in this field increased since 2003. They state the presence of a wide range of methods, also due to local specifications, but they also state the need of using further interdisciplinary, multidisciplinary and transdisciplinary approaches for climate change adaptation. Current approaches such as in [59] and [60], consider the change of attributes, metrics and weights of the cultural resources over time and suggest a regular update of these. In [61], Forino et al. provide a value-focused, decision-analytic approach for climate adaptation planning for buildings in Newcastel, Australia. They present the cultural heritage risk index (CHRI) for assessing climate change-related risk for CHP, which incorporates risk as a function of hazard, exposure and vulnerability.

2.5. DSS in the context of Climate Change Adaptation

In this section, we summarise the main challenges in Climate Change Adaptation (CCA), motivate the need for specific Decision Support (DS) for stakeholders and actors in urban CCA, and give an overview on methods, tools, and recent standardisation activities in CCA. We conclude with pointing to recent best practices in DS for CCA.

2.5.1. Main challenges in Climate Change Adaptation

Climate Change Adaptation is a challenging task for the entire society. This task involves many different stakeholders, actors and practically all governance levels. Focal points of adaptation activity are urban and built-up areas, since more than 73% of the population of the EU-28 live in these types of areas.

As mentioned in the introduction, CCA has the characteristics of a ‘wicked problem’. In the following paragraphs, we characterise some of the factors that add to the complexity of CCA for urban areas, based on own experiences in the RESIN project [46].

The first, three-fold challenge is the related to actors in CCA. In many cities, there is still no dedicated person or department in charge of CCA. That is, the ownership of the CCA process is unclear, which may result in a delayed start of the CCA process or in less than optimal adaptation planning. The second part of this challenge refers to the fact that in the large agglomerations that urban areas are, a multitude of stakeholders needs to be included in the CCA process. These can be subject matter experts from different municipal departments, operators of infrastructure, stakeholders from the local economy, and last, but not least, the citizens. With so many actors involved, it is only natural that any planning of adaptation measures may lead to conflicts of interest. The third part of the challenge is related to governance. At certain points in the CCA process, the policy level needs to be involved. The policy level needs to approve adaptation plans and grant the required resources.

The second challenge arises from the uncertainties that CCA actors need to deal with. The first uncertainty is inherent to today's climate models that are available. This includes the correctness of the predictions (like rise in average temperature, change in rainfall patterns), the possible spatial precision of the predictions (which are decisive for effective local adaptation planning), and the correctness and the completeness of data for performing local risk assessments (if available at all).

More than thirty years ago, investigations of climate change started and simultaneously research and development on climate protection and climate change adaptation commenced on a global scale. These activities produced a wealth of information sources on climate change and guidelines and tools for climate change adaptation. Thus, the third challenge for CCA actors who want to make use of this wealth off assets is to identify relevant and well-suited assets for their needs.

Lastly, the fourth challenge is related to a recent change in fundamental methodology. Five years ago, the Intergovernmental Panel on Climate Change (IPCC) proposed a paradigmatic shift from indicator-based vulnerability assessment of climate-related hazards to a risk-oriented assessment, motivated by the desire to converge with concepts used in related domains like Disaster Risk Reduction (DRR) and Critical Infrastructure Protection (CIP). This shift in paradigm is suited to foster coordination of action in these domains for making better use of limited resources by using synergies. However, the proposed shift to risk assessment lacked a concrete method describing how to apply it practically, which constituted a barrier for inclined early adopters. Hence several different institutions started developing their own risk assessment scheme for CCA [44][45], which contributes again to the third challenge.

2.5.2. Types of Decision Support for Climate Change Adaptation

Experiences in projects like RESIN [44] and RAMSES [39] showed that it is possible and necessary to employ a mixture of both types of methods. For some areas of decision support in CCA, it is indeed possible to use quantitative analyses, as in assessing specific risks like fluvial flooding or heat stress. In addition, the availability of quantitative analyses may help convincing the policy level setting the right priorities.

For the remainder of this section, we provide a brief overview of the state of the art in decision support for CCA along five categories: frameworks, methods, general tools, information technology-based tools (IT tools), and standardisation.

Frameworks

Frameworks are a means of visualising proposed decision support processes and their embedding in or relation to other processes. Figure 1 shows an example from Wijnmalen et al. [47] that depicts the four main stages of decision support (after initiation). Each stage has, recursively, a similar four-stage structure. In addition, the entire process may need to be repeated. For the RESIN project, Carter and Connelly [48] present a cyclic framework for CCA, shown in Figure 2. The first cycle starts with a baseline risk assessment, continues with selecting and prioritising adaptation options, planning adaptation measures and ends with monitoring their implementation. A second, parallel cyclic – or rather continuous – process is shown that depicts the changes in the environment while the adaptation process takes place. These changes require a repetition of the adaptation process.

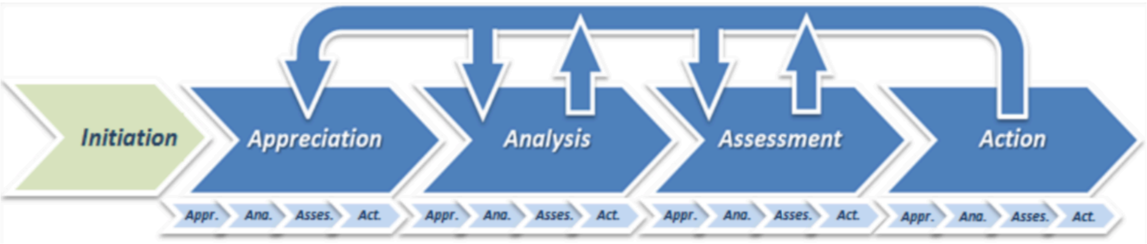

Figure 1: **Four main decision support stages [47].**

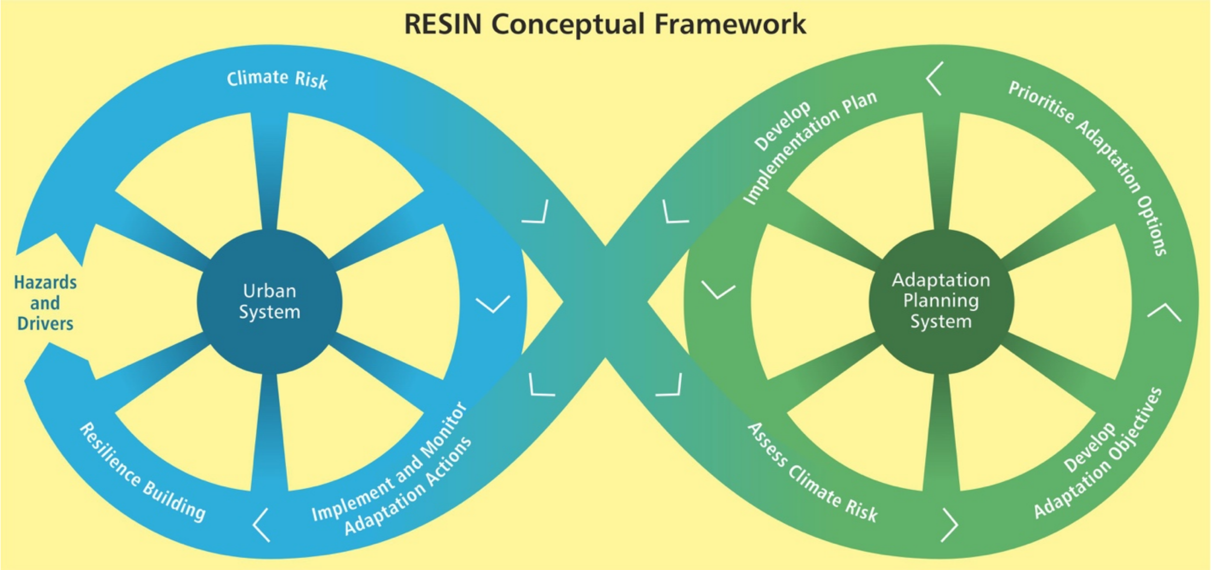

Figure 2: **RESIN concept framework for climate change adaptation processes [48]**

Methods

The ultimate goal of decision making in CCA is making optimal use of the limited available resources for achieving the highest possible degree of urban resilience against consequences of climate change. Decision support developed for and used in the complex task of CCA can be roughly divided into the following categories of action:

1) Assessment
    a. Vulnerability assessment (qualitative / quantitative)
    b. Risk assessment (qualitative / quantitative)
2) Reporting and presenting results to the political level
3) Planning, implementing, and monitoring adaptation measures

Ad 1) Assessment. Up to the publication of IPCC Assessment Report 5 (AR5) in 2014 [42], indicator-based vulnerability assessment (IBVA) was the general method of choices for performing assessments, though a standard implementation was lacking. Tapia et al. (2015, [50]) list some 70 papers in their literature review, most of them published in the 20 years since 1994. Compared to this wealth of vulnerability assessment methods, there are of course less papers that have addressed the paradigmatic shift to risk-oriented assessment proposed in the IPCC AR5. Tapia et al. (2015, [50]) were one of the first to react to the AR5 publication. They propose to calculate relative climate risk for cities as a score composed of aggregated and weighted indicators for hazard, exposure and vulnerability for each consider climate change induced hazard ([50], p. 68).

The German GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH) developed a modular method for vulnerability assessment, the Vulnerability Sourcebook Method (VSBM, [40] and [41]), published in the same year as AR5. Targeted mainly towards CCA in developing countries, this method has been widely used. In 2017, the same authors published a risk supplement, in which they adapted the VSBM for addressing risk rather than vulnerability.

Simultaneously, the RESIN project developed IVAVIA (Impact and Vulnerability Assessment for Vital Infrastructures and built-up Areas), which proposed a different way for adapting the VSBM to risk assessment [44]. The IVAVIA methodology aims to guide a risk-based vulnerability assessment, helping to map, analyse and communicate the impact of climate trends and weather events on key elements of your city's physical, social and economic fabric. IVAVIA provides guidance on how to prepare, gather, and structure data for risk-based vulnerability assessment; quantify and combine vulnerability indicators; assess risk; and present outcomes. As such it helps in understanding and visualising the cause-and-effect relationships of climate change, identifying geographical risk and vulnerability hotspots, assessing the demographic, economic and local impacts of climate change now and in the future, identifying entry-points for adaptation measures and areas where priority action is needed.

Both VSBM and IVAVIA include qualitative and quantitative methods for risk assessment. This allows stakeholders to choose a method depending on available resources and data. Since quantitative assessment requires data availability, knowledge in statistics, and more time than qualitative assessment, it may not be feasible for some stakeholders to perform a quantitative assessment. This makes quantitative assessment an area that is predestined for tool support.

Ad 2) Reporting and presenting results to the political level. After concluding an initial risk assessment, the results must typically be presented to the political level in order to get their support. Since this is a crucial stage in the adaptation process, some sources provide also guidance for presenting the results ([40], [44]).

Nowadays, many cities participate in frameworks like 'Covenant of Mayors for Climate and Energy'[1] or the '100 Resilient Cities'[2] initiative of the Rockefeller Foundation. Typically, these frameworks require periodic reporting of their members on their progress in CCA in a standardised (within one such framework) way. The mutual exchange and learning in such frameworks may also be considered a decision support method.

Ad 3) Planning, implementing, and monitoring adaptation measures. This category of action covers a good part of the right cycle in the RESIN conceptual framework, namely developing

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[1] https://energy-cities.eu/project/covenant-of-mayors-for-climate-energy/

[2] http://www.100resilientcities.org

and prioritising adaptation options, and developing, implementing, and monitoring an adaptation plan. This category of action involves to a good part finding and identifying best practices (relevant adaptation options, existing adaptation plans), but involves also application of methods for assessing adaptation options (like cost-effectiveness analysis, multi-criteria analysis) and monitoring the implementation of selected adaptation measures (using monitoring indicators).

General tools

General tools typically come in two flavours: comprehensive guidance documents and web-based information systems. Examples for step-by-step guides that guide the stakeholders through the adaptation process are the already mentioned Vulnerability Sourcebook ([40], [41], [45]), the RESIN IVAVIA Guideline document [44], ICLEI ACCCRN Process manual [52] and the RAMSES transition handbook and training package [39]. The regional Asian Cities Climate Change Resilience Network (ACCCRN) connects professionals and communities across Asia to build inclusive urban climate change resilience (UCCR) that focuses on poor and vulnerable people affected by climate change. It empowers people in building climate resilience, influence urban agendas, and build a regional resilient community in Asia where there is rapid urbanization and fast-growing cities that are prone to sudden shocks, as well as long-term stresses. Experiences and lessons learned from the ACCCRN will benefit the co-creativity in ARCH.

From the plethora of web-based information sources we just want to mention two. The first one is the EU Climate-Adapt Platform. It is maintained by the European Environmental Agency (EEA) and thus has an official character. EU Climate-Adapt is well-suited for aligning local adaptation with EU policies. The platform has also adopted selected mature results of EU funded research projects and offers a number of CCA tools.

The second web-based information source is the RESIN e-Guide[3], which consists of a learning centre and a workspace for own CCA projects. The learning centre describes all stages of the adaptation process and lists related information sources and tools. The workspace, accessible only for registered users, is a private workspace that allows creating and editing adaptation projects. Users can upload data, manage access rights, store intermediate results and monitor progress.

Nieuwenhuijs [51] provides a comprehensive list of adaptation support tools covering one or more of these stages, with a focus on urban adaptation support. Some of the tools are focused on a specific type of hazard such as heat stress, some for specific regions such as coastal regions and some are of more general nature. The take home message here is that the EU Climate Adapt platform has gathered many useful such tools from concluded projects and other parties and offers and maintains them on their website. Examples are the EU Climate Adapt Adaptation Support Tool[4] and the Urban Adaptation Support Tool.

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[3] http://wiki.resin.itti.com.pl

[4] https://climate-adapt.eea.europa.eu/knowledge/tools/adaptation-support-tool

Specific IT tools

The entire process chain from risk assessment to adaptation monitoring can benefit from specific IT-based decision support tools. For risk identification, it is quite common to use IT tools based on Geographical Information Systems (GIS). One example is the RESIN European Climate Risk Typology[5], which provides a categorisation of risk based on geographical location at the spatial resolution of NUTS3 regions in Europe. For each such region, a wide range of climate risk indicators is provided, including risk relative to the average within the same type of region.

Databases are typically employed for gathering indicator data or whenever large datasets need to be collected and maintained. An example of a customised database for CCA is the RESIN Adaptation Options Library[6], which provides access to a structured body of adaptation options gathered from some 1,200 publications and tagged with additional information like a cost-effectiveness assessment.

Specific IT tools include tools for reporting, for the presentation of results, for visualising impact chains, and sometimes pre-configured Excel sheets like the UNDRR Scorecard Excel Sheets for applying the UNDRR Disaster Resilience Scorecard for cities [53]. It goes beyond the scope of this State of the Art report to present more such tools. The interested reader may refer to the RESIN e-Guide that provides a comprehensive overview of existing tools for each of the phases of the CCA process.

Standardisation

Several standardisation activities that are relevant for urban actors in CCA have been started in the last five years. A recent study of the RESIN project provides a comprehensive overview of the status of the national and international activities in this respect as of October 2018 [49]. We have listed below a selection of eight of the international activities that we consider most relevant. They comprise a glossary of terms in environmental management, three guides (risk assessment and adaptation planning for CCA, smart city operating models for sustainable communities), and three lists of indicators related to different aspects of sustainable cities. As of September 2019, six of these standards have been published and three are still under development.

Table 1: Standards relevant to urban CCA

Standard	Title	Status
ISO 14050:2009	Environmental management: vocabulary	Published
ISO 14090:2019	Adaptation to climate change: principles, requirements and guidelines	Published

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[5] http://www.resin-cities.eu/resources/risk-typology/ direct link: http://european-crt.org

[6] https://resin.vmz.services/apps/adaptation/v4/#!/app/landing

ISO/CD 14091	Adaptation to climate change: vulnerability, impacts and risk assessment	Draft
ISO/AWI TS 14092	Green House Gas (GHG) management & related activities: requirement & guidance of adaptation planning for organizations including local governments and communities	Draft
ISO 37106:2018	Sustainable cities and communities: guidance on establishing smart city operating models for sustainable communities	Published
ISO 37120:2018	Sustainable cities and communities: indicators for city services and quality of life	Published
ISO 37122:2019	Sustainable cities and communities: indicators for smart cities	Published
ISO/FDIS 37123	Sustainable cities and communities: indicators for resilient cities	Draft

2.5.3. Best practices in Decision Support for Climate Change Adaptation

As mentioned earlier, CCA is a multi-stakeholder endeavour. Stakeholder Workshops are the preferred means to bring stakeholders from various involved domains together for joint goal definition, risk assessment, and planning. The choice of methods for the different phases of the adaptation process depends on factors like available resources (person power, knowledge, data) and targeted time frames or deadlines. An adaptation team in a small city may not have the knowledge in statistics for performing a thorough quantitative analysis. Here, scientific support from local universities and academic institutions may alleviate the situation.

In times of limited resources, we recommend also using synergies with related domains like Disaster Risk Reduction and Critical Infrastructure Protection (CIP). Such collaboration is suited to identify common interests, the potential for coordinated action, and new options for financing adaptation measures. Actors in CCA, DRR, and CIP may resort to broader resilience assessments methods like Resilience Maturity Model of the SMR project [38] or the Disaster Resilience Scorecard for Cities of the UN Office for Disaster Risk Reduction (UNDRR) [53].

Lastly, we strongly recommend subject matter experts and actors in urban CCA to make use of the existing and forthcoming standards mentioned in Section 2.5.2. Using standards has a high potential of benefits. It would facilitate mutual exchange and comparability of adaptation measures and progress in CCA. In addition, we expect that further tool development will also built on or support published standards.

3. Environmental monitoring and 3D object/area scanning

For DSS in the fields of CCA (Climate Change Adaptation) and CHC (Cultural Heritage Conservation) a multitude of data that provide information concerning environmental aspects are needed. Often such data are not yet available and need to be elicited anew, like 3D data of cultural heritage buildings and artefacts, or need to be updated regularly.

This section gives an overview on relevant environmental issues surveyed in ARCH and a non-exhaustive roundup of systems as well as already existing platforms that enable the respective monitoring, like sensor systems for capturing data, platforms for accessing, processing, and displaying data.

3.1. Environmental issues addressed in ARCH

In ARCH, we comprehensively address a multitude of important environmental issues that may have direct impact on current and future condition of tangible and intangible cultural heritage:

- Air pollution and contamination with gases and substances: have potentially negative effect not only on human health, but also on degradation of global environment, in the context of ARCH project, specifically damaging to outdoor cultural heritage. Concentrations of such gases such as CO, CO_2, NO_2, H_2S, NH_4, SO_2 etc. and their relation to transport and energy production and consumption in densely populated residential areas, and heavily industrialized regions are of highest importance due to their erosive character especially when combined with high levels of humidity and in extreme cases also immersion in water
- Water: referring to local, regional and global hydrological risk (e.g. floods, droughts) assessment, prediction and management systems and expanded applications of integrated water resource management for sustained development
- Noise/Vibrations: commonly identified in urban environments with transport (mainly road transport) is both annoying and reduces quality of life of citizens, but in the context of cultural heritage objects the exposure to long-term ground and air vibrations, especially at low frequencies, may cause physical destructions to cultural heritage in long terms
- Weather: monitoring basic meteorological parameters (temperature, humidity, pressure wind speed and wind direction) are key to determining and predicting risk of erosions as well as chemical changes to material that cultural heritage objects are composed of, especially when combined with other types of pollutions
- Climate change: delivering reliable climate information of a quality needed for predicting, mitigating and adapting to climate variability, including for better understanding of the global carbon cycle, offering access to observational data for climate monitoring and services in support of adaptation to climate variability and change, facilitating a comprehensive global observation and analysis system in support of monitoring based decision-making and environmental treaty obligations to World Climate Research Programme

(WCRP)[7], Intergovernmental Panel on Climate Change (IPCC)[8] and United Nations Framework Convention on Climate Change (UNFCCC)[9].

- Natural and man-made disasters: involving all phases of the risk management cycle associated with hazards. This includes timely exchange of relevant information with globally-coordinated systems for monitoring, predicting, risk assessment, early warning, mitigating and responding to hazards, also means of wide dissemination of information. Information and knowledge processing lead to modelling of incident progress and possible prediction of risks of their occurrence, with likely impacts on cultural heritage.
- Biodiversity: worldwide biodiversity observation network to collect, manage, share and analyse observations of the status and trends of the world's biodiversity, and enable decision-making in support of the conservation and improved management of natural resources. Indirectly contributes to protection of cultural heritage by creating green zones insulating them from urban pollutions and reducing impacts from climate change, in some cases leading to possible reduction of possible impacts from natural/industrial disasters.

Considering the vast number of possible sources of information that have possible usability in ARCH and that might be considered for integration into its processes and tools, few examples of such sources of environmental data are described in the following sub-sections. It does not mean an exhaustive SotA analysis, considering the vast range of technologies and platforms available on the market, both commercial and private ones, developed in EU funded projects as well as commercially available from major industries, SMEs and academia. They range from long range and general overview, like satellite observations, to locally deployable sensor nodes for monitoring of specific areas, extrapolating also to larger ones by combining multiple sensors with innovative modelling algorithms.

3.2. Earth Observation for environmental monitoring

Current green social networking platforms are immature and mainly exist in the form of blogs where people write articles/ideas and others comment, suggest, etc. No connection with actually monitored data exists, no involvement of or connection with responsible authorities and organisations is introduced. On the other hand, a number of initiatives that try to overcome these limitations exists. The Global Earth Observation System of Systems (GEOSS) [66] is a framework with the purpose to link together existing and planned environment observing systems around the world and support the development of new systems where gaps currently exist, by promoting common technical standards. This will offer decision makers a variety of tools and access to a 'global' database. GEOSS offers a single Internet access point for users seeking environmental data, imagery and analytical software packages relevant to all parts of the globe, based on Earth Observation sensors. Its purpose is to enhance the coordination of efforts to strengthen individual, institutional and infrastructure capacities, particularly in developing countries, to produce and use Earth Observations and derived information products. Compliant with GEOSS standards, ARCH sensing system will offer interfaces to environmental

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[7] World Climate Research Programme (WCRP): https://www.wcrp-climate.org

[8] Intergovernmental Panel on Climate Change (IPCC): https://www.ipcc.ch

[9] United Nations Framework Convention on Climate Change (UNFCCC): https://unfccc.int

organizations either to retrieve (aggregated) user-driven measurements enhancing their models.

3.3. EU environmental monitoring by European Environmental Agency (EEA)

The most advanced and comprehensive environmental observation approach is “Eye on Earth” [64] platform recently deployed by the European Environment Agency and developed using Microsoft Fusion Engine. It is an environmental information portal currently supporting air quality monitoring and water quality in bathing sites across Europe using limited amounts of data from local environmental observatories. For example, the ‘Water Watch’ service allows users to rate beaches and to share their comments with others. The portal has not progressed much since its launch, in the sense that the only new set of environmental information added is that of air stations. Its usability is basic and not interactive enough to attract general users. Interface is based on web search for a given map of the beach and its custom rating. ARCH sensors’ platform will take advantage of data stored in Eye-on-Earth platform, combining it with various other sources of information including from dedicated sensors developed in ARCH, by having at its disposal vast amounts of RAW and processed data being able to produce more reliable value-added data processing and modelling applications etc.

3.4. Relevant EU funded projects

Various research and development activities have been funded either by the European Research Funding Framework, National Research Funding and proprietary in-house developments related to Environmental monitoring. The research is being driven by European Commission Environmental monitoring programme[10] of recurring, systematic studies that reveals the state of the environment. The specific aspects of the environment to be studied are determined by environmental objectives and environmental legislation. The purpose of environmental monitoring is to assess the progress made to achieve given environmental objectives and to help detect new environmental issues. Part of those activities is public funding of projects aimed at diverse activities related to monitoring environment and climate change effects. As of November 2019, there have been more than 814 projects[11] funded by Horizon 2020 program alone that are related to environment and climate change.

One of the most relevant ones is ‘EveryAware’, an FP7 ICT project aimed to integrate all crucial phases (environmental monitoring, awareness enhancement, behavioural change) in the management of the environment in a unified framework, by creating a new technological platform combining sensing technologies, networking applications and data-processing tools. It involved, through case studies, as many citizens as possible through low cost and high usability.

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[10] EC Environmental monitoring program: https://ec.europa.eu/jrc/en/research-topic/environmental-monitoring

[11] Projects funded by Horizon 2020 program and related to environment and climate changehttps://cordis.europa.eu/search/en?q=contenttype%3D%27project%27%20AND%20(programme%2Fcode%3D%27H2020-EU.3.5.%27%20OR%20programme%2Fcode%3D%27H2020%27)%20AND%20applicationDomain%2Fcode%3D%27env%27&p=1&num=10&srt=Relevance:decreasing

It mentions use of participatory sensing, gathering subjective opinions about local environmental issues to evolve into socially-shared opinions, for subsequently driving behavioural changes and offer effective communication of desirable environmental strategies to the general public and to institutional agencies.

Another important one is INSPIRE[12] Directive, creating a European Union spatial data infrastructure for the purposes of EU environmental policies and policies or activities which may have an impact on the environment. This European Spatial Data Infrastructure enables sharing of environmental spatial information among public sector organisations, facilitate public access to spatial information across Europe and assist in policy-making across boundaries.

3.5. Sensors and sensor networks

The previously mentioned platforms and systems, despite vast amounts of data, they still do not offer sufficient level of information for ARCH to offer sufficient amount of sensor data, based on which information and knowledge could be produced to the levels required by (local) authorities for the protection of cultural heritage objects and areas. Satellite systems, despite covering wide range of pollutants, do not give sufficient spatial resolution. Participatory climate monitoring systems like Netatmo Weathermap [67], give access to vast amount of sensor data, but limited to basic thermodynamic parameters (temperature, humidity and pressure, in smaller number of cases only to wind and rain as well) lacking info about various air pollutants at local scales. Various EU funded projects have built environmental monitoring platforms, but they are generally small-scale deployments with areas covered that do not include cultural heritage areas, often due to restrictions of access.

Therefore, ARCH project will also be required to make its own deployments of sensor monitoring in specific areas of interest. Those will take advantage of the SotA sensors for monitoring diverse pollutants, use most innovative embedded sensor technologies from collaborating industries, often not yet available on the market (e.g. new long-range embedded sensor nodes from Analog Devices). Many of such technologies will be integrated in such small factors that they will be possible to be deployed on micro-UAVs in (semi)autonomous manner, thus more acceptable by national Aerospace Agencies for operating in populated urban environments.

In terms of sensing technologies, there is a vast number of sensing elements and sensor nodes that are on the market that all constitute the Internet of Things[13] hype. Increased level of miniaturisation of embedded computers allowed to create micro sensing devices that may also have control capabilities. Very soon, probably they will have also reasoning abilities when Artificial Intelligence[14] becomes a practical reality.

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[12] INSPIRE: https://inspire.ec.europa.eu/

[13] Internet of Things consortium: https://iofthings.org/

[14] Association for the Advancement of Artificial Intelligence: http://www.aaai.org/

3.6. Industrially-driven participatory sensing platforms

There are various types of environmental platforms produced by industry and usually associated with e.g. climate sensors produced by them. Since it would be impractical to perform a comprehensive market analysis, we decided to focus on only those technologies that we will integrate with for the purpose of the ARCH project, with aim to progress further with the SotA of those developments and/or provide added value applications and services. Such an approach will also follow in other sections, such as when describing sensing technologies.

One of the most prominent industrially drive approaches taking advantage of the Participatory Sensing is NetAtmo Weathermap[15]. It is an online repository of climate data collected from NetAtmo (https://www.netatmo.com/) sensors deployed by people who purchased those and agreed to voluntarily contribute data from their sensors to public community, in return, getting access to accurate and timely information in almost any location on Earth. As a result, the Weathermap gathers information from nearly 35.000 sensor nodes, making the data available (certainly in compliance with GDPR, i.e. removing any identifiable private information) via easily usable NetAtmo-API[16].

3.7. 3D scanning and modelling of cultural objects and areas

The 3D scanning of cultural heritage has been around for more than a decade, originally driven by professional systems. Since the introduction of the Microsoft Kinect (version 1) in 2010 for Xbox and in 2012 for PCs along with an SDK[17] for MS Windows, such technologies started to pick up a momentum and used by many non-expert citizens. Apple systems also have such sensors available with most famous one being the Structure[18] sensor. Since then, several consumer and professional software technologies have been launched. The most prominent is Autodesk ReCap[19] (previously Autodesk ReMake[20]) with a suite of 3D model management applications such as 3D Studio MAX[21], Maya[22], etc. Other commonly used software tools include: Agisoft Megasoft[23] (previously Photoscan), Artec Studio[24], Meshlab[25], community-built Blender[26] and many other ones.

Models produced by any of the above-mentioned applications can be easily manipulated and imported into a majority of Gaming Engines, thus enabling developers to produce Virtual and Augmented Reality environments taking advantage of such models, such as Virtual Museums[27], Galleries[28], both for fixed computing platforms and mobile ones like smartphones alike.

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[15] NetAtmo Weathermap: https://weathermap.netatmo.com/
[16] NetAtmo API: https://dev.netatmo.com/en-US/resources/technical/reference/weatherapi
[17] MS Kinect SDK: https://developer.microsoft.com/en-us/windows/kinect
[18] Structure sensor: https://structure.io/structure-sensor
[19] Autodesk ReCap: https://www.autodesk.com/products/recap/overview
[20] Autodesk ReMake: https://www.autodesk.com/products/remake/overview
[21] Autodesk 3D Studio MAX: https://www.autodesk.com/products/3ds-max/overview
[22] Autodesk Maya: https://www.autodesk.com/products/maya/overview
[23] Agisoft Megasoft: https://www.agisoft.com/
[24] Artec Studio: https://www.artec3d.com/3d-software/artec-studio
[25] Meshlab: http://www.meshlab.net/
[26] Blender: https://www.blender.org/
[27] SCAN4RECO Virtual Museum: https://www.scan4reco.eu/content/scan4reco-virtual-museum
[28] RFSAT Virtual Gallery: https://www.rfsat.com/index.php/en/results/3d-gallery.html

The most well-known 3D Gaming Engines offering free development access are: Unity[29], Unreal Engine[30], CRYENGINE[31] from CryTek.

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[29] Unity: https://unity.com/
[30] Unreal Engine: https://www.unrealengine.com/en-US/feed
[31] CRYENGINE: https://www.cryengine.com/

4. Information and knowledge management

Information and knowledge management constitute an intelligence layer, where sensor data, pre-processed information, and individual knowledge are combined into a general knowledge of the state and the evolution of the environment. In doing this, ARCH exploits the latest advances in semantic annotation and analysis of citizen environmental sensor data, machine reasoning and learning, knowledge representation and engineering from sparse, incomplete and uncertain information supported by ontological engineering geared to environmental purposes. Novel algorithms will enable ARCH to identify possible inter-relationships among various parameters with purpose-built risk assessment, situation prediction and forecasting services. Examples of such tools include prediction and simulation of ageing effects that based on known condition of cultural heritage objects and detected environmental conditions could help in predicting progressing ageing of objects and their deteriorations, thus enabling decision makers to determine best ways of preventing such effects. Instrumental to this is use of participatory sensing techniques, where citizens who often have access to own sensors deployed at their local environment, offer invaluable source of data that even if of lower quality, may supplement data coming from sparse meteorological and/or purpose deployed monitoring stations. Integration with diverse networks of natural disaster monitoring and predictive further enhances the preciseness of effects that can be linked to climate change effects.

4.1. Ageing simulation of chemical changes and geometrical erosions

Ageing depends on material composition, object usage, and other physical, biological, and chemical parameters. Ageing phenomena often play a key role in realistic rendering. Their absence results to non-realistic surfaces, looking too clean and smooth. Each specific ageing process is considered according to [84][85] as a challenging task in computer graphics, because of the often-complex underlying physics involved and the need for providing designers with usable tools. Capturing ageing in computer graphics is simulated by modelling object morphology changes such as cracks, fractures, patina, corrosion, erosion, burning, melting, decay, rotting and weathering.

4.1.1. Artificial ageing

The ageing process depends on material composition, object usage, weathering conditions, and a large number of other physical, biological, and chemical parameters. Some ageing phenomena of-ten play a key role in realistic rendering (except when the desired result is specifically a brand-new virtual object). Their absence results to non-realistic surfaces, looking too clean and too smooth. To solve these problems, artists either compose complex textures manually or through other techniques [91]. Ageing also can describe a number of methods used in computer graphics to simulate object morphology changes due natural influences, such as cracks, fractures, patina, corrosion, erosion, burning, melting, decay, rotting and withering. Those approaches consider effects which influence the geometry of an entire object, instead of the surface appearance alone [92].

In the SCAN4RECO project, a State-of-the-Art renderer was employed for visualization [86]. While the simulation of fracture physics has been studied in computer graphics [87], reproducing fracture patterns observed in real-world materials remains a difficult problem. In [88] a highpoly mesh is dynamically produced locally to adaptively capture details wherever it is required by the simulation. Crack patterns observed in materials arise due to small-scale interactions between elastic strain, plastic yielding, and material failure. Stress gradients can be very large near the crack tip where the stress field often approaches singularity. In [89] the surface of wood is defined by values assigned to tetrahedral mesh vertices. Changes in the surface are achieved by value changes. CERTH has built on this background in SCAN4RECO to model cracks, whereby [90] demonstrates how a Bayesian optimization method can determine the parameters of a fracture model patterns based on examples.

4.1.2. Simulation techniques

Simulation is one of many techniques used for deriving sample results. Specifically, photo-realistic rendering techniques are capable of rendering images that predict the appearance of yet to be manufactured objects [93]. Physical, chemical, biological, environmental, and weathering effects produce a range of 3D model, shape, and appearance changes. To be able to visualise all these effects we need a novel simulation technique for geometrically and visually stimulating these processes to create visually realistic scenes [96].

4.1.3. Multi-fragment rendering

Depth-ordered fragment determination is a standard stage in developing numerous appealing and plausible visual effects for interactive 3D games and graphics applications. A variety of algorithms ranging from photorealistic rendering, such as global illumination, order-independent transparency for forward, deferred, volumetric shading and shadowing to volume visualization and processing of flow, molecular, hair and solid geometry require accurate multi-fragment processing at interactive speeds. [94] presents a thorough survey and comparison of multi-fragment methods. In this work we have adapted S-buffer [95], a two-geometry-passes A-buffer implementation on the GPU, that overcomes the limitations of both linked-lists and fixed-array techniques by taking advantage of the fragment distribution and the sparsity of the pixel-space.

4.1.4. Simulated ageing based from aging of physical samples

The SCAN4RECO project addressed also effects of ageing on both metals and paints, whereby experiments performed by OF-ADC, UNIVR and OPD focussed on assessing effects of ageing on paints and metals respectively. Both CERTH and RFSAT have taken advantage of those results in determining future evolution of the model containing such materials in their simulations. In case of CERTH, deep-learning algorithms and neural networks were used to provide future prediction based on images of real samples taken at different time intervals. In case of RFSAT two methods have been used and compared. One performed similar analysis to CERTH's by directly working on images of real aged samples. The alternative method focussed more on the analysis of actual physical effects of ageing, physicochemical reactions with the environmental elements (e.g. gases and liquids), combined with environmental parameters (e.g. pressure, temperature and humidity) having direct impact on actual speed of deteriorations through changes to material composition, such as reactions of metals with oxygen, ionised particles of different reactive atoms and their compounds, such as anhydrides that combine with water and form acids.

4.2. Disaster simulations

Mainly, two types of natural disasters are being considered in ARCH: floods and earthquakes. The first one will concern our pilot case of Hamburg city and the second one will be analysed for the area of Camerino town, in Central Italy, a region prone to seismic hazard.

During the last decade, an enormous amount of work on mathematical modelling has been performed (see [99]). The advent of more capable computing machines has paved the way to the use of mathematical models in all aspects of engineering, including hydraulics and, more specifically, flood propagation. It must be said that this effort started already during the ‘80s and that pioneer works can be traced back to the ‘60s and earlier [100]-[105].

The progress of flood propagation models is linked directly to:

i) Understanding the flow processes relative to the problem

ii) Formulation of appropriate mathematical laws

iii) Development of numerical techniques to solve them and

iv) Validation of model output against experimental and real-life data.

Flood and Earthquake simulations software have been around for many years already. Several institutions have developed their own simulation software that take advantage of past incidents. Flood models help simulating the progress of, say, a fluvial flooding, which may help in planning protection and evacuation measures. In case of earthquakes, shake models based on assumed epicentre, assumed magnitude, assumed soil structure and assumed type of earth movement allow assessing possible damage to buildings and settlements, which may help in planning prevention and mitigation measures. Systems using real-time sensing can predict next events to a certain level of accuracy and time in advance. In the case of earthquakes, the early warning time ranges from seconds to minutes. A flooding can be anticipated with longer advance time, especially when it is caused by physical damages to dams or similar protective systems, or if it is a fluvial flooding caused by torrential rainfalls in upstream regions. Some research claims also the ability to predict seismic activities based on statistical data even six months earlier[32]. However, in this case the prediction of epicentre, magnitude, type of movement and potential damage has a much larger degree of uncertainty than in the case of a sensed real quake event. Certainly, observations of different indicators may lead to different level of certainty and ability to predict time in advance before the event. Software can also predict how far the water can flow inside the land depending on its structure, elevations and built structures. As for earthquakes, structural building analysis helps in determining possible damages that might occur when facing an incident of a given scale.

In terms of available commercial software, one of most known ones comes from Autodesk which offers River and Flood Analysis Module for Civil 3D 2019[33], Civil infrastructure design and documentation software. Regarding ground shaking simulations, the biggest authority in

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[32] https://www.theguardian.com/environment/2014/sep/21/scientists-predicting-earthquakes-advance

[33] River and Flood Analysis Module for Civil 3D: https://www.autodesk.com/products/civil-3d/overview

this area is USGS[34]. Structural damage simulations have been performed also by Fraunhofer EMI working on risk and resilience analyses, especially in urban developments[35], while Camerino city has been using simulation methods from University of Camerino [106].

4.3. Participatory Sensing and Decision Making (e-Governance)

There are many systems already deployed by different organizations and local authorities for dealing with only very specific environmental problems, whether it is air or water quality, noise, soil contamination etc., despite the fact that they face in reality multiple problems. Extending their systems to cover additional environmental parameters is both technologically tiresome and significantly costly. An attractive way to overcome these problems is by exploring the opportunities lying in increasing the engagement of the public in measurement acquisition as well as in creating a dialogue between the public and relevant authorities and non-governmental agencies.

Priorities concentrate on three core thematic areas:

1. Participatory sensing: citizens participate in environmental monitoring
2. Dialog & collaborative decision making between authorities & citizens
3. Integrated collection and free sharing of environmental data and knowledge in line with Infrastructure for Spatial Information in Europe (INSPIRE) and Shared Environmental Information System (SEIS) provisions.

Our significant novelty is the exploration of the latest advancements in social collaborative environments and related Information Technologies, applying them in the context of building environmental awareness, active monitoring and protection. Social computing and online communities are changing the fundamental way the people share information and communicate. Individuals increasingly take cues from one another and communities, rather than from institutional sources like corporations.

Any DSS system needs to follow the INSPIRE and SEIS provisions, GEOSS policies and objectives in a wide range of environmental areas, integrating with a vast range of already existing environmental observatories including satellite observation systems (GEOS), bringing in diverse systems deployed also by local authorities and NGO’s in addition to general Europe-wide initiatives. There is a recognizable importance of the Europe-wide initiative of the European Environmental Agency (EEA) and the development of the Eye-on-Earth system.

Significant added value can be offered to such initiatives through the development of supplementary technologies, like mass citizen engagement, involvement of local communities, social knowledge building, collaborative decision making, voting etc. Flexibility of integration with existing sensing networks, both controlled by authorities and individual users, would be combined with a powerful range of data analysis and risk assessment applications, coupled with a range of information and alerting services using public channels as well as direct citizen notification

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[34] USGS ground shaking simulation: https://earthquake.usgs.gov/learn/topics/shakingsimulations/

[35] Urban risk and resilience (FhG-EMI): https://www.emi.fraunhofer.de/en/business-units/security/research.html

system thus contributing to a better understanding of the spatiotemporal changes of environmental parameters.

5. Progress Beyond the State of Art

ARCH partners are either using DSS (typically, the city partners) or have developed DSS for CCA and related purposes in other projects (typically, the R&D partners). We start this section by briefly characterising some of these DSS and conclude it by discussing outcomes and conclusions indicating expected progress beyond the State of the Art (BSotA) as sketched in the project's work plan.

5.1. DSS developed by or in use by ARCH partners

One of the major R&D results of the EU H2020 Network of Excellence project CIPRNet[36] is the prototype of a DSS for the risk forecast of Critical Infrastructure (CI) elements, CIPcast. The DSS CIPcast addresses different players involved in the emergency management operations, like CI operators, Civil Protection, and Public Administration. CIPcast solves the problem of estimating the threats to which each element of CI is subjected due to extreme events (either of geophysical or meteo-climatological origin), the damage that they could inflict, the subsequent reduction or loss of functionality of all CI involved (also through cascading effects) and the related consequences on society (citizens, goods, land etc.). Since 2013, ENEA has continually improved CIPcast (with some support of CIPRNet project partners, including Fraunhofer), its functionality has been extended, and it has been opened to new areas of application. Since 2017, ENEA and INGV use CIPcast regularly at the Italian node of the European Infrastructure Simulation and Analysis Center[37] (EISAC) and has now reached a high Technological Readiness Level (TRL 7).

In the EU H2020 project RESIN[38], several project partners, including Fraunhofer and Tecnalia, developed a suite of DSS tools for Climate Change Adaptation in urban areas. All these tools have been employed in four city case studies (for Bilbao, Bratislava, Greater Manchester, and Paris), managed by ICLEI, and results of their applications have been used by the cities for their adaptation planning and risk analyses. Fraunhofer has developed a modular method for qualitative and quantitative risk analysis, called IVAVIA. The method is documented in a published Guideline document. For supporting some parts of the IVAVIA method, Fraunhofer has developed special IT tools. A graphical Impact Chain Editor supports automatic layout of Impact Chain diagrams (qualitative part of IVAVIA). The aggregation and weighting of indicator data for estimating numeric risk values for geographical areas is supported by a browser-based tool. The tool can generate maps of a city and smaller geographical units (districts or grid cells), coloured according to the risk categories that correspond to the computed risk values. The frontend of the tool has been developed by Fraunhofer and the numeric part by Tecnalia. For RESIN, Tecnalia has also developed a database of adaptation options, categorised by the type of hazard and the entities exposed to the hazard, such that suitable adaptation options can be quickly identified. The database is available online, a user account is required. A workflow

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[36] Critical Infrastructure Preparedness and Resilience Research Network – CIPRNet: https://www.ciprnet.eu

[37] Italian node of the European Infrastructure Simulation and Analysis Center: http://www.eisac.it

[38] Climate Resilient Cities and Infrastructures (RESIN): http://www.resin-project.eu

support tool, developed by four of the RESIN R&D partners, connects the RESIN tool suite and automates some parts of the risk analysis and adaptation planning workflow.

For the EU project RAMSES[39], Tecnalia has developed a Transition Handbook and Training Package for supporting cities in decision-making for urban adaptation. The Free and Hanseatic City of Hamburg (FHH) maintains a portfolio of geoportals, all based on a geographical information system called ATLAS, which is being developed, deployed and maintained by Hamburg's Landesbetrieb Geoinformation und Vermessung (State Geoinformation and Surveying Office). A public geoportal of Hamburg contains basic geographical information visible for everyone[40]. Hamburg's ministries and offices use private versions of ATLAS. The version in use at Hamburg's cultural heritage preservation office contains additional geo-tagged information on several thousand of Hamburg's monuments.

5.2. Outcomes and conclusions indicating expected progress BSotA

For supporting the decision-making in CCA for urban historic areas, the ARCH consortium plans to leverage on previously co-created and tested tools (e.g., from the projects RESIN, RAMSES, and CIPRNet). Connections to the related area of Disaster Risk Reduction are also planned. Here, the Disaster Resilience Scorecard for Cities[41], developed by UNDRR (formerly UNISDR) shall be assessed for potential adaptation to the requirements in ARCH.

Where city partners already employ DSS (like Hamburg's ATLAS system), extensions or enrichments need to be considered instead of developing a completely new DSS. Enrichments include new types of information and data, e.g. 3D models of buildings and areas. Enrichments are supported by the use of environmental sensing technology as described in Section 0 of this report. Extensions may include new analysis or information functions. For example, the ATLAS instance in use at the CH department of Hamburg does not yet contain information on materials of heritage buildings, nor 3D models. Enrichments of the system could include detailed information on materials used in specific buildings. Extensions could be the addition of functions for handling 3D models of specific buildings or entire areas (importing, viewing, searching, exporting 3D models) that have been acquired using sensor technology.

The authors consider that it is crucial to assess the existing DSS and data infrastructures of the involved cities in order to agree with a co-creation approach enrichment and/or extension of a suitable existing DSS or development of a new, specialised DSS. All these approaches are suitable to introduce innovation into urban adaptation and resilience building processes.

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[39] Reconciling Adaptation, Mitigation and Sustainable Development for Cities (RAMSES): http://ramses-cities.eu

[40] Hamburg's public geoportal: https://geoportal-hamburg.de/geoportal/geo-online/

[41] Disaster resilience scorecard for cities – UNDRR: https://www.unisdr.org

6. Conclusions

We began this report with a summary of the development and history of decision support systems in the last 50 years. Much of the early research was dedicated to understanding what DSS could be, what support they could provide, and what limitations they have. Several different methodologies for designing DSS have been reported, including model-driven, data-driven, knowledge-driven, and communication-driven DSS. Whatever methodology is employed for DSS, a few most essential properties and rules need to be fulfilled:

- The DSS recommends, the human decides. Decisions cannot be left to the machine alone, and the use of DSS must never be an excuse for poor decision-making of the human decision-taker.
- This implies that the human user needs to understand the way the recommendation has been generated, what the limitations of the DSS are, and how certain the DSS recommendation is.

In the main part of the report, we presented an overview of computer-based decision support systems for ARCH's core application domains, namely climate change adaptation (CCA) and cultural heritage preservation and conservation. All decision-making in these domains relies on data and information derived from these data or other sources. Therefore, the overview also covers the range of available and necessary technology for eliciting required data, like environmental monitoring and 3D object/areas scanning, and information and knowledge management systems for processing the elicited data and information derived thereof.

We concur with the view of the RESIN project that decision-making in the fields of CCA and CHP is a 'wicked problem', involving variance by the diversity of involved stakeholders and limitations by lack of sufficient and quantifiable data. In the last core section, we characterised DSS in use or developed by ARCH partners and discussed first ideas for kicking off co-creating DSS beyond the current State of the Art.

7. List of Figures

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9. References

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10. Annex

10.1. Annex A– Glossary of specialist terms

Term	Explanation	Source
Cooked data	Data that has been processed, as opposed to the RAW data.	[64]
Cultural Heritage Conservation	All measures and actions aimed at safeguarding tangible cultural heritage while ensuring its accessibility to present and future generations. Conservation embraces preventive conservation, remedial conservation and restoration. All measures and actions should respect the significance and the physical properties of the cultural heritage item.	[54]
Decision Support System	A computer system that supports the structured process of activities that support decision makers and other stakeholders in coping with and resolving problems they are faced with.	-
Participatory Sensing	Concept of communities or other groups of people contributing sensor information to form a body of knowledge.	[63]
RAW data	Also referred to as source data or atomic data, is data that has not been processed. It is distinct from information to the effect that the latter one is the end product of data processing.	[64]
Wicked problem	A problem that is categorised by a great number of uncertainties on stakeholders involved, boundaries of the problem, long term developments, organisation and responsibilities, and more.	[37]

10.2. Annex B – Key resources

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This publication covers several decades of developments of and insights in using DSS. The basic properties of and issues with DSS can be looked up in this survey.

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Download from: http://www.resin-cities.eu/resources/sota/decisionsupport/
This newer and more specialised report views the State of the Art in DSS for CCA from the perspective of their utility in a framework for action.

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This is a forthcoming standard that should be consulted in ARCH as soon as it has been published.