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Published in:
Proceedings of the IEEE/ACM 16th International Conference on Utility and Cloud Computing

Link to article, DOI:
10.1145/3603166.3632539

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

An urgent computing oriented architecture for dynamic climate risk management framework

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ABSTRACT

The Computing Continuum drives holistic system integration, especially in the road sector, where there's a growing need for comprehensive Decision Support Systems in operation and maintenance strategies based on sensor data. These systems offer dynamic assessments, critical for managing road assets vulnerable to climate change and extreme weather events. The resulting data uncertainties, including variations in data *veracity* and *variability* require timely decision-making for coordination and adaptiveness of the system as a whole. We introduce an urgent computing architecture for a dynamic risk management framework, discussing its related challenges and software design patterns.

ACM Reference Format:
Shahrzad Pour, Daniel Balouek, Amir Masoumi, and Martin Brynskov. 2023. An urgent computing oriented architecture for dynamic climate risk management framework. In *(UCC '23)*. ACM, New York, NY, USA, 4 pages. https://doi.org/10.1145/3492323.3495590

1 INTRODUCTION

The impact of climate change heavily influences operation and maintenance activities of critical infrastructure at strategic, tactical, and operational decision levels [13], [11]. Extreme weather events impact transportation systems, including roads, rails, and electrical lines, to a significant degree. An illustration of this can be seen in the trends of economic losses caused by climate-related events in EEA member states from 1980 to 2020, which total over 500 million euros. A substantial 80% of this sum is attributable to severe weather phenomena, whereas insured losses comprised a mere 25% to 33% of the total losses [7]. Although the financial implications of climate change are well understood, there is still a lack of information concerning its operational implications, particularly with regard to precautionary measures against the inevitable changes that arise.

UCC '23, December 6–9, 2023, Messina,Italy

ACM ISBN 978-1-4503-9163-4/21/12…$15.00
https://doi.org/10.1145/3492323.3495590

The Internet of Things has been one of the enablers of smart services across various domains. At a higher level of abstraction, it encourages a holistic approach to software design by fostering the integration of multiple isolated systems. In practice, the physical division of these systems into distinct sub-units systems results in the management of separate silos, to the detriments of cross-domain decision making. At the same time, modern applications are moving in the direction of the Continuum Computing, a distributed approach where Cloud, Edge and IoT aim to collaborate for publishing, cleaning and computing data while managing aspects of performance, security and QoS [6, 9].

A class of time-sensitive systems and applications known as Urgent Computing makes use of distributed data sources to speed up the making of important decisions [3]. Similar requirements apply to risk assessment for road infrastructure, specifically for predictive models, reactive/adaptive planning, and KPI monitoring, as outlined in [10]. In order to avoid or mitigate the adverse effects of climate change on road infrastructure, there is an opportunity to use distributed resources throughout the Computing Continuum and leverage urgent computing principles to predict the outcomes of scenarios [3]. In the context of road safety, the wide array of system capacities and varying service capabilities, alongside the significant uncertainty stemming from disparities in data quality and availability, present the primary challenges in constructing an adaptive Decision Support System (DSS) [21]. Addressing the vulnerability of road assets to weather conditions, the authors have incorporated a climate risk management framework in line with the definition provided in [18]. This comprehensive risk management framework is typically recognized as either an independent module or an essential component within a DSS, often implemented through iterative processes as outlined in [18].

In this paper, we propose a proactive, holistic architecture for risk management and road safety. This is a major shift in the way transport networks function, and it requires the ability to effectively estimate road conditions risk as a function of operating conditions and information technology. By integrating IoT and climate risk data into all decision-making levels, we move away from current approaches. Our method combines an architecture for data-driven workflows across systems with the needs of a big data pipeline for a risk management framework. The goal is to address the uncertainty surrounding climate data (*veracity*) and the demanding time and

quality constraints when making decisions based on significant variations in data patterns (*variability*).

The remainder of the paper is organized as follows. Section 2 discusses the motivation, background, and challenges for this work. Section 3 proposes an architectural vision for the risk management framework. Finally, in Section 4, we summarize this paper and discuss future works.

2 MOTIVATION, BACKGROUND AND CHALLENGES

2.1 Motivating Use Case

During severe weather events, there's a significant surge in data from diverse sensors and weather stations, especially upon surpassing specific thresholds. Urgent data preprocessing becomes crucial due to immediate actions required during these events and uncertainties regarding the number of interoperable subsystems necessitating data exchanges. This surge affects operation and maintenance activities, presenting two primary challenges: insufficient **coordination** and **adaptiveness** among agencies.

2.2 Background

Holistic Decision Support Systems in road sector The integration of decision-making processes within road domain literature has been relatively underexplored. Early studies, like [15], focused on integrating maintenance into Pavement Management Systems. Recent research, such as [16], delves into real-time GPS and GIS technology integration. While [19] offers a comprehensive survey of advancements in the road sector, rarely studies [21] explicitly addresses the vital requirement for adaptation mechanisms to handle uncertainties within Decision Support Systems (DSSs).

Architecture-oriented approaches for addressing the Continuum. Architectural approaches are vital for managing the Computing Continuum, introducing unique challenges concerning subcomponent control and adaptation. The aggregation of architectural and algorithmic challenges within individual components [6, 9] poses complexities as these subcomponents inherently influence each other while conducting urgent analytics [1]. Predicting infrastructure volatility and meeting the demands of urgent analytics is challenging due to their unpredictable ature [5].To best of our knowledge, leveraging the Computing Continuum for this application constitutes a novel direction in the field.

Dynamic Risk Management framework A dynamic risk management framework involves five iterative steps: context establishment, risk assessment using various techniques and algorithms, exploration of mitigation strategies (often in consultation with stakeholders), implementation of these measures, and continuous monitoring and review through KPI dashboards. This comprehensive definition is part of an overview paper on adaptive decision support systems in the context of climate change [18] and is depicted in Figure 1. Bayesian Believe Network (BBN) as a bottom-up approach [18] has been the chosen approach[21]. However, the details of risk assessment model is not the focus this paper,the risk assessment model can continually mature over time using the BBN model, integrating stakeholders' beliefs or new inputs whenever necessary.

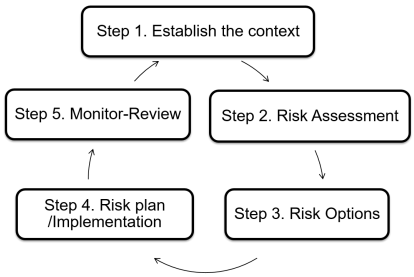

Figure 1: Dynamic Risk Management Framework

2.3 Challenges

Urgent data-driven workflows must be efficiently coordinated by developers and service providers in order to construct time-sensitive decision-making pipelines. Accommodating the considerable infrastructure heterogeneity, this coordination must address uncertainties related to data source dependability and availability [17]. In the realm of road safety, three specific challenges stand out:

Automated data collection Currently, operational technologies in this domain are functionally silo applications [21]. Edge technologies can provide incentives to sanitize data and respect the privacy of individual systems while allowing for the sharing of information to make the system unbiased and flexible.

Autonomics Programming abstractions that allow the specification of application behaviors that can react to unforeseen events during runtime are therefore critical to the overall performance of applications deployed throughout the continuum [12, 14]. Furthermore, to enable resource and execution path adaptability across the continuum, autonomic runtime techniques are required [20].

Integration of Smart Solvers: Decision Systems are essentially alike to solving combinatorial problems. Constraint programming (CP), particularly in the form of Constraint Satisfaction Problem (CSP), is well-suited for generating feasible planning solutions and strategies swiftly in scenarios involving real-time uncertainties across various resource classes. Additionally, Constraint Optimization Problem (COP) is a viable option when time and resources permit for plan optimization.

Online/Real-time Communication: Modern data services and messaging protocols allows and simplifies the development of a holistic DSS [8]. The current state of the management systems used in the road sector (PMSs & MMSs) do not utilize direct data exchange and communication between the systems. Introducing online and real-time communication between systems in a unified architecture that includes both management components, will allow for knowledge-oriented communication.

3 ARCHITECTURE

3.1 Architecture Goals: Functionality and Interoperability Design

The design goals of this architecture are as follows:

3.1.1 ***Functional Requirement:*** The architecture should consider the required data sources, end-to-end process, actors, and deployment:

Data sources: Various static and dynamic data sources are involved

in the use case, including the meteorological and hydrological data, flood-sensitive areas (blue spot data model [2]), and road infrastructure condition data.

End-to-end Process: The pipeline should address the data collection, orchestrating operations, and demanded data operations i.e. modules of the risk management framework in uncertainty situations, including extreme weather events and climate changes.

Actors: Actors include infrastructure owners or maintainers, with road authorities and municipalities being predominant in the former category and consulting companies in the latter. Additional actors could include citizens, particularly if the system is used as an early warning system to notify them about extreme weather events.

Deployment: The system as an infrastructure as code per stakeholder or per region, while most subsystems are partly autonomous on the device edges or fog but able to receive the task upon decision by the system.

3.1.2 ***Interoperability as quality attribute:*** The required architecture for the dynamic risk management framework demands interoperability. As shown in Figure 2, there are three interoperability aspects involved in the problem:

Level 3 - Horizontal interoperability (Over Actors – orange dotted line): Infrastructure owners, road authorities, municipalities, and consulting companies are key actors in the domain, with a focus on their involvement in the problem.

Level 2 - Horizontal interoperability (Over systems in various geographical regions – violet dotted line): The architecture must support cross-sectorial applications in environmental and mobility/-transport domains across different geographical regions, ensuring Continuum software abstraction.

Level 1 - Vertical interoperability (Over data spaces – blue dotted lines): The system should seamlessly integrate within a broad spectrum of digital solutions and sub-systems, particularly addressing urgent computing demands.

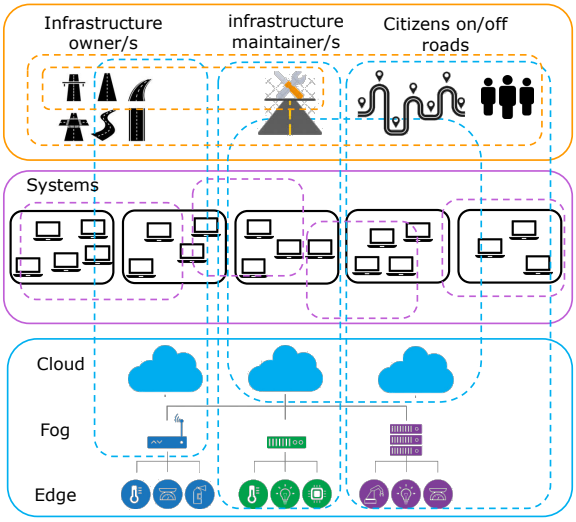

Figure 2: Horizontal and Vertical Interoperability of the Dynamic Risk Assessment Domain

3.1.3 ***Urgent Services:*** The architecture should address the necessary services required for fulfilling urgent tasks, including identifying available computing resources and data sources within the computing environment as well as ensuring that resources are allocated efficiently to meet the immediate computation demand.

3.2 Proposed Architecture

Figure 3 depicts our software architecture, responsible for gathering data from diverse sources such as road asset conditions, flood-sensitive areas, and various climatological data including precipitation, zero-crossing (indicating fluctuations around zero degrees), and sea-level rise. This data is fed into the pipeline, triggering an 'event receiver' for extreme weather events and data changes. Orchestration manages essential services, communicating through a message broker. The resulting information is utilized by applications.

3.2.1 ***Addressing Functional requirements.*** We endorse an event-driven microservice architecture as our chosen architectural style, wherein 'event-driven' characterizes our coordination/communication model, and 'microservices' define the pattern for allocating responsibilities.

Microservice architecture for allocation of responsibilities: The module of orchestration service, and all the modules of Interaction, Discovery, and Optimization as part of urgent computing modules plus the modules of dynamic risk assessment are developed each as one separate microservice.

Event-Driven Architecture as coordination/communication model: Event-driven architecture utilizes a message broker to reduce coupling between producers and consumers. This intermediary element effectively handles high volumes of data at different speeds by storing data or notifications in a queue until resources are available for processing.

3.2.2 ***Interoperability tactics.*** Among two main categories of interoperability tactics i.e. *locate* and *manage interfaces* [4], we use below tactics:

Urgent Discovery Service: a *locate* tactic: When it comes to addressing urgent requirements for processing extreme weather events, the initial step involves activating a discovery service. This service is tasked with identifying and pinpointing accessible data sources residing in edge, fog, or cloud as data spaces.

Interaction Service: an *Interface* tactic This service acts as an interface to interact with multiple external subsystems and various actors. A RESTful API is designed for minimal interdependency between clients and servers. It is worth mentioning the efforts made to establish minimal interoperability standards and tools for enhancing data, system, and service interoperability between cities and supplier stakeholders [22].

Orchestration Service: an *interface* tactic The orchestrator acts as a middleware enabling the composition of services based on specific goals and content, rather than directly engaging with devices or names. In this scenario, the architecture becomes domain-agnostic, and interoperability is enhanced through the use of discovery services and optimization services to address resource uncertainty and data availability.

Optimization Service: a *locate* tactic: This service plays a crucial role in efficiently and effectively managing computational

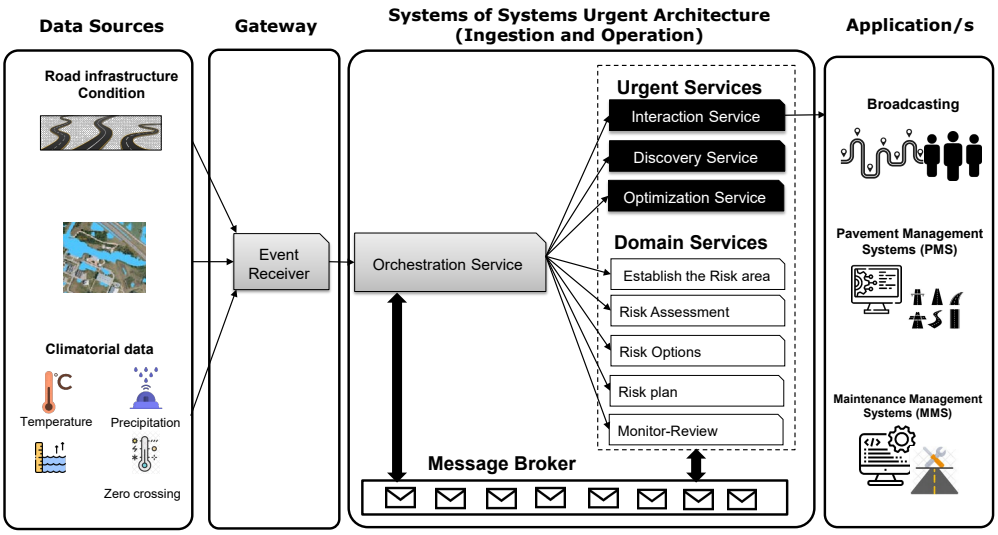

Figure 3: Proposed Urgent Computing Architecture for Dynamic Risk Management Framework

resources to meet the urgent demands of tasks in the whole data space environment to make sure all the systems and subsystems are interoperable resource-wise towards a common goal. The service is modeled as CSP, in case of urgency and is run as a COP upon having enough resources time-wise.

4 CONCLUSION AND FUTURE WORKS

In this study, we've integrated an urgent computing architecture into a dynamic risk management framework to manage time-sensitive tasks during extreme weather events. This approach addresses big data challenges posed by variability and reliability across IoT-Edge-Cloud resources. The architecture's implementation and evaluation will be based on real data from the Danish Meteorological and Hydrological Institutes (DMI, and DHI), coupled with road condition data from authorities. Furthermore, our plan includes enhancing the risk assessment model by integrating pavement bearing capacity data to evaluate pavement structure functionality.

ACKNOWLEDGMENTS

Thanks to the *ELEXIA* (Horizon Europe No. 101075656) and *IEA EBC - Annex 81 - Data-Driven Smart Buildings* (EUDP Project No. 64019-0539) projects, which have supported partly this research. This research is supported in part by the NSF under OAC 2238064.

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