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School of Computer Science, Physics and Mathematics

Licentiate Thesis

Architectural Concepts

Implications for the Design and Implementation of Web and Mobile Applications to Support Inquiry Learning

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Architectural Concepts: Implications for the Design and Implementation of Web and Mobile Applications to Support Inquiry Learning

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To my sister

Abstract

The integration of mobile and sensor technologies, and the design and implementation of different web-enabled visualizations to support inquiry learning in different educational scenarios encompass the main research efforts carried out in this thesis. These challenges are addressed from the perspectives of mobile and web engineering, visualization and technology-enhanced learning (TEL). Thus, the main research question investigated in this thesis relates to the identification of the main features that can guide the design and implementation of web and mobile applications to support inquiry learning in different contexts.

This thesis consists of a collection of four publications that describe the research efforts conducted during a period of three years in relation to the Learning Ecology through Science with Global Outcomes (LETS GO) research project. The research questions investigated and the implemented technological solutions reported in these publications are closely related to the main goals and challenges of this thesis. The design and implementation of the proposed software system was guided, deployed and refined having the following aspects in mind: (1) System Requirements and Architectural Design, (2) System Implementation and Deployment, and (3) System Assessment and Web Usability Testing. During the three years of development efforts, three software prototypes were implemented utilizing service-oriented approaches. These efforts have been tested with more than 200 users in connection to several trials that took place during this period. The user trials allowed testing the software application throughout three development iterations on authentic settings, while new requirements continuously emerged in these activities. This process made it possible to verify that user requirements were adequately addressed while satisfying their needs.

The outcomes of these activities led to the design and implementation of a system architecture that relies on service-oriented approaches and open standards. The main outcomes of this thesis are presented in the form of Architectural Concepts, as they can be used to guide the design and implementation of web and mobile applications to support inquiry learning. The idea behind architectural concepts is to provide a set of tools for supporting the overall life cycle of a software development process, such as requirements, design, implementation, deployment and testing while coping with rapid changes of technological implementations. Some of the architectural concepts identified in this thesis correspond well with the kind of support that inquiry-learning activities require. They provide solid foundations in terms of possibilities to tackle the requirements for supporting inquiry learning in a flexible manner.

Keywords: mobile and web engineering; visualization; TEL; system architecture; interoperability; open standards; prototyping; usability; user testing; inquiry learning.

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I am deeply thankful to all my family members. Especially to my parents Maliq and Sadete. Their understanding and love encouraged me to work hard towards the PhD studies, even if geographical distance has separated us for more than a decade now. Special thanks go to my sisters Belkize and Mirjeta for their endless love and encouragement. I would like to thank my aunt Minire and my cousins Orhan, Kader, Avni and Fitim for being close to me and to my parents, and always providing support without any hesitation. I'm greatly thankful to all of my nephews and nieces that always fill my life with joyful moments. This thesis is dedicated to my sister Fetije, who no longer is with us, but I'm really happy that I had such a sister in my life, I miss and I love you.

I would like to convey my deepest gratitude to “InterAdria” - Software Development Company located in Prishtina, Kosova from where I started to pursue the first steps of my carrier. Thank you.

My greatest gratitude goes to my devoted fiancé Miranda Kajtazi. She is the origin of my happiness. Without her this academic journey would not have started at all. Thank you for always being close to me, your love and support has enabled me to be here where I am today. Thank you and I love you.

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January 2012

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Abbreviations

API – Application Programming Interfaces
CSV – Comma-Separated Values
CERN – European Nuclear Research Centre
GeoVis – Geographic Visualization
GPS – Global Positioning System
HTML – Hyper Text Markup Language
HTTP – Hypertext Transfer Protocol
InfoVis – Information Visualization
ISO/IEC 9126-1 – Software Engineering. Product Quality - Part 1: Quality model
IT – Information Technology
JSON – JavaScript Object Notation
KML – Keyhole Markup Language
LETS GO – Learning Ecology through Science with Global Outcomes
OAuth – Open Authorization protocol
OO – Object-Oriented
REST – Representative State Transfer
SaaS – Software as a Service
SciVis – Scientific Visualization
SDK – Software Development Kit
SOA – Service-Oriented Architecture
SOAP – Simple Object Access Protocol
SQL – Structured Query Language
TEL – Technology-Enhanced Learning
UI – User Interface
XForm – A standard based on a W3C recommendation that is used to build web forms using XML as the data format.
XML – Extensible Markup Language

1. Introduction

In 1989 at CERN (European Nuclear Research Centre) Tim Berners-Lee, the inventor of the World Wide Web, was the first to develop a web site with a static content, which was encoded in Hyper Text Markup Language (HTML) [1]. Since then the evolution of the Web started. Today, the "*Web is an amazing platform for rapid prototyping, application integration, and innovation*" [2]. Web technologies are enabling cloud applications and services to become easily integrated in interactive systems [3]. The evolution of the Web went from being a tool for static media presentation towards a more service-oriented platform that relies on software components. The web is gradually becoming a "central computer" by connecting diverse computing and data resources and people [4, 5]. Furthermore, the web makes it easier to integrate different data sources. The integration of different data sources and web components such as web Application Programming Interfaces (APIs), web services and cloud frameworks into a web-based application has resulted in the creation of the concept of *mashups* [6, 7]. One of the key aspects of technological resources that relate to the notion of mashups is concerned with data interoperability. Interoperability takes place at the data layer, which is "*affected by the number of data formats for information exchange* [7]. From this perspective, mashups operate with open data in useable formats. Therefore, data interoperability simplifies the development of mashup tools and speeds up the development time.

Rapid developments in mobile, web and sensor technologies provide new possibilities for the implementation and deployment of software applications to support a wide variety of human activities. As a result, the evolution of these technologies is moving from static computers and content into dynamic environments. Embedding all these technologies into a physical environment by using mobile devices with different sensors and actuators can respond to users' needs and actions, as they are seamlessly integrated into our everyday activities [8, 9]. Such technologies are becoming heterogeneous, distributed and decentralized and operate in dynamic environments [10].

One of the main characteristics of the latest developments in the web is the gradual increase of the amount of data and user-generated content that arises from mobile devices [11]. Mobile devices have become "*ubiquitous nano-sensors*" that produce an increasing amount of data about the environment [12] and can be used to process and visualize information in novel ways. APIs, sensor data, geo-tagging and web-based visualization tools play an important role in the collection, storage, processing, retrieval and presentation of digital content [3, 13]. Therefore, as the amount of available data grows, conceptualizing and developing new interactive tools for visualization becomes an important challenge, for, e.g., seeking new ways of presenting and sorting appropriate and relevant data, or managing and analyzing information [11]. Visualizing data interactively through the use of different dynamic presentations that rely on graphs, charts, maps and other techniques is often a powerful way to make sense of these vast amounts of gathered data [14]. The extension of web-based visualization approaches, along with new forms of collaborative technologies, is constantly growing [15]. During the last decade, researchers and developers in the field of visualization have been implementing powerful tools for presenting and analyzing data across different disciplines [16].

The evolution of mobile, web and sensor technologies has affected our everyday activities in different domains. Yet, simply finding an effective way to integrate these different types of technologies in one software system remains a challenging task in the field of Technology-Enhanced Learning (TEL) [17]. In the last three years, my research has been carried on in the CeLeKT[1] research group. The focus of our particular research efforts in this group is oriented towards the exploration of new design and implementation approaches and innovative uses of mobile and ubiquitous technologies (including topics such as contextual information and mobile services, digital media content, geo-location and visualization techniques) in a variety of collaborative educational settings. Some of the current key technological trends identified in this field are: *mobile* and *cloud computing*, *visual data analysis*, *web technologies* and *geocoded data*, *smart objects*, *open content,* etc. [18, 19, 20]. Furthermore, the latest Horizon Report [20] remarks that these technologies are increasingly becoming cloud-based and decentralized. This report points out that these emerging technologies continue to be adopted and influenced by educational institutions. From a technical perspective in TEL, Hoppe [21] claims that one of the main challenges we are facing involves the need for integration of diverse technological recourses in broader educational scenarios. However, since the topic of this thesis is closely related to the field of TEL, the instantiation of the challenge defined by Hoppe in our research context can be addressed as: *integration of mobile and sensor technologies, and different web-enabled visualizations with a particular focus on supporting inquiry learning activities.*

In the next section, we introduce the research goals, and describe the scope of the thesis. Then at the end of the section we briefly introduce the structure and overview of this thesis.

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[1] Center for Learning and Knowledge Technologies located at the School of Computer Science, Physics and Mathematics, Linnaeus University.

1.1. Scope and Research Goals

The research in this thesis was conducted as part of the research project "Learning Ecology through Science with Global Outcomes (LETS GO)" [22]. One of the aims of this project is to integrate geo-location sensing, multimedia communication, web technologies and visualization techniques for developing and fostering collaborative science learning activities in the field of TEL. As part of this project, we performed a set of activities over a three year period. In these activities, users were utilizing sensor and mobile devices for data collection in the field, and web-based visualization tools for data visualization in the classroom.

In the previous section, several key technological trends that motivated our research were presented, such as mobile and cloud computing, visual data analysis, web technologies and geocoded data. In relation to this, the thesis deals with several diverse areas within the field of computer science, namely mobile and web engineering, visualization and TEL. While conducting this research, several challenges were identified arising from these three areas, to be described in the lines below. The challenges identified in mobile and web engineering are related to mobile developments used for data collection (geo-tagged content and sensor data), web developments integrating and consuming different web APIs and cloud services, and usability evaluation of the web-based tools. The area of visualization deals with challenges related to users that enable them in an easy manner to perform visual exploration and analysis of data, facilitate the understanding of particular phenomena, and also communicate their findings [23, 24].

The field of TEL faces a number of challenges that concern software tools for supporting inquiry learning activities. These challenges are defined by Tchounikine [17] in terms of "*building new technologies or further developing existing technologies to create novel possibilities for supporting human activities*". Some of the processes involved in inquiry learning are to problematize, demand, discover and refine, and apply [25]. Inquiry learning activities are considered as requirements. Thus, the focus of this thesis is not to model these requirements but to design and implement a software system to support inquiry learning activities.

To give an illustration of the scope of this thesis, Figure 1.1 introduces the intersection of three main areas of investigation, namely *mobile* and *web engineering*, *visualization* and *TEL*, including a number of subdomains within these three respective fields.

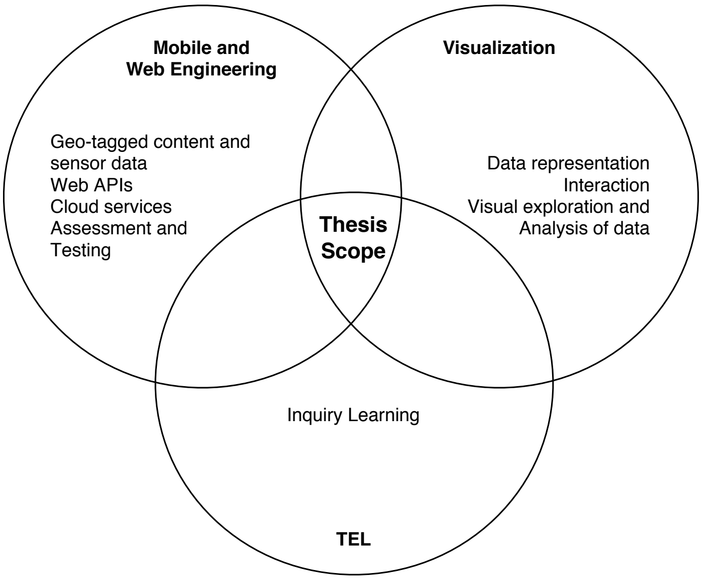

Figure 1.1: An illustration of the research scope.

Having in mind the three above-mentioned areas of investigation in Figure 1.1 and the challenges introduced, the initial problem statement (PS) related to this thesis is formulated as follows:

> **PS** Considering the challenges and technological trends mentioned above, the focal problem of this thesis is based on the integration of different technological resources (such as sensor, mobile and web technologies) while designing and implementing a software system for supporting inquiry learning in different contexts.

A system (software and hardware) is defined by the purpose with which users are engaged. Therefore, to integrate diverse technological resources, both software and hardware, represents a challenging task. These challenges become evident when it comes to integrating software tools in the TEL field. Developing a software system in the TEL field requires thinking, problematizing, representing, modelling, implementing and analyzing learning objectives and issues; it also requires conceptual models and architectural designs [17]. In order to address the stated problem and challenges, the following three main categories are identified for the purpose of formulating and exploring the goals that serve as a driver for the research results presented in this thesis:

Requirements and Design:
The requirements and design category represents efforts to identify the initial requirements of a software system. It also addresses aspects related to architectural design. The requirements are used to identify the goals that must be accomplished. In this respect the goal for this category is:

> **Goal 1** To investigate the integration possibilities between heterogeneous mobile devices and service-oriented environments.

Implementation and Deployment:
In the area of mobile, web and sensor technologies the development environments, tools and platforms are evolving rapidly. These rapid changes bring more complexity when it comes to meeting the design requirements. Therefore the goal for this category is formulated as follows:

> **Goal 2** To find a balance between the design and implementation of a system, by taking into consideration the rapid evolution of software technologies (mainly software technologies based on the internet).

Assessment and Testing:
Every software system is implemented for a purpose. The quality aspect of the software system is represented by the extent to which it fulfills that purpose. One of the main quality characteristics of the software quality model is usability (ISO/IEC 9126). Therefore the final goal of this thesis is:

> **Goal 3** To conduct a usability assessment of the developed system - Usability Study.

These specific research goals are intended for the design and implementation of a software system consisting of mobile, web and sensor technologies for supporting inquiry learning activities across different contexts. Figure 1.2 provides an initial overview of our settings related to the LETS GO project, and presents some of the initial requirements. Moreover, this Figure describes aspects related to data collection and interpretation, exploration and reflection, drawing conclusions and communicating the results in relation to inquiry learning activities [25, 26].

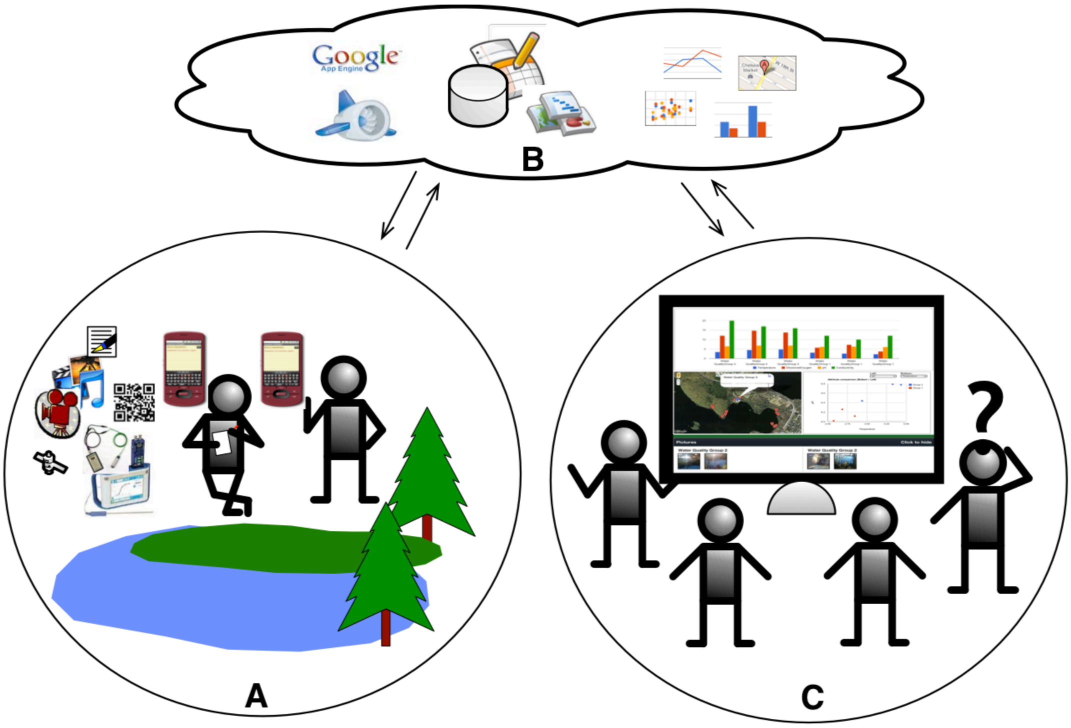

Figure 1.2: Illustration of the initial requirements related to the LETS GO project.

The initial requirements of our research efforts are presented in terms of:

- Mobility,
- Service-oriented systems,
- Distributed environments,
- The need for reflection, and
- Collaborative technologies.

Details for these initial listed requirements are given in the upcoming chapters. The goals and initial requirements presented will lead towards the design, implementation, deployment, piloting and testing of a software system that includes architectural design, and consists of various versions of the mobile, sensor, web and visualization elements for supporting user activities in authentic settings.

1.2. Limitations

The diversity of the areas of investigation in this thesis poses a number of constraints and limitations. No new visualization techniques are developed; they are rather reused from existing sources in our implementations (such as web APIs or cloud services). The usability assessment is conducted only for the web-based visualization tool (the assessment for the mobile application will be considered in our future work). The usability study was conducted with a limited number of users. This thesis does not cover any aspects related to security issues and privacy of content generated by the users that took part in our experiments (trials).

1.3. Definitions

Several definitions are used in the thesis for the purpose of illustrating key concepts engaged for our research needs, and for the design and implementation of mobile and web-based applications. Below, we introduce some of the definitions that we explicitly deal with.

Software system. In the context of this thesis software system means a collection of applications consisting of sensor, mobile and web-based technologies.

Stakeholder. In the context of this thesis stakeholder refers to both teachers and students.

Interoperability. (a) The ability of a system or a product to work with other systems or products without special effort on the part of the customer [27].

(b) At the data layer it deals with data formats accepted for information exchange [7].

Visualization. Integration of visualizations [28, 29] and interactive technologies [30] in the field of scientific computing [23].

Usability. The extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use (Part 11 of the ISO 9241).

1.4. Thesis Overview

This thesis comprises four peer-reviewed papers published at international scientific conferences. These papers have been written as a part of several experiments and testing within the LETS GO research project. The papers are accompanied by a thesis that is based on six chapters including the present one.

Chapter two presents the foundations of this thesis such as the areas of concern and the state of the art projects, from which it identifies several challenges that guide this research. Chapter three describes the research settings, and addresses the research problem where research questions are presented and the strategy of investigation is introduced. This is followed by Chapter four, which introduces and summarizes the four published papers. Discussion of research findings and analysis of this thesis are presented in Chapter five which introduces the first set of implications. Finally, Chapter six presents the main conclusions from this research and introduces future work.

An initial diagram of the thesis overview in Figure 1.3 attempts to illustrate the three main categories, namely Requirements and Design, Implementation and Deployment, and Assessment and Testing that comprise the main body of the research activities reported in this thesis.

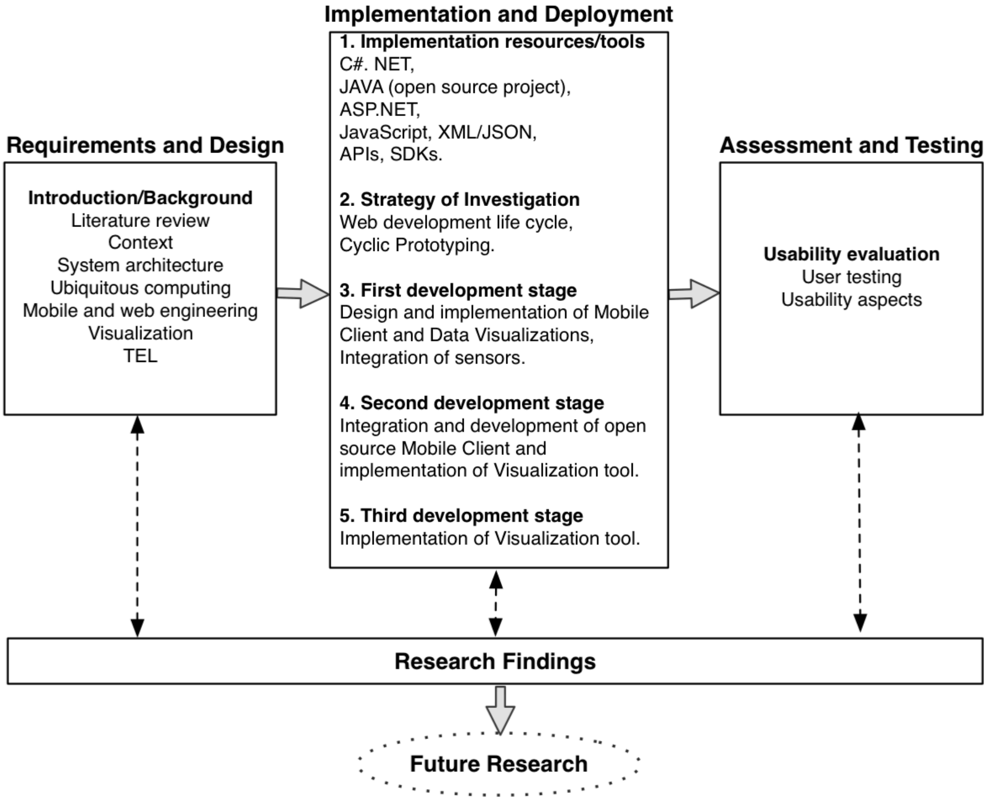

Figure 1.3: Initial overview of research efforts.

2. Foundations

This chapter presents the foundations of this thesis. The following sections introduce the fundamentals that provide an overview and basic concepts behind the areas of mobile and web engineering, visualization, technology-enhanced learning and usability. Thereafter, state of the art projects are presented. Finally, the main challenges identified throughout this chapter in relation to the research goals of this thesis are introduced.

2.1. Areas of Concern

2.1.1. Mobile and Web Engineering

In the last decade, there has been an exponential growth of mobile and web application developments [31]. While mobile application developments date back to the late 90's, the exponential growth in this area is now developing even faster with the introduction of the iPhone AppStore, Android Market, Nokia Ovi, and Windows phone [31]. Such developments are made possible by several powerful tools, frameworks, SDKs, APIs and so on, which are available for developers of applications for different mobile platforms. Additionally, many mobile applications are already using sensors for, e.g., accelerometers for movements, touch screens for gestures, geo-location, cameras for different content generation, etc., all facilitating interactivity.

Current trends in web and mobile application development point out to convergent processes with regard to software design, implementation and deployment [32]. Web applications are largely based on "*mashups*" that occur at the data level, and often involve the "*read-write*" nature of web applications [2]. Furthermore, many web APIs are constructed based on web services by moving away from Simple Object Access Protocol (SOAP)-based web services (using open web APIs). These web API services are wrapped into libraries usually written in Java, .NET, JavaScript, etc. These make it easier for web developers to use such services while developing both mobile and web applications. Two major classes of web services are identified[2]: 1) Representative State Transfer (REST) web service

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[2] http://www.w3.org/TR/ws-arch/#relwwwrest

using uniform set of "*stateless operations*", and 2) arbitrary web services based on SOAP, using an "*arbitrary set of operations*". Both principles would naturally share the same XML schema in web applications for resource representations [1]. It is evident that web services have shifted the web towards more platform- and service-based developments, where developers can basically deploy different applications and consume different services in a flexible manner. In general, from software systems that are based on the Internet (web), the use of Service-Oriented Architecture (SOA) becomes a core pattern in cloud computing [33]. Moreover, software solutions, mainly delivered over the Internet, are closely related to the term Software as a Service (SaaS) [34]. The SaaS concept delivers computational functionality on the cloud environment. Cloud computing is defined in the literature as: "*both the applications delivered as services over the Internet and the hardware and systems software in the data centers that provide those services*" [34].

Such software systems rely on various standards for data exchange, which make the development of interoperable mobile, web and sensor-based applications a challenging task. Moreover, by integrating these applications into one system the problem of interoperability arises [35]. Interoperability remains a key feature to resolve while dealing with diverse data exchange issues across different software and hardware components. Many software systems including hardware components have a closed system approach that restricts their development. The challenge in this sense is formulated as: *What are the potential tools/frameworks/solutions to be used by developers in order to allow easy data interoperability between diverse applications/devices*?

All these software systems, different service-oriented platforms, and frameworks mentioned above simplify the mobile and web development processes. However, it will be essential for developers to consider system and software architectural processes to provide the development of mobile and web-based applications of higher quality [31, 36]. Mobile and web developers who implement applications try to satisfy users' needs and expectations. Furthermore, developing a good mobile and web application requires a deep understanding of the principles driving mobile and web trends in general, by considering architectural patterns, communication techniques, design and development methods, etc. [31, 36]. Figure 2.1 describes the mobile and web engineering scenario, inspired by [36] with the extension of a mobile part. Both mobile and web development in general are divided into several architectural layers. With layered architecture, developers increase flexibility, maintainability and scalability [37]. Reusability of different software components is a key advantage of layered architecture. To be more specific, if a developer wants to reuse a software component by simply changing the User Interface (UI) from mobile to web, the developer needs only to replace the UI component. However, because of the layering, the disadvantage sometimes may be in terms of the use of UI components in connection to the database, in which data can take longer to load. Below, we introduce some of the general features behind the layered architecture. The *data layer* is used to identify the structuring of data, which data formats or what database management system to use, or even external resources. The *application layer* is used for deciding the programming and markup languages, models, protocols, application architecture, and logic behind it. Finally, the *presentation layer* is focused on the design and layout of the applications' front end in both the mobile and web applications [36].

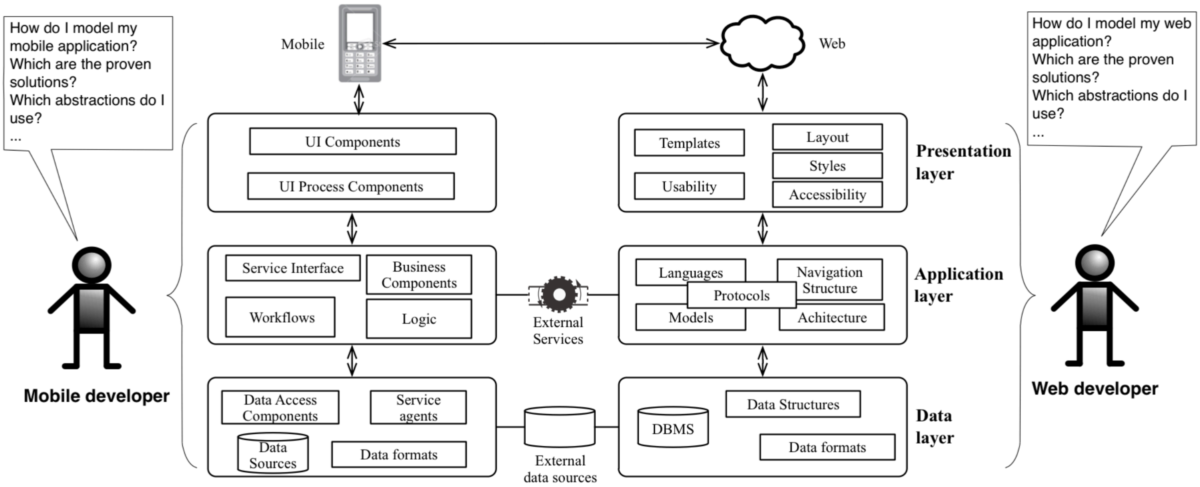

Figure 2.1: The mobile and web engineering scenario.

Another challenge in this research study is to integrate sensor data in the software system. Therefore, it can be beneficial to integrate services or applications that can act as a bridge between mobile and web technologies [35]. The web has become a "*multi domain platform*", which consists of eCommerce, social networks, mobile services and applications, cloud services, distributed environments, etc., being useful and present in our everyday lives [36]. Such developments, especially with sensor integration, have transformed the presentation of data into meaningful and easy accessible content. For integrating sensors in a cloud computing infrastructure, the top-down approach to sensor network design needs to be considered during the development phase, as, for example, in Figure 2.2. Thus, in a cloud computing architecture, the data and services reside in scalable data centres, which can be accessed from any connected device over the Internet. By this, the thin client (mobile device) collects and forwards the data on the cloud with an Internet connected large-scale set of thin client sensors, based on cloud computing infrastructure [38], which brings the concept of the mobile cloud.

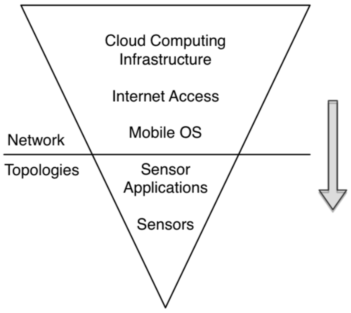

Figure 2.2: Sensor network design methodology – top down approach, taken from [38].

Yet, the continuous use of mobile and web technologies produces massive amounts of data. This is another challenging task that requires attention in making sense of the data generated by users that utilize mobile and web technologies. Certainly, such a challenge has been addressed in several technical approaches, ranging from data management to tools designed for data handling, data mining and reporting. One of the approaches that tackle this challenge fundamentally and with novel techniques is visualization, which attempts to represent and provide a clear overview of the data available [39]. Different visual representations can provide different insights to users by enabling them to observe data in context, to analyze these data and to draw different conclusions by using different analytical approaches [40, 41]. In the context of this thesis, the data collected from mobile devices is used for visualization purposes (as illustrated earlier in Figure 1.2 caption 'A'). Hence, in the next section, we provide a brief overview of visualization that serves as a basis of inspiration for our work.

2.1.2. Visualization

The field of visualization deals with the presentation of visual images that communicate information about data and processes [42, 29]. It is used as a data analysis technique that supports interactive exploration of data on the screen [43]. Furthermore, visualizations must be *novel* (gain some new insights), *informative* (gain knowledge) and *efficient* (have a clear goal or a message) [44]. The term visualization was first introduced in cartographic literature in an article by the geographer Allen K. Philbrick in 1953. Later this term was explained from a computer science perspective, in terms of computer graphics, image processing, user interface design, etc. [45].

Historically, the issue of representing or providing insights from a vast amount of data has been tackled from a data visualization perspective. One of the major sources of inspiration in visualization fields in general is Napoleon's mapmaker, Monsieur Minard [28]. He designed a map of the march to, and retreat from, Moscow by Napoleon's army. The map, presented in Figure 2.3, also served as a source of inspiration for our work, especially for its aspects related to environmental conditions (e.g., temperature). The map presents several variables in this single two-dimensional image. The line coded in brown presents the number of soldiers at any location, showing where units split and rejoin. The black line similarly encodes the retreat [28]. Of 422,000 soldiers at the beginning, only 10,000 returned. The weather conditions affected the retreat, accounting for the small number of soldiers that came back. It can be clearly seen how low temperatures affected the retreat of the soldiers, as presented in the plot at the bottom of this figure [28].

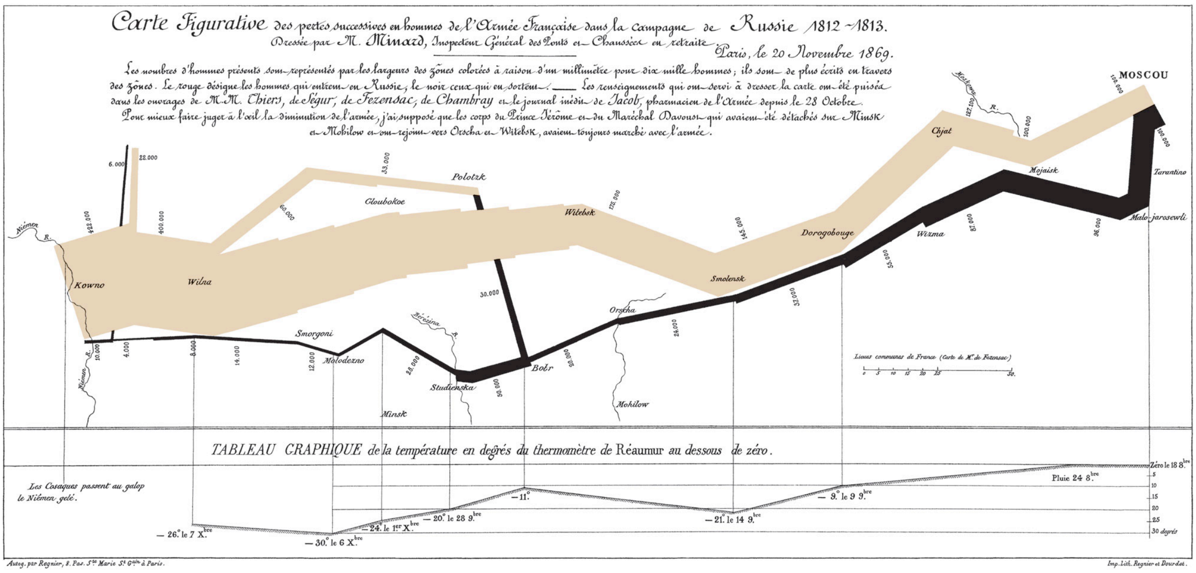

Figure 2.3: Minard's map: Napoleon's march to, and retreat from, Moscow, taken from [28].

The visual representation given in Figure 2.3 shows an interesting point for discussing visualization techniques. As a matter of fact, there are many ways of data visualization that also correspond to several definitions and fields. One of the key definitions of visualization is related to the field of Information Visualization (InfoVis). InfoVis is defined as "*The use of computer-supported, interactive, visual representations of abstract data to amplify cognition*" [46]. This notion is closely related to Scientific Visualization (SciVis) [47]. The main difference between the InfoVis and SciVis fields is based on the data they deal with. SciVis uses spatial data with physical space and the data here tend to be continuous, whereas in InfoVis correlation between spatial data usually does not exist, and it deals with the presentation of abstract data [47]. The interaction in the visualization can provide new possibilities for exploration of data, thus enhancing its human decision making [42].

As introduced in the previous section, the evolution of mobile, web and sensor technologies makes it possible for a wide range of data types to become available to end users. One simple example in this case is the visualization of geo-referenced data sources using digital maps (geographical data like Google Maps, open street maps, etc.). Digital mapping services are now technically sufficient to be adapted by developers, making it easier to explore geospatial information resources, at any time and anywhere. In crisis management, public health or learning systems, the availability of online digital mapping and different web services can easily be delivered to the users in the field and beyond [48, 49, 50, 51]. This kind of visualization represents a type of geo-mashup tool that makes use of different data sources that are presented in a combined view in one screen [7, 52]. A way of presenting these data as information is by using data visualizations such as charts, maps and graphs. Such representations of data in the context of this thesis were used for data analysis and exploration using different available visualizations offered over the web. There are numerous cloud services available through implementations of different available web APIs with the purpose to present such data in rich chart formats. Some of the novel and available APIs used for visualization purposes are: Google Visualizations[3], Protovis[4]. JavaScript InfoVis toolkit[5], etc. In accordance with our research efforts, Geographic Visualization (GeoVis) refers to a set of tools and techniques that supports geospatial data analysis, through the use of interactive visualizations [53]. In addition, GeoVis is defined as "*the creation and use of visual representations to facilitate thinking, understanding, and knowledge construction about geospatial data*" [54].

The idea behind visualization fields (such as, InfoVis and GeoVis) is to enable users to easily perform visual exploration and analysis of data, and also to communicate their findings [24] so that increased awareness of meaning in the data is possible [23]. Visual representations involving interaction provide a mechanism that allows users to explore and understand large volumes of data, regardless of the format or data type of the original data [55]. According to Shapiro [56], to understand why data visualization is important, most of the visualizations deal somehow with a story. Furthermore, he implies that stories start with a question that introduces the users to the topic; this places the visualization in a context. Using the visual data in the context of a story is an excellent way to give meaning to the data. Therefore, they introduce these concepts as follows [56]:

$$\textbf{Question} + \textbf{Visual Data} + \textbf{Context} = \textbf{Story}$$

For visualizing data, communicating and sharing it with other users, in today's digital environment there are a lot of online visualization services that are also quite innovative. These include Many Eyes, Wordle, Swivel or Gapminder, which can be used in many disciplines [19]. These represent new and innovative tools that provide new and interesting ways to visualize data. Lately, TEL researchers have been taking advantage of visualizations [26]. Research in this area shows that visualizations have the potential to improve outcomes, especially in aspects related to inquiry learning [19, 25, 26, 57]. Moreover, visualizations support and increase students' engagement in scientific inquiry [26, 57]. In the scope of this thesis, "learning through collaborative visualization" refers to developments of "scientific knowledge that is mediated by scientific visualization tools in a collaborative learning context" [57]. Furthermore, the domain of exploration where we apply and conduct testing of our technological developments in this study lies in the field of TEL.

2.1.3. Technology-Enhanced Learning (TEL)

The TEL field has greatly benefited from advances in mobile, wireless and sensor technologies along with web services and visualizations offered over the web [58].

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[3] http://code.google.com/apis/chart/interactive/docs/gallery.html

[4] http://vis.stanford.edu/protovis/

[5] http://thejit.org/

Human and social aspects of computer system design, usage and evaluation are central issues in the TEL field [17]. The aim of this field is to provide pedagogical and technological support in order to promote learning in different settings [59].

Mobile and web developments provide new possibilities for augmenting learning activities. These are technology-enhanced learning activities that can be spatially distributed and can incorporate different physical and environmental sensor data [60]. There are different sensor-based technologies that provide new perspectives on how learning activities can be embedded in different settings and across contexts [61]. Mobile learning is defined as learning across contexts by utilizing mobile technologies [62]. A recent study conducted by Frohberg and colleagues emphasized how context can be used for the classification of mobile learning [63]. One of the main conclusions of their study was that "*mobile learning can best provide support for learning in context.*" In this thesis, context can be regarded as any information that illustrates the situation of a group of learners, including location, time, activities, and their preferences [64]. One innovative aspect of these new learning landscapes is the combination of learning activities to be conducted across different educational contexts such as schools, nature and science centres/museums, parks, and field trips [65].

There are several significant efforts in the domain of TEL that make use of these advances to support learning across different settings such as in museums, parks, and field trips [66]. These developed technologies support learning processes that allow data collection and analysis in environmental sciences, letting both teachers and students reflect collaboratively upon the data they have gathered [67]. According to Knapp and Barrie [68], to effectively learn about science, field trips should also be considered in environmental sciences. It is suggested that field trips can be helpful to generate relevancy to classroom learning when connected with the outdoor environment. For students, such an approach may raise the interest in and aspirations for science-related careers [69]. The data collected in such field trips play an important role for analysis, and hence should be saved and carried back to the classroom. Presenting and analyzing the data using visualization tools may help to increase the understanding of the data even more. Furthermore, the Horizon Report [19] for visual analysis of data, states, "*one of the most compelling aspects of visual data analysis is in the ways it augments the natural abilities humans have to seek and find patterns in what they see. By manipulating variables, or simply seeing them change over time if patterns exist (or if they don't), that fact is easily discoverable.*"

Reflecting upon our understandings of TEL, two important issues are identified for supporting environmental inquiry science learning:

1. Outdoor activity in terms of performing field trips by collecting data, and
2. Indoor activity by visualizing, exploring and analyzing the collected data.

Furthermore, this can be supported by mobile and web technologies, which are continuously becoming cloud-based and decentralized as mentioned earlier. Hence, mobile and web-based learning tools and applications including interactive visualizations have the potential to increase learners' engagement and curiosity, thus promoting scientific inquiry thinking [57].

As mentioned earlier, a lot of different software systems including visualization types, tools, frameworks and techniques exist; however, when users interact with these, some may be satisfactory, while some may not. This implies that there is a need for some kind of assessment of the visualization tools in order to identify if they fulfill users' needs by considering their functionalities and interactions in the specific context of use [29]. The following section tackles several approaches and challenges related to the usability aspects and testing in connection to our research efforts.

2.1.4. Usability

During the last years, a lot of attention has been given to the quality of web-based applications in web engineering research [36]. One of the main goals of such research is to define proper methods for assessing the quality of a web-based application [36, 70, 71]. According to Castelyen [36], there are two important aspects to be considered for assessing a web-based application: 1) testing the code and architectural failures while developing it: and, 2) usability evaluation of the application that is related to users' needs and their requirements [36, 70, 71].

According to the ISO 8402-86 standard, quality is defined as "*totality of features and characteristics of a software product that relate to its ability to satisfy stated or implied needs*". Quality models are used to guide the application evaluation process during the development life cycle [36]. Also, it is important to mention that one or more quality characteristics need to be addressed during the development process of a web-based application. Table 2.1 below lists six characteristics and their definitions of a software quality model with the goal of facilitating the quality of the software system (ISO/IEC 9126).

Table 2.1: Six quality characteristics definitions (ISO/IEC 9126 standard).

Characteristics	Description
Functionality	A set of attributes that bear on the existence of a set of functions and their specified properties. The functions are those that satisfy stated or implied needs.
Reliability	A set of attributes related to the capability of the software system to maintain its level of performance under stated conditions for a stated period of time.
Usability	A set of attributes that bear on the effort needed for use, and on the individual assessment of such use, by a stated or implied set of users.
Efficiency	A set of attributes related to the relationship between the level of performance of the software system and the amount of resources used, under stated conditions.
Maintainability	A set of attributes related to the effort needed to make specified modifications. Modifications may include corrections, improvements, or adaptation of software to changes in environment and in requirements and functional specifications.
Portability	A set of attributes related to the ability of the software system to be transferred from one environment to another.

Among the six characteristics listed in Table 2.1, 'usability' stands as the most crucial for this thesis, when it comes to assessing the web-based application, specifically considering the nature of the research scope presented earlier. Moreover, usability testing helps to assess an artifact by testing it with users. In terms of users, with usability they will be more satisfied, by enjoying and interacting with the product, possibly without frustration and achieving their goals effectively.

Meanwhile, the developers' benefits in usability are mainly based on development time and costs, and reduced user errors. The importance of usability is also noted in an interesting statistical report on web metrics, presented by Castelyen [36], who found that from 326 metrics defined in literature, 53% were about usability. By considering the nature of our study in the field of TEL, usability testing provides insights on how users use the developed tool in authentic settings, which allows us to advance the development of existing applications.

According to Part 11 of the ISO 9241 international standard, usability is defined as "*the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use*". Usability evaluation is used to test the final product features and to verify user requirements, which can be done on the basis of three methods: user testing, usability inspection and web usage analysis [36]. Of these three methods, in our study we apply the user testing method, as an efficient way to handle users' needs and expectations.

Additionally, user testing is used to improve functionalities, the performance of the web-based tool, and the user's experience in general, by leading towards a better system [36, 70, 71]. In order to conduct a user testing study, it is required that users perform a set of tasks through the interaction with physical artifacts, prototypes and/or final solutions [36, 70]. Therefore usability issues with the web-based solution must be identified in order to increase the value of the tool's usability aspects. Besides, user testing is an effective way to assess the web-based application usage and performance, since it involves real users. Applying usability evaluation to visualization tools and geo-temporal applications throughout the whole development process still remains challenging [72, 73]. Evaluation in the visualization field is closely related to Human Computer Interaction, where assessment of the tools considering usability testing is relevant. Moreover, the idea of usability in this field is to identify if the tool supports users' information tasks, so that the visualization tool can be better designed to support them [29]. Therefore, one important challenge in this field deals with identifying proper ways to conduct user testing. Concerning this thesis, the goal of the usability study is to identify usability issues of a web-based visualization tool and to propose potential suggestions for enhancing and improving further development of this tool.

2.2. State of the Art Projects

In this section, we discuss related work in the context of *technology* and *engineering* challenges related to TEL by considering the areas of mobile and web engineering, and visualization. A brief description related to several research initiatives that consider these areas is given below.

Liang et al. [4] discuss issues related to the presence of in situ sensors, the availability of ubiquitous devices, wireless access and geospatial software that have become a technological trend. Furthermore, they examine sensor webs that provide monitoring and sensing data from various sensors. They present a prototype that serves as a gateway to integrate spatially referenced sensors. Another similar approach is taken in the work of Nair and Gopalakrishna [74], who discuss issues related to generic reusable web services, composed from both mobile and web applications, for collecting and monitoring weather data. Their prototype implementation approach is related to the area of SaaS as a proof of concept, thus orienting their SaaS architecture towards green computing.

Hansen and Bouvin's HyCon framework [75] was developed to provide a platform for experiments with hypermedia mechanisms in context-aware and mobile environments. HyCon is a layered framework consisting of four layers: a storage layer, a server layer, a terminal layer, and a sensor layer. At the application level this framework aims to support several aspects of mobile learning activities, such as field trips and problem-based education. This support is constructed by using different sensors to collect contextual information that can be used to link, annotate, and tag different learning resources. Another similar approach that addresses the issue of context awareness in inquiry-based learning activities is the ButterflyNet project developed by the Stanford HCI Group [49]. This project is built upon an n-tier architecture that deals with data capture, structure, access, and transformation. Resources in this architecture include visual codes, digital pens, cameras, GPS devices, and audio and video recorders. In the application domain, this project supports inquiry learning in biology. An interesting feature of this project is the ability to visualize notes captured with a digital pen during inquiry activities. Collins and colleagues [66], in their Personal Inquiry project, have developed and introduced a system that supports location-based science inquiry learning across school, field and home contexts using mobile, sensor and web technologies. They present the design of technology-supported inquiry activities and how to develop flexible, reusable tools to support and bridge sequences of activities. They also discuss how the use of digital maps and the visualization of sensor data can be used for bridging representations across field and classroom activities.

A number of research efforts have been carried out in relation to visualizing geo-tagged and sensor data using the technologies and concepts described above. Rodrigues and Rodrigues [76] have developed a visualization tool that makes use of maps APIs and Web 2.0 technologies to support asynchronous spatial collaboration between physically distributed users. In GeoJunction [50], the authors propose a web-based geo-visualization tool for exploring geo-temporal data related to public health. The need for supporting collaboration by these technologies has been emphasized by MacEachren and Brewer [77] and their framework for visually enabled geo-collaboration. Overall, throughout these projects, there is a need for conducting usability assessment in order to validate these novel concepts and ideas that involve the visualization of geo-temporal data sets. There are several approaches that deal with user testing and usability of web-based applications and prototypes evaluation, such as those discussed in [70, 78, 79]. One of the main results of their efforts is to determine that usability concerns should be taken into account in the process of web development. This latest issue has been addressed also by the work of Shneiderman [80] and Preece [81]. They suggest that usability testing could be used in order to reduce the effort at the maintenance stages of the web-based applications.

However, despite these technological advances, many issues still remain challenging in connection to the integration of different technological resources for use in broader educational scenarios in TEL, as addressed by Hoppe [21]. With reference to the state of the art projects mentioned above, we have identified a couple of deficiencies in the existing approaches that require further research attention. The main deficiencies that we take into account are as follows:

a) Lack of full utilization of the sensor data;

b) Not fully developed tools for visualizing sensor data to support users' reflections about their inquiry process;

c) Extensibility of such systems when it comes to using different open systems and available APIs on the web, including internet-based services;

d) A common denominator in these projects is the lack of standards to provide seamless data exchange among the devices and applications used in these projects.

Comparing our research efforts with the above-mentioned projects and the identified deficiencies, this thesis investigates the integration possibilities in heterogeneous mobile device and service-oriented environments. These may facilitate the identification of the main features for guiding the design and implementation of a software system for supporting inquiry learning in different contexts. Finding a balance between the design and implementation of the software system by considering rapid technological changes (Web APIs and internet-based services) may help to cope with such changes. Finally, conducting a usability study for assessment purposes in order to further improve the system is an important issue.

2.3. Challenges

The research background and state of the art projects elaborated in this chapter present several key notions and concepts that the research in this thesis deals with. The focus of this research is in the intersection between three different but interconnected areas as mentioned earlier: mobile and web engineering, visualization and TEL. In mobile and web engineering, issues related to the design and development process of mobile and web-based applications towards service-oriented environments are discussed. The visualization area involves some of the main notions and concepts that deal with visualizations, which influence the thesis in terms of implementing and understanding the visualization. The requirements that guided this research have been identified from the field of TEL. Moreover, the overview given above of existing technologies and trends in mobile and web technologies, and visualization have allowed us to identify several technical and design challenges that guide our current research efforts related to the field of TEL. The following challenges have been identified and are addressed in this thesis:

Challenge 1 Integrating and facilitating interoperability among mobile, web and sensor components and technologies in the software system.

Challenge 2 Adaptation of rapid changes of software technologies and techniques based on Internet to cope/deal with dynamic user needs.

Challenge 3 Making use of usability evaluation methods for assessment and testing purposes in order to verify and understand if the design and implementation of our system fulfills the user requirements.

These challenges provide a good outline for us to investigate concepts related to integration and interoperability in the area of mobile and web technologies, which support and enhance TEL activities.

3. Research Settings, Problem and Strategy of Investigation

The previous two chapters elaborated the scope of this thesis; goals and challenges have also been presented. The present chapter introduces the research settings. It then presents the research problem that is addressed in this thesis, followed by the main research question. Finally, this is concluded with a strategy of investigation where initial requirements are introduced and the scientific investigation process is addressed.

3.1. Research Settings

The piloting or prototype experiments were conducted as part of the LETS GO project. The aim of the project was to design challenging collaborative learning activities by utilizing mobile, sensor and visualization technologies for supporting inquiry science learning. These combinations of technologies enable the creation of "mobile science collaboratories" that are defined as a set of mobile devices, open software tools, and resources, with online participation frameworks for learner collaboration and inquiry [22].

Project Description: Ubiquitous and mobile multimedia technologies provide the opportunity to interact in new ways with the physical world as they allow allocation of computational power and interaction away from the limitations of desktop computers. From this perspective, learners are given the opportunity to explore the physical world and interact with it in new ways, in addition to which the physical world can be augmented through digital technologies. K-12 learning and education (primary and secondary education) stand to benefit substantially from new designs for open learning environments that incorporate these technologies and collaborative activity designs for advancing knowledge-building using inquiry and reflection cycles. The vision of "open inquiry" in this project is framed as the opportunity to catalyze and sustain global learning using mobile science collaboratories that provide open software tools and resources, and participation frameworks for learner project collaboration, mobile media and data capture, analysis, reflection and publishing. In the LETS GO project, Stanford University in the learning sciences and Linnaeus University in the computer science departments aim to develop, implement and research a new paradigm for fostering high school student learning in teams for environmental science. This project will productively integrate geo-location sensing, multimedia communication, information visualization and Web 2.0 mashup technologies, to create science learning collaboratories using interdisciplinary co-design methodologies with teachers, learners, teachers-to-be, technology developers, domain experts, and learning scientists.

3.2. Research Problem

As elaborated in previous chapters, the scope of this study lies in technology and engineering challenges, mainly focusing on mobile and web engineering, and visualization. This thesis addresses the issues related to the integration of different technological resources such as sensor, mobile and web. Moreover, this thesis explores new opportunities for identifying features to guide the design and implementation of the software system in these particular settings. Our technological solutions are developed for supporting environmental science inquiry learning activities particularly for outdoor and indoor settings. For example, users in outdoor activities can geo-tag different content and sensory data about environmental issues (e.g., soil or water quality) using mobile applications. Subsequently they upload these data to the system, which allows them to perform visual exploration of the data using data visualization tools in indoor activities.

In considering the research problem and the goals and challenges identified in previous chapters, this thesis is guided by the following main research question:

> *What are the main features that guide the design and implementation of a software system for supporting inquiry learning in different contexts?*

In different contexts, we label the activities (user trials) conducted across different situations or settings. In order to carefully examine the main research question, two sub-research questions are formulated for the purpose of bringing into discussion the focus of this thesis as follows:

> **Q1** How to facilitate interoperability among mobile, web and sensor technologies by integrating them in the proposed system architecture?
>
> **Q2** How to utilize Internet-based services for visualization purposes and what are the potential benefits of such an implementation?

These questions relate to examining the main features by looking at design and implementation challenges that may lead to identifying potential benefits for developing a software system that can support, for instance, TEL activities in different contexts.

As presented earlier, our exploratory investigation, which continued with the requirements elicitation workshop, generated some initial requirements for the design and implementation of the software system within the LETS GO project. Initial requirements are summarized and presented below, together with a detailed explanation of the strategy of investigation of this thesis.

3.3. Strategy of Investigation

The investigation process in this thesis followed four lines of exploration. This was achieved by looking at general issues within the scope of the thesis. The exploratory investigation followed a requirements elicitation workshop. This was based on identifying initial requirements, which were specific and considered design and development challenges through the implementation and testing of a software system for supporting TEL activities in different contexts. These considerations led our study to evolve along four lines of exploration by following the goals and challenges identified earlier:

(1) Features of technologies: our initial sessions with stakeholders took place in the fall of 2008, aimed at exploring the required and desired features of technologies. The outcomes of these efforts led us to continue with:

(2) Design and literature review: previous work and a requirements elicitation workshop with stakeholders allowed us to identify some challenges in relation to architectural design, implementation and integration of technologies (mobile, web and sensor technologies) in our domain of exploration (TEL and environmental science inquiry learning).

(3) Implementation: considering the above lines of exploration that guided this thesis, this stage continued with the design and implementation of a software system by integrating different technological resources. The focus here was on identifying the main features that can guide the design and implementation of such a system for supporting inquiry learning.

(4) Testing: the final stage of this thesis is guided by assessment of the system in order to meet users' needs, and to identify potential suggestions for further improvement of the software system.

The process of determining the system design and architectural requirements was motivated by Gorton [82]. The initial *requirements elicitations* with stakeholders were followed by a workshop within the LETS GO project as described above. This workshop identified the need to integrate *geo-location* and *environmental sensing*, *visualization*, and *Web 2.0 mashup technologies*, as part of a broader educational scenario. As a result, there was a need to develop different software components and to integrate several hardware resources. This generated requirements required us to provide *sensor networks, live mapping tools, data visualization* and *collaboration tools*, and the *learning resources*; required us to cover *usability*, *low cost*, *open standards*, *multiple application support*, and support for different types and *contexts collaboration* [22].

The design and implementation of our software system was achieved by employing the following two approaches:

1. Web development life cycle with prototyping that followed a strategy for design and implementation, and

2. User testing by using tasks and questionnaire for data collection, and by performing quantitative and qualitative analysis within this approach.

These two specific approaches were used for guiding the design and implementation of our software system that integrates different resources for supporting TEL activities in different contexts, and identifying the main features that guided these developments.

3.3.1. Development Life Cycle – Prototyping

The web development life cycle approach is used to design and implement the system effectively and to achieve quality as a process of web engineering. This is achieved by following a number of standard stages for development. We have considered the work of Abou-Zahra [83], which relates to web engineering research. He states that the development life cycle of an application can be categorized according to four main stages: *Requirements, Design, Implementation* and *Operation* (see Figure 3.1*).* In our research efforts, these four stages have played a crucial role. During the requirements stage (Req), we identified some initial requirements that included the need to integrate geo-location and environmental sensing, visualization, and mashup technologies [22], as stated earlier. After the first stage, we developed a prototype and implemented it in order to validate those requirements. The second (Des) and third (Imp) stages of design and implementation guided the design concepts, navigational features, and the general content. Then, the final (Op) stage of operation was intended to maintain and identify additional improvements during the prototype testing.

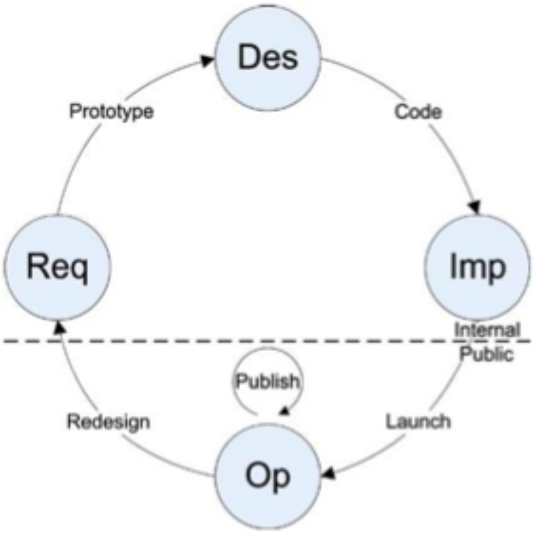


Figure 3.1: Stages of the web development life cycle, taken from [83].

There are several benefits with regard to using prototyping. The main benefit is that the requirements can be tested at an early stage towards the final product. Several other benefits can be mentioned: the prototype is fully interactive, it is completely functional, it is user-driven, it has the "look and feel" of the final product, and it may save time and money [84].

In prototyping, there are two different development principles - evolutionary prototyping and throwaway prototyping [84]. The four stages of web development cycles introduced earlier in this section are mapped to our developments, following these two principles of prototyping:

Throwaway prototyping – considers creating the basis of a final product, which is eventually thrown away; however, it remains valuable to construct further evolving ideas related to the final product.

Evolutionary prototyping – considers the evolution of a prototype toward a robust final product.

We applied both these principles throughout our development process. In the next section, we describe the experimental settings, procedures and methods we used in this research.

3.3.2. Participants, Settings and Methods

All user trials (prototype testing) in this research involved some general methods and procedures. The participants in user trials were either students from K-12 schools (such as Katedral, Teleborg and Kronoberg schools in the city of Växjö) or undergraduate students (students on the teacher training program at Linnaeus University). None of the participants had prior knowledge of our developed technologies. The procedures that were followed in these user trials involved students who participated in two-hour sessions once per week. As part of the students' environmental science curriculum, they investigated soil quality (woodland ecology, in a study conducted over a period of two weeks) and water quality in surrounding lakes (the study was conducted over a period of five weeks). The activities carried out by the students included classroom lessons, field trips and lab work. The students filled out worksheet surveys at the first session of the classroom activity. This was done after the field activity and after the lab work. In addition, we videotaped different sessions for future analysis and some of the researchers from our group used a systematic observation sheet during field and lab sessions.

The two principles of prototyping (throwaway and evolutionary, as mentioned in the previous section) led to the development of an application that was later used in testing. The design and implementation of the three prototypes was made possible by an evolutionary process through several iterations. In our case, the implementation of the software system was based on cyclic prototyping to enable us to validate, test and refine different versions of the software system based on users' feedback. This allowed us to conduct testing of several prototypes with the users (user trials). Finally, our efforts were followed with assessment and testing of one part of our software system (web-based visualization tool). From around 200 users that participated in these prototype tests (user trials), a user testing study was conducted with only 18 of them.

Moreover, according to Castelyen [36], good usability testing should consider the following:

1. Defining the goal of the test.
2. Defining the sample of users that will participate in the test.
3. Selecting tasks and scenarios.
4. Establishing how to measure the level of the usability of the system.
5. Preparing the needed material and the experimental environment.

We considered these suggestions carefully and mapped them with our usability testing study, as described below. In this research a user testing approach was conducted to assess the usability aspects of our web-based visualization tool and to make potential suggestions for enhancing and improving further development of this tool (1. *the goal of the test*). Eighteen undergraduate students participated in the testing, as mentioned earlier (2. *sample of users that will participate in the test*). User testing was necessarily involved as an approach that allowed us to improve different tool functionalities by also improving its performance for users [36, 70, 71]. Throughout the user testing approach, we closely followed the cyclic evaluation process of a web-based visualization tool as described in Figure 3.2. This was inspired by the work of Harms and Schweibenz [85].

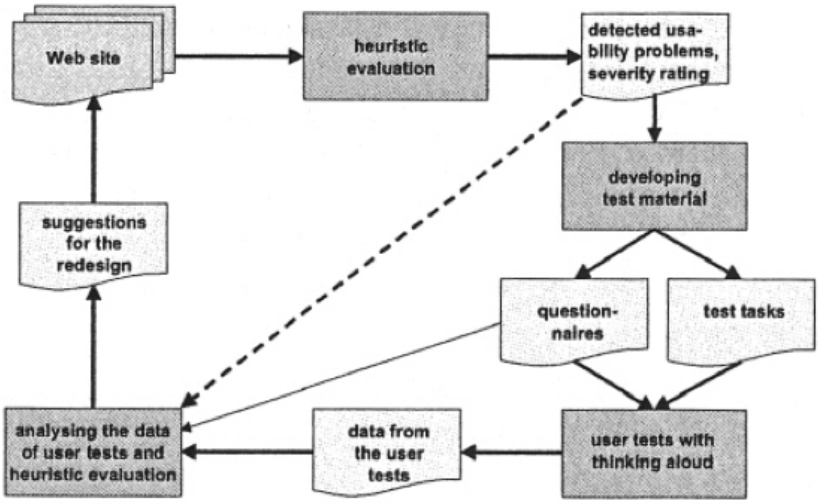


Figure 3.2: The cyclic evaluation process, taken from [85].

For developing materials and conducting the user testing, a mixed method using quantitative and qualitative analysis was employed [86]. Prior to performing the user testing, participants were involved in a series of learning activities related to the topic of water quality in which the students measured water quality and collected sensor data using mobile devices as described previously (3. *scenario*). In order to carry out the user testing, we first developed a couple of tasks for the participants (Appendix B). The tasks were used to test and validate the functionalities, navigation and interaction mechanisms of the tool (3. *tasks*). Then we developed a questionnaire (Appendix C). Questions were specifically related to the tasks, while the last ones were related to the overall rating of the tool. Quantitative data gathered from tasks and questionnaires were analyzed using descriptive statistics by calculating the mean, standard deviation and confidence interval (4. *establishing how to measure the level of the usability of the system*). Typical data of interest to us and of great importance collected during user testing activities are user satisfaction, errors, execution time, and continuous observation [36]. The data collected in our study rely on usability aspects that included tasks and questionnaires that were followed with observation, analysis of screen capturing, and follow-up interviews (5. *the needed material*). The user testing study was conducted in a computer laboratory located at our university (5 *the experimental environment*). While users performed the tasks with the tool, we also used screen capturing on each computer to save their activities. Each task had its own time-stamp marked with start and end time. After initial analysis of data gathered from the questionnaire, we conducted follow-up interviews with users and initial analysis of screen capturing. These procedures were followed in order to increase the reliability of our results.

3.4. The Scientific Investigation Process

As elaborated in the strategy of investigation section, our research efforts can be divided into four stages. The first stage was identified during the requirements elicitation workshop and literature review from which the initial *requirements* were derived, and then the second stage was the design and implementation of the software system that followed with *cyclic prototyping.* The prototyping helped and guided the development process, which was followed by the third stage that resulted in a *robust application.* In the last stage, a user study was conducted for *evaluation/assessment* purposes. In Figure 3.3 below we summarize our overall investigation process.

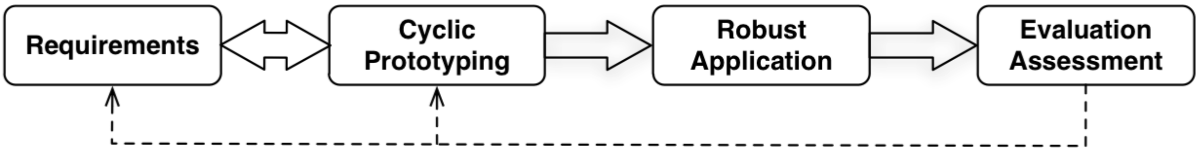


Figure 3.3: Investigation process.

To further elaborate the scientific investigation process of this research, Table 3.1 below summarizes it in more detail. The first stage "requirements" resulted in the implementation of the prototype. In the second stage, the "cyclic prototyping" helped us to further clarify the requirements, by following different development iterations. After finishing these two stages, our software system gradually started to become a "robust application" (third stage), which was tested with more than 200 users in different settings. These tests (user trials) were conducted in different schools in the Vaxjo area, such as Katedral Skolan, Teleborg Skolan, Kronoberg Skolan and Linnaeus University. However, the idea was to further improve our software system, so we conducted a user study for evaluation/assessment purposes. This assessment was conducted only for the visualization tool. The detailed concepts of the investigation process and its effect that were followed in this research can be seen in our four publications.

Table 3.1: Investigation process in more detail.

Requirements	**Cyclic Prototyping**	**Robust Application**	**Evaluation/Assessment**
Provide sensor network	Web development life cycle	Tested with more than 200 users	User testing
Provide data collection tools	Throwaway prototyping	Katedral Skolan	Usability aspects
Provide data visualization tools	Evolutionary prototyping	Teleborg Skolan	Potential suggestions for the rebuild of the tool.
Provide live mapping tools		Kronoberg skolan	
Provide collaboration tools			
Provide easy to use system		Linnaeus University	
Provide affordable cost of hardware			
Multiple application support and easy integration			

4. Overview of Research Efforts - Papers

The research efforts discussed in this chapter provide an overview of four publications presented at peer-reviewed international conferences. These efforts are closely related to the goals and challenges described in the previous chapters, as well as to the research questions. The interconnection between the problem statement, goals, and foundations of the thesis, challenges and research questions with the publications is illustrated in Figure 4.1. The first layer introduces the research scope, which was the starting point of this thesis that led us to formulate the problem statement. To address the problem statement, three areas of concern are identified, namely: *Requirements & Design*, *Implementation & Deployment*, and *Assessment & Testing*. These areas of concern are presented with the purpose of better illustrating and positioning the goals of this thesis. The foundations layer introduces the fundamentals that provide an overview and central concepts constructed from four areas of investigation, namely mobile and web engineering, visualization, TEL and usability. Following these foundations, an overview of state of the art projects is presented with the purpose of identifying specific aspects that deserve further research attention. Thereafter, the challenges that were identified in the foundations layer are introduced. These challenges serve as the basis for posing the main research question of this thesis. In order to provide an answer to this question, two additional sub-questions are formulated. These sub-questions, as shown in Figure 4.1, are closely related to the four papers that will be briefly described below. To recall again, the main objective of this thesis is to integrate different technological resources and identify features for guiding the design and implementation of a software system for supporting inquiry learning in different contexts (mainly indoor and outdoor settings). Furthermore, we have developed a technological solution for supporting environmental science activities in the domain of TEL, as part of the LETS GO research project. In the following subsections we highlight the main concerns of the research challenges in connection to each one of the papers by providing an overview of the purpose, development, pilot testing and the outcomes.

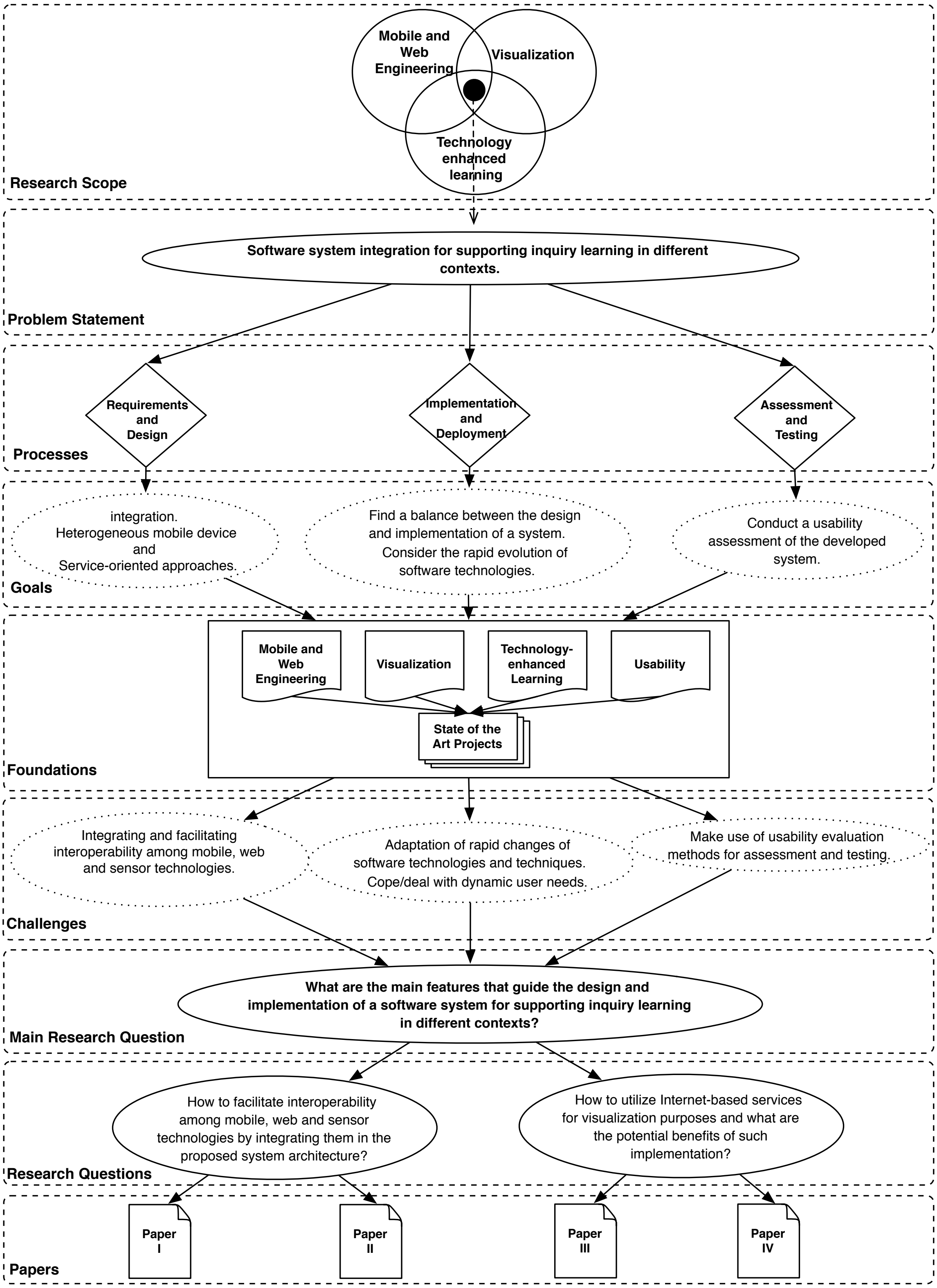


Figure 4.1: Mapping of the four publications into the context of the thesis.

4.1. Paper I: Integrating Mobile, Web and Sensory Technologies to Support Inquiry-Based Science Learning

Vogel, B., Spikol, D., Kurti, A, & Milrad, M. (2010). Integrating Mobile, Web and Sensory Technologies to Support Inquiry-Based Science Learning. Proceedings of the *6th IEEE WMUTE International Conference on Wireless, Mobile and Ubiquitous Technologies in Education*, WMUTE 2010 held in Kaohsiung, Taiwan, April 12-16th, 2010, pp. 65-72.

The efforts described in this paper explore the challenges related to the technological integration of different devices, sensors and software solutions to support science inquiry learning. The main purpose of this paper was to explore how mobile, web and sensor technologies could be integrated to support science inquiry learning activities in the classroom and in outdoor settings. In this paper, we present our technical efforts in relation to the design and implementation of mobile and web applications that integrate sensor data for supporting such activities. This paper represents initial efforts in the requirement and design activities with an initial implementation. This is followed by a proposed system architecture comprising different building blocks. The blocks of this architecture aim to provide some logical divisions of the resources in our system. The architecture organizes available resources into the following blocks: sensors, mobile devices and the transmission of sensor data, repositories, external APIs, and visualization. In order to test the validity of our solution and its functionality and novelty, we conducted a pilot test (prototype experiment) with high school students in the field of environmental sciences. The subject of exploration was woodland ecology (soil quality) and formed part of the environmental science class in the school. Students began their investigation by heading to the local forest, to collect data and carry out measurements including: pictures, location, pH, soil temperature, soil moisture and so on. After the data collection process, students went to the lab to explore the collected data using the visualization tool, where they compared the health of the trees between locations. Figure 4.2 below illustrates the different phases of the pilot testing and the technology in use.

Figure 4.2: 1st Pilot testing – technologies in use.

In this paper we wanted to explore the use of mobile and sensor applications, geo-tagged content, and to provide data visualization and collaborative inquiry tools for the students. In general we consider that the outcome of the trial validated our proposed system architecture. Our system architecture, besides customization and implementations, enabled the integration of off-the-shelf technologies to be used with the newly developed infrastructure by allowing multiple streams of data to be aggregated and analyzed for use in science learning activities. The system architecture and technical overview in this particular implementation provide a future roadmap for our development, with context sensing and awareness integrated with the smartphones, sensor-based technologies, and digital pens. Different instantiations of the system developed for the purpose of this trial were easy to use and well received by students participating in the pilot testing. The students thought that using the smartphone in the field and lab expedited the work. Hence, the visualization provided a new window for the students to reflect, discuss, and share different opinions in the group and as a whole. One issue that was identified based on our developments was the lack of *interoperability* between the different tools and technologies. Each of the devices had, to a large extent, a closed system approach that restricts the development of customized and integrated approaches advocated by the requirements. Moreover, the scientific sensors system required manual synchronization of data before we could provide the visualization tools. The identified issue of interoperability is one of the motivations for the next paper.

4.2. Paper II: Exploring the Benefits of Open Standard Initiatives for Supporting Inquiry-Based Science Learning

Vogel, B., Kurti, A., Spikol, D, & Milrad, M. (2010). Exploring the benefits of open standard initiatives for supporting inquiry-based science learning. Proceedings of the *Fifth European Conference on Technology Enhanced Learning,* EC-TEL 2010, held in Barcelona, Spain, September 28 - October 1, 2010, LNCS, Springer-Verlag, Berlin Heidelberg, pp. 596-601.

This paper investigates interoperability issues between different technological resources, as identified in the previous study (Paper I). The main purpose of this contribution was to explore how open standards approaches for data exchange could be used to facilitate interoperability across heterogeneous devices used for supporting inquiry-based science learning. Therefore, new technical implementation took place. To validate the potential benefits of this approach, we developed a prototype implementation and conducted a pilot test with high school students in the field of environmental science, as in our previous study. As part of the students' environmental science curriculum, they investigated water quality in surrounding lakes. The activities carried out by the students included classroom lessons, field trips and lab work. Students conducted field experiments at a local lake and collected samples for lab analysis such as geo-tagged content and sensor data (pH, dissolved oxygen, temperature, conductivity) (see Figure 4.3).

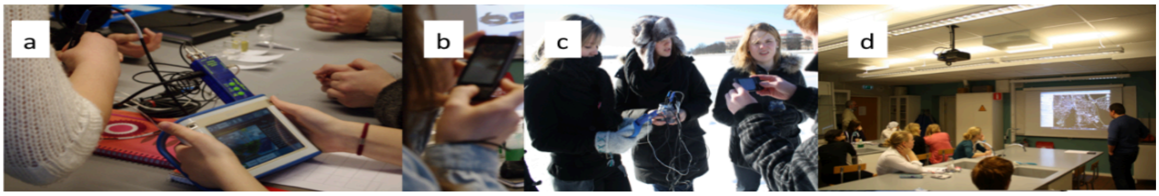


Figure 4.3: 2nd Pilot testing – technologies in use.

In this particular implementation we utilized open standards approaches, with the integration of the ODK platform [73]. Moreover, the use of standard-based forms facilitated data interoperability across diverse devices and applications that comprise our system. In the pilot testing described in this part, interoperability simplifies the integration of data generated by various technological resources and applications. Interoperability remains a key feature to resolve while dealing with diverse data exchange issues across different software and hardware components. Open standards approaches deal with the interoperability of data using transparent descriptions, by which different software systems can easily exchange information. The initial results of this paper indicate the potential benefits of open standards and clearly demonstrate how they help with the integration of various technological resources and applications by supporting data collection, interoperability, analysis and visualization in the context of inquiry learning. This approach enables rapid development and reuse of technological resources for supporting different activities, thus resulting in the seamless integration of data coming from multiple devices. One issue that we considered in this paper in relation to our future work is the full utilization of the visualization component, by incorporating different techniques that provide interactive spaces for discussion, sharing and collaboration. This particular effort is described in the next paper, which also provides a detailed description of the different development cycles of the interactive visualization tool.

4.3. Paper III: An Interactive Web-based Visualization Tool: Design and Development Cycles

Vogel, B. (2011). An Interactive Web-based Visualization Tool: Design and Development Cycles. Proceedings of the *IEEE 35th Annual International Computer Software and Applications Conference Workshops* (COMPSAC 2011) held in Munich, Germany, July 18-21, 2011, pp. 279-285.

The purpose of this paper was to present our efforts in relation to the development cycles of the web-based visualization tool that took place during the last two years. Therefore, this paper addresses issues related to the design and implementation cycles of web-based visualization tools that utilize web data and cloud computing resources. The efforts presented in this paper are related to the development of three prototypes of a web-based visualization tool that uses Google Cloud Services to process and visualize geo-temporal data. The main motivation for the development of these prototypes and the evolution of our visualization tool rely on the use of: Web APIs, Software as a Service (SaaS) concept, cyclic prototyping in the context of TEL. The paper discusses our experiences and reflections while designing, implementing, deploying and piloting such a system. It elaborates on those issues related to how rapid technological changes have affected the development process of the web-based visualization prototype. Thus, it presents the prototyping cycles of the visualization tool across several iterations that include four pilot testing trials connected to activities that include data collection in the field using mobile devices and sensors. The need for web-based visualization tools in this area indicates the importance of allowing users in an interactive manner to explore, analyze and reflect on different representations of environmental data. Throughout the entire process described in this paper, users were actively involved in testing the different features of the web-based visualization tool (Figure 4.4).

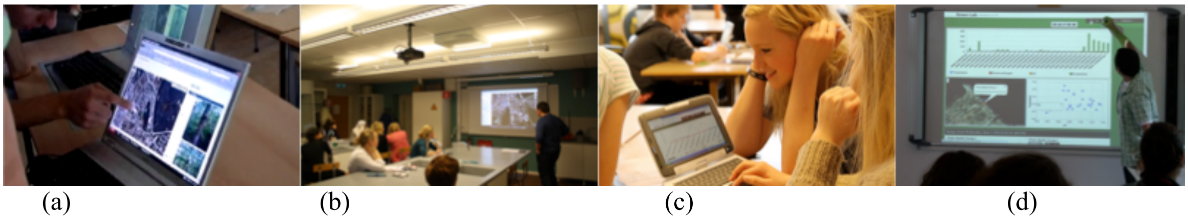


Figure 4.4: The different prototypes in use. (a) First prototype in 1st Pilot testing, (b) Second prototype in 2nd Pilot testing, (c) Third prototype in 3rd Pilot testing and again (d) Third prototype but in 4th Pilot testing.

Piloting with users provided us with feedback regarding improvements to the web-based visualization tool. This was achieved through prototyping cycles that helped us to further enhance the tool and its maintenance on the cloud environments. To date, the prototypes have validated the usage and engagement of the users. Cyclic prototyping proved to be a useful approach to obtain flexible ways to cope with requirements engineering and for visualizing data. The outcomes of the development and implementation processes indicate that the user feedback generated during the prototyping cycles provided valuable insights for improving the functionality of the tool, as well as guiding future developments. Thus, our study emphasizes the need to find a balance between design and development in order to consider how the rapid evolution of web technologies should be taken into account during the design and planning of different cycles of web prototyping. Another important issue identified was that it was necessary to conduct a usability study for our latest prototype based on web engineering research, which motivated the next paper.

4.4. Paper IV: An Interactive Web-based Visualization Tool in Action: User Testing and Usability Aspects

Vogel, B., Kurti, A., Milrad, M., and Kerren, A. (2011). An Interactive Web-based Visualization Tool in Action: User Testing and Usability Aspects. In Proceedings of the 11th *IEEE International Conference on Computer and Information Technology*, IEEE Computer Society Press, (CIT '11), Paphos, Cyprus, 2011, pp. 403-408.

This main purpose of this contribution was to present the usability evaluation process of the web-based visualization tool (third prototype) from a web engineering research perspective. The specific aim was to conduct a user study in order to identify usability issues of this latest prototype (Figure 4.5). Furthermore, this user study was conducted to identify potential suggestions for enhancing and improving the further development of the tool. The method employed in our user study is based on user testing. This study relies on usability approaches that include observations, tasks and questionnaires, analysis of screen capturing, and follow-up interviews. The main purpose that guided this study is formulated as follows: To verify and understand if the design and development of our web-based visualization tool fulfills the user requirements in relation to application functionality, navigation and interactivity for supporting environmental science learning.

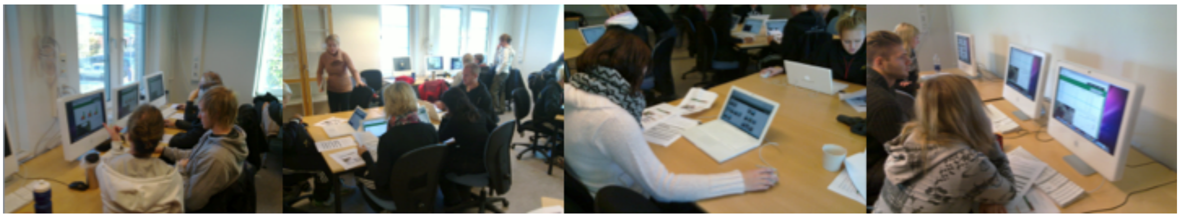


Figure 4.5: User testing study.

Based on the analysis of the data we collected, two important aspects were identified: 1) Users found the tool consistent and satisfactory for achieving their needs related to learning and exploring different aspects related to environmental sciences; 2) While performing relatively complex tasks, users identified a number of difficulties related to usability issues. The results indicated that overall there was a high level of satisfaction with the tool (mean 4.2, stdev 0.721, and confidence interval ±0.33 with the range for true population mean from 3.87 to 4.53). Statistical results, especially those related to some specific tasks, pointed to some issues related to the usability of our tool. Data gathered from the screen capturing and follow up interviews strengthened these results and suggested that there were some problems while changing different visualizations, obtaining individual values, annotating the data, and loading the pictures.

The outcomes of our results indicate that the current version of our web-based visualization tool meets the basic needs of the users in order to perform specific tasks and activities in the field of environmental sciences. Furthermore, some of the basic design and implementation aspects of the tool have been fulfilled in terms of application functionality, navigation and interactivity. However, as the results indicated, not all aspects of application functionality, navigational and interaction of our prototype application are satisfactory. On the other hand, it could be seen that there is a linear dependency between the complexity of the task, the functionality provided by the tool and the results gained from the questionnaires. In particular, these issues were evident in two tasks, where it was required to explore, search, retrieve and annotate different content and sensor data using multiple representations. The overall analysis for these two tasks (standard deviation, number of occurrences, time completion and confidence interval) provides a strong indication that affected the usability of the tool. The analysis of the data we collected (tasks and questionnaires, analysis of screen capturing, and follow-up interviews) indicates that participants experienced the web-based visualization tool as easy to use, with a high level of satisfaction overall. Users also provided valuable and constructive feedback in relation to further enhancements of the tool, which will serve as concrete suggestions for the rebuilding of the tool.

4.5. Summary

This chapter outlines the empirical work that was presented in the four research papers summarized above. These efforts started with initial explorations towards developing a robust application (software system) that was tested with around 200 users. In this software system, mobile, web and sensor technologies were integrated for supporting TEL activities in the field of science learning. Some of the main concepts identified through the developments and integration were architectural design, interoperability; service-oriented resources such as cloud services and web APIs; and user testing. For the system to become more interoperable and flexible we found that utilizing open standards and open source projects might be a suitable solution. Furthermore, cloud services and Web APIs provided intuitive and cost (time) effective solutions for the development of new types of applications, especially if considering prototyping and web development life cycles. With prototyping, our requirements engineering evolved flexibly towards constructing a final product, by coping with the latest developments of web technologies. Another important aspect was the usability evaluation of the web visualization tool, which had positive implications to identify usability aspects of the application tested with users in authentic settings. In our research efforts several research questions were investigated, and different goals and challenges were addressed and identified. Mapping of the flow of the main concepts and ideas related to our study is summarized in Table 4.1.

Table 4.1: Mapping the flow of the concepts and ideas presented in Figure 4.1 with papers.

Goals	**Challenges**	**Questions**	**Papers**
Integration. Heterogeneous mobile device and service-oriented resources.	Integrating and facilitating interoperability among mobile, web and sensor technologies.	How to facilitate interoperability among mobile, web and sensor technologies by integrating them in the proposed system architecture?	I & II
Find a balance between the design and implementation of a system. Consider the rapid evolution of software technologies	Adaptation of rapid changes of software technologies and techniques. Cope/deal with dynamic user needs	How to utilize cloud services for visualization purposes and what are the potential benefits of such an implementation?	III & IV
Conduct a usability assessment of the developed system.	Make use of usability evaluation methods for assessment and testing.		

5. Discussion of Research Findings

In this chapter we discuss the research findings related to the three goals and challenges introduced in earlier chapters. Figure 5.1 illustrates the progression and development of these research efforts in order to initiate a discussion related to the goals and challenges presented in the previous chapters.

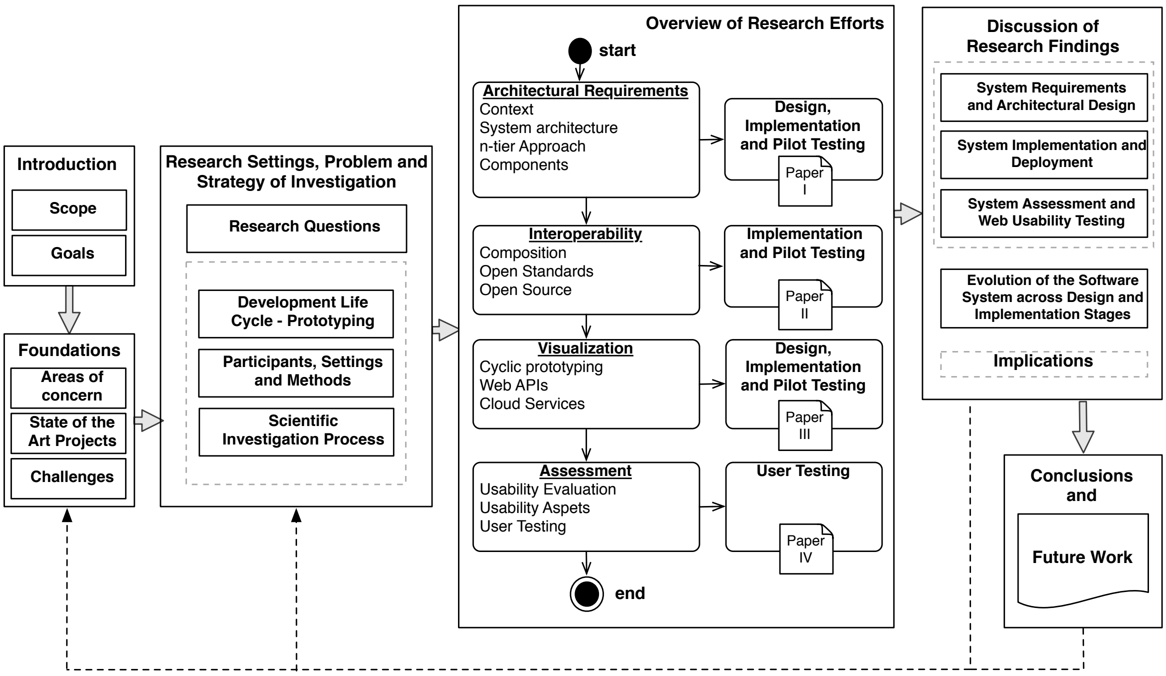


Figure 5.1: Overview of the research efforts.

The main research findings to be discussed in this chapter are based upon the four scientific publications appended to this thesis. The scientific investigation process (see Figure 3.3) in this thesis has presented several development cycles. Starting with requirements and the design of a system, along with the implementation of several prototypes in a cyclic manner. These design and implementation efforts allowed our system to become more robust, as it was tested with more than 200 users. The final publication that forms part of this thesis is related to the assessment and testing of the system.

The following subsections present the results and findings of the research efforts conducted in this thesis. These research efforts are described according to three categories, namely System Requirements and Architectural Design, System Implementation and Deployment, and System Assessment and Web Usability Testing.

5.1. System Requirements and Architectural Design

The integration of different technological resources for supporting TEL activities in the context of inquiry learning is a challenging task. The current section addresses the design issues of the system by providing a general overview of the architecture that is derived and inspired from the requirements. According to Taylor et al. [37], "*every application has architecture and an architect"* and *"architecture is not a phase of development"*. His definition of architecture is: "*architecture is the set of principal design decisions made about a system; it is a characterization of the essence and essential of the application"* [37]. The architectural design activities presented in this thesis have been guided and inspired by the above-mentioned definitions.

Determining the requirements and understanding the overall system's needs is a key part of every software system. In order to identify the architectural requirements, the functional requirements and stakeholder requirements are the main sources in that process [82]. Inspired by Gorton [82], the phases of architectural requirements identification carried out in this research are illustrated in Figure 5.2.

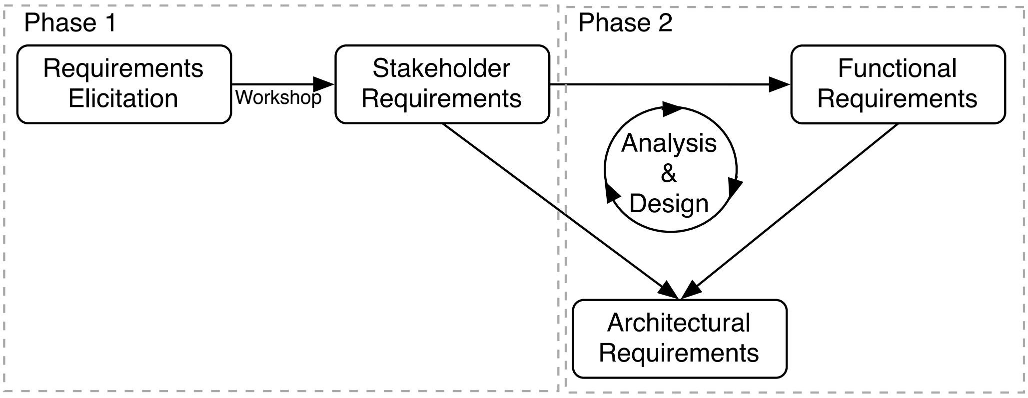


Figure 5.2: Phases of architectural requirements identification.

To understand the stakeholder requirements, requirements elicitation workshops were conducted (as described earlier in Chapter 3). The first phase was conducted by domain experts (teachers) and researchers from our research group [22]. During the second phase, the functional requirements were initially identified by closely addressing the stakeholder requirements. In the final stages of the analysis and design, the stakeholder requirements and main functional requirements have been translated into architectural requirements, which represent the starting point for the implementation process. The mapping process of these efforts is presented in Table 5.1 in greater detail.

Table 5.1: Stakeholder, Functional and Architectural Requirements.

1. Stakeholder Requirements	2. Main Functional Requirements	3. Architectural Requirements
a. Provide sensor network	a. The system should be able to collect geo-tagged content and sensor data.	a. Sensor components
b. Provide data collection tools	b. The system should provide features for data annotation	b. Mobile unit components
c. Provide data visualization tools	c. The system should be able to visualize geo-tagged content and sensor data	c. Visualization and collaboration components
d. Provide live mapping tools	d. The system should provide digital map representation	
e. Provide collaboration tools	e. The system should represent data using various visualizations techniques/types	d. External services components
f. Provide an easy to use system	f. The system should provide data filtering capabilities	e. Server and data aggregation components
g. Affordable cost of hardware	g. The system should have a content repository	f. Data repository components
h. Multiple application support and easy integration	h. The system should have a mobile and web interface	

The requirements identified in Table 5.1 have been addressed in our research efforts (see for e.g. Papers I and II), where we have proposed several solutions starting from the system architecture (see Figure 5.3) and its overview. The aim of the proposed system architecture is to understand the rationale behind the architectural choices (based on the content of Table 5.1) and perspectives, with the integration of a set of hardware and software components into our system. In our earlier implementations, from the perspective of heterogeneous devices and services based on SOA that had different computational capabilities, the best approach was to use an n-tier architecture [87]. This approach offers flexibility in distribution, where the tiers can reside anywhere, such as in mobile or desktop clients to servers or services provided through a network. Thus, the design of the initial system architecture (Figure 5.3 and as presented in Paper I) has been inspired by an n-tier approach. From a software and web engineering perspective, a client-server architecture is a special instance of n-tier architecture [37], in which the presentation, logic, and data tiers are logically three separate processes, as described within the mobile and web engineering section in Chapter 2. In the proposed architecture, resources are organised into different building blocks that integrate sensors, mobile units, server side components used as data and content storage, and visualization components that utilize diverse web APIs. The numbers presented (3a, 3b, 3c, 3d, 3e and 3f) within the blocks of the proposed system architecture in Figure 5.3 relate to the architectural requirements introduced in Table 5.1. In the current design of the architecture, instances of the “data aggregation” and “data repository” components were applied to the same block of the architecture in the “server” block. Nevertheless, they could be implemented as independent components residing in different blocks.

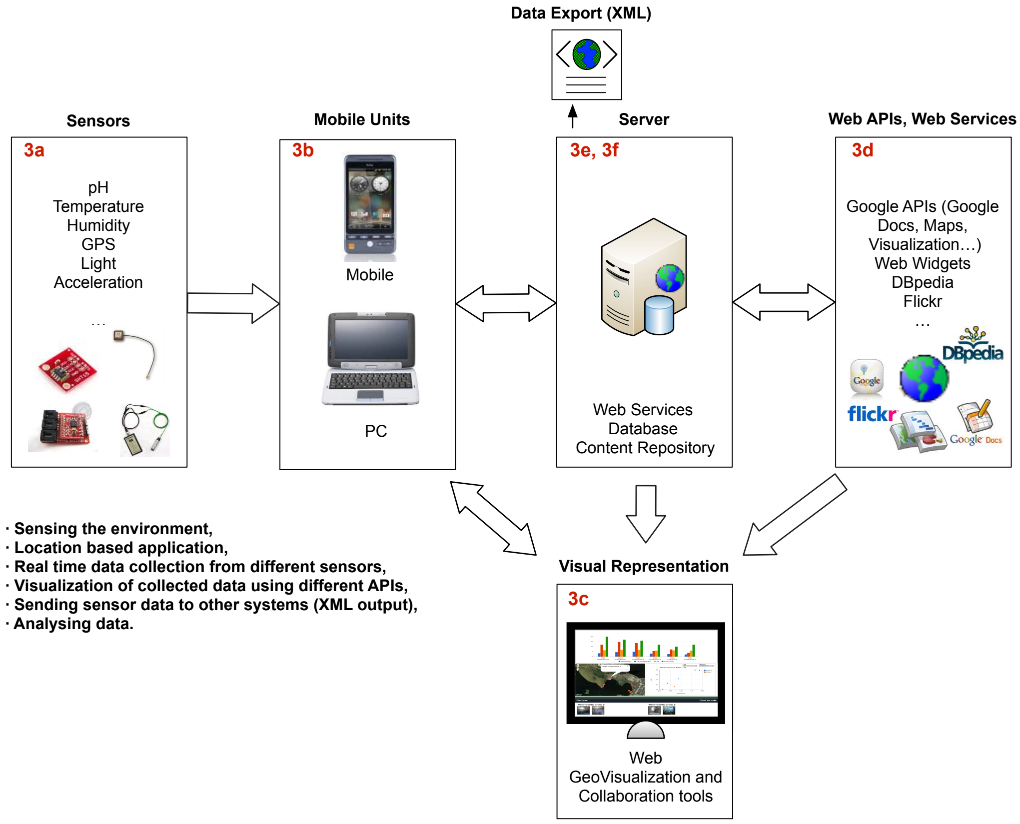


Figure 5.3: Initial system architecture.

In Figure 5.3, the initial system architecture shows that stakeholder requirements are transformed through the architectural design and process of analysis into various software and hardware components. Some of the challenges identified from the architectural design process are data serialisation and interoperability between different components and blocks of the proposed system architecture. In the following section, different requirements from Table 5.1 are mapped with the components of the architecture in Figure 5.3, with an instantiation of three implementation and deployment stages.

5.2. System Implementation and Deployment

The following subsections summarise the efforts in the form of three development stages, as introduced in Chapter 1 of this thesis (Figure 1.3). Overall, this section addresses implementation and deployment issues such as requirements, instantiation of architectural models, integration, interoperability and service-oriented approaches.

5.2.1. First Development Stage

The first prototype for the software system followed the requirements identified and the initial system architecture proposed. As a result, there was a need to implement different software components and integrate several hardware resources, as illustrated in Figure 5.4. An application for a Windows-based *smartphone* with built-in sensors (camera, location) was developed for observation and data collection purposes. A *Pasco Spark Device* with a built-in interface and various sensors were used for the collection of sensor data, such as pH, temperature, humidity, etc. The *Livescribe* digital pen that digitises the users´ notes and records audio was also used for data collection and the recording of discussions conducted during the field investigations. The final component is the *visual representation* block, which was used to tailor different geo-tagged sensor data and digital content. This component is utilized to support analytical thinking (e.g. reflection) using multiple representations (graphs, maps, data tables, etc) and for developing scientific arguments from the data.

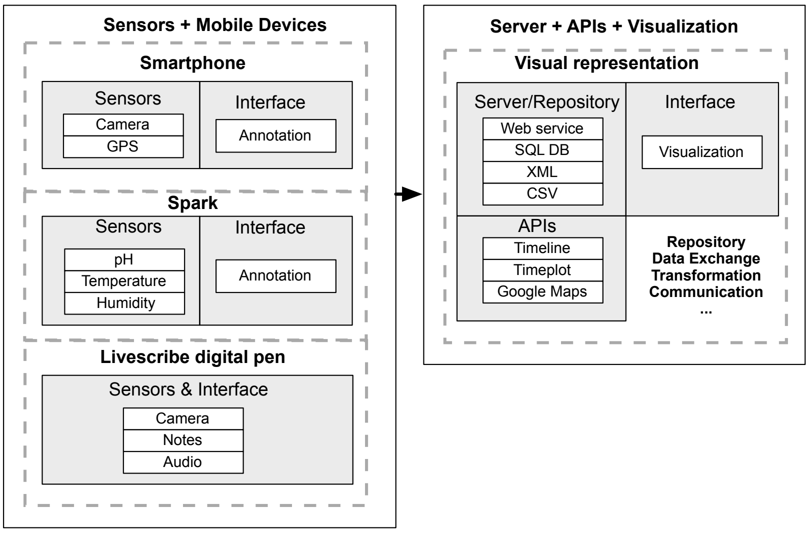


Figure 5.4: Implementation overview – first development stage.

The first mobile prototype was implemented using .Net C# and was deployed in several mobile devices running Windows mobile, which served as data collection tools. The mobile application supported several options for field and lab work. It was connected to the SQL database server, from where it loaded the predefined dataset into the form. This mobile application offered support for geo-tagging images with a built-in GPS sensor. The content created in this manner was enhanced with different sensor values, with the integration of a Pasco Spark Device using pH, temp, humidity, etc. These values were stored as unique objects in the content repository. Besides automatic tagging by the built in sensors, the application also supported users making their own annotations. These aspects of geo-tagging and sensor-enriched content were very useful for visualization purposes. The infrastructure consisted of HTTP requests and response commands by integrating multiple web services to allow requests and responses to pass easily across applications. In this particular implementation, XML and JSON were used as the data interchange formats. An instance of the Microsoft SQL database has also been used as a data and content repository. The visualization tool enabled the visualization of different geo-tagged content and sensor data. It offered the possibility of interactively exploring the gathered data using two visualization techniques: timeline and timeplot. These two techniques were integrated with Google Maps APIs in a dynamic manner.

This software prototype was only tied for one particular platform and was piloted with 8 users. The main drawback of this prototype was that it only worked in an online mode and was not flexible and able to be extended for other user activities. However, the main concerns identified with this prototype were related to interoperability, in terms of the manual synchronisation of data. While the first set of technologies (during the first development stage) was mostly customised and developed for one particular platform (Windows Mobile) and activity (soil quality); changing it to a different user activity (for example to water quality) posed new requirements that forced us to explore alternative solutions.

5.2.2. Second Development Stage

The idea of the second development stage was to make the software system more interoperable and flexible (as further requirements emerged for conducting user trials with different sets of activities and settings). Each of the devices used in our first development stage had, to a large extent, a closed system approach that restricted its development. In our case, for example, the scientific sensors system typically provided data in a binary format that needed to be appropriately serialised and decoded in order to obtain the sensor values correctly. We therefore considered that data interoperability needs to be supported by open standards in order to provide a more flexible and interoperable software system, especially when it comes to mobile and web based applications.

The design and implementation during this stage was followed with the integration of an open source Java based project into our software system [88]. This project/solution supported the use of a particular open standard named XForm. XForm is a standard based on a W3C recommendation that is used to build web forms for the easy exchange of data across platforms and devices using XML as the data format. The design of the forms for mobile applications was developed following the requirements identified from stakeholders, as introduced above. The solution based on Open Data Kit (ODK) supported various types of data and content inputs, such as text, audio, pictures, video, visual codes and GPS, which made it possible to annotate the collected sensor data and content with location metadata [88]. Moreover, ODK Aggregate provided the server companion that runs on the Google App Engine and was used to host XForms, as well as for storing the collected data submitted from the mobile devices. The use of XForms facilitated data interoperability across a diverse range devices and applications that compose our system. We have therefore developed several mobile forms that rely on the use of open standards, which provided us with flexibility, fast development and easy adaptation and integration of technological resources for different scenarios (user trials). The system overview that describes the integration of the components and resources used in this implementation is illustrated in Figure 5.5.

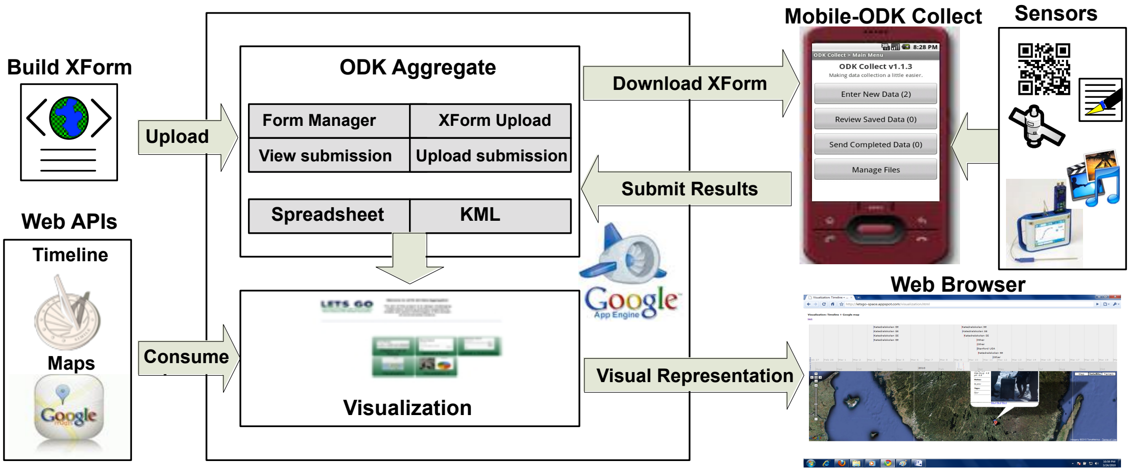


Figure 5.5: Implementation overview – second development stage.

The web-based visualization tool developed utilizes several web APIs. We have implemented two visualization components that include a timeline and Google maps that use XML and JavaScript API, provided by the Simile project at MIT (http://www.simile-widgets.org/). The visualization tool made use of the data collected by the mobile application that was stored in App Engine and Google spreadsheet format. The tool allowed users to select geographical data and filter them dynamically using a timeline.

This second stage of development, compared with the first stage, made our technology implementations more flexible. It provided us with easy exchange and sharing of data between diverse systems, and therefore offered flexibility to start visualizing the data using web-based service-oriented approaches. This solution also supported the work of the system (the mobile part), both in an online and offline mode. The mobile part of the system was successfully integrated with an external web-based system as described by Milrad et al. [89].

5.2.3. Third Development Stage

In the third development stage, we took advantage of the interoperability facilitated by XForms and mainly focused our efforts on the visualization part that integrated all the data and content generated in a unified user experience.

The latest version of this tool enables the visualization of different types of geo-tagged content and sensor data collected using mobile devices. It also utilizes APIs that provide multiple visual representations of the data set. These representations allow users to actively interact with graphs, maps, images, and data tables. Figure 5.6 depicts the visualization components and the implementation overview that have been integrated into the third prototype.

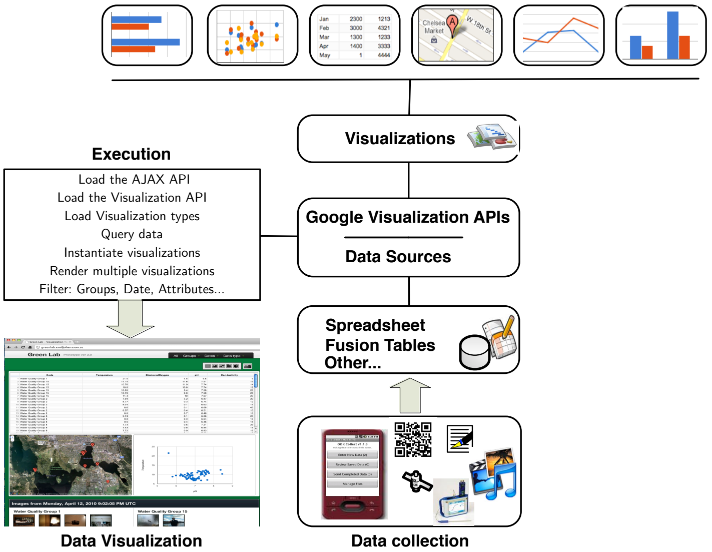


Figure 5.6: Implementation overview – third development stage.

Three core libraries of Google Visualization API were included and loaded onto the tool. The data (which previously has been uploaded via mobile devices) was queried from the spreadsheets in the remote server in order to visualize them. After loading the libraries and querying the data, the chosen visualization representations (e.g. scatterplot, line chart, etc.) are instantiated. Finally, multiple representations are rendered in this prototype. We have also implemented several filtering mechanisms, according to date, group and attribute (data type). The data represented in the data table sorts the values in an ascending or descending order.

An important issue to mention during this development stage is related to the rapid changes of technologies (software technologies and techniques based on the Internet), there was a need to cope with those changes during the design and implementation processes. One of the aspects that we started to make use of with regards to these technological changes was that our system completely moved to a cloud infrastructure.

5.3. System Assessment and Web Usability Testing

The three development stages made our software system more robust as a product compared with the earlier implementations described in section 5.2. A usability study was conducted for assessing the web-based visualization tool since it aggregated and presented the entire data collected using mobile devices. Assessment and testing of the web-based visualization tool was an important issue, in order to identify usability aspects that resulted in a number of concrete suggestions for the further enhancement and improvement of our visualization tool.

As identified in Chapter 2, applying usability evaluation to such tools and applications throughout the whole development process still remains challenging. For assessment and testing purposes, we made use of usability evaluation methods in order to verify and understand whether the design and implementation of our system fulfilled the user requirements.

The process for conducting a usability study includes a complementary approach that combines heuristic evaluation and user testing methods [85]. A heuristic evaluation approach has been used during the three cycles of the prototyping process of the web-based visualization tool as mentioned earlier. This evaluation was related to the systematic inspection of a user interface performed during the different testing (piloting) and development stages. Heuristic evaluation represents the *first step* of the cyclic evaluation process.

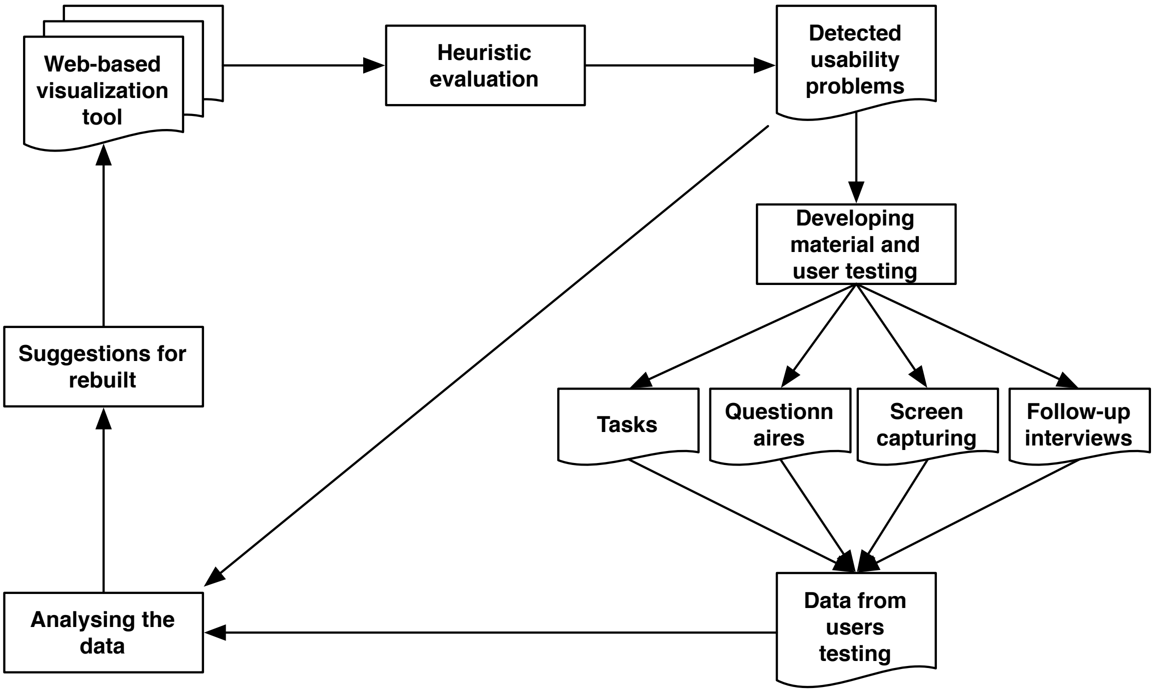


Figure 5.7: Cyclic evaluation process.

Throughout this user testing of the web-based visualization tool, the cyclic evaluation process is closely followed as described in Figure 5.7. Inspired by the work of Harms and Schweibenz [85], the *second step* of the evaluation process (developing materials and user testing) is modified and extended by including screen capturing and follow-up interviews as additional techniques for collecting data that may help further identify usability issues. In our user testing study, 18 university students were involved (for more detail see Paper IV). The tasks developed for this study were divided into different categories in order to assess the functionality, navigation and interactivity of our tool. The developed materials such as tasks and questionnaires are presented in Appendices B and C.

Figure 5.8 represents the overall results of the questionnaire. The bar chart presents the mean for each task as answered by the participants, and the error bars present the standard deviation for each task. The results suggest that the overall mean derived from all tasks is 4.2 with an overall standard deviation of 0.721. The overall confidence interval was ± 0.33 and the range for the true population mean falls from 3.87 to 4.53.

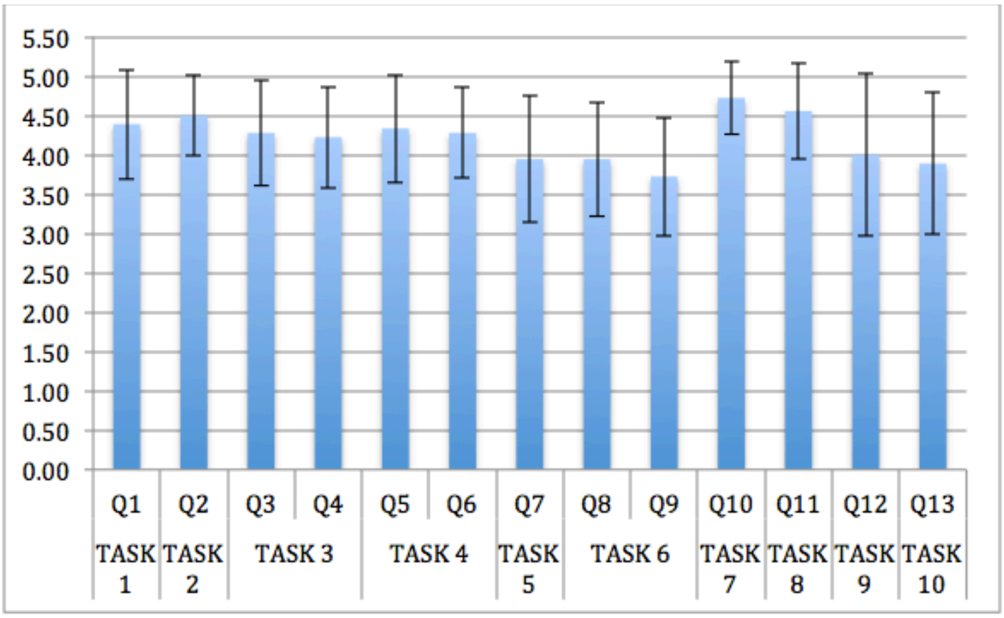
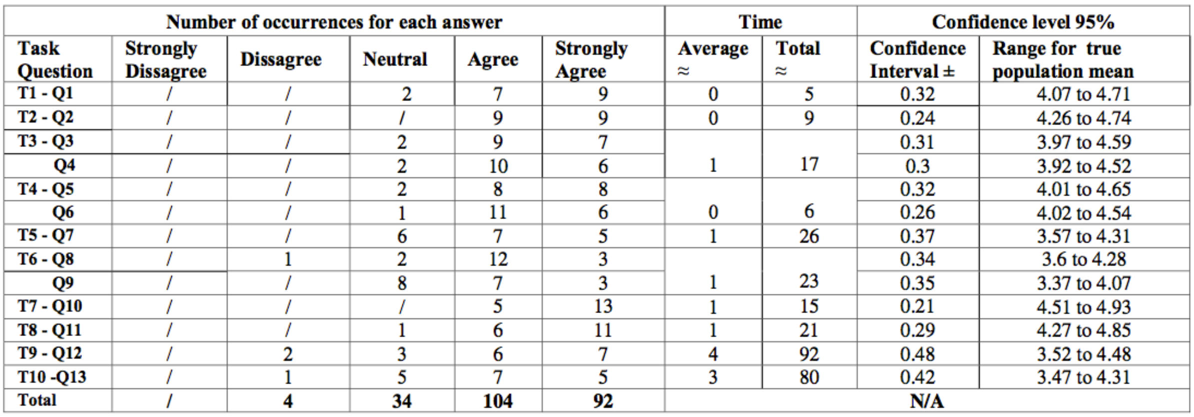


Figure 5.8: Questionnaire/task results.

Although the overall results show a high level of satisfaction of the users, we have identified, especially from Tasks 9 and 10, that there were usability issues. The purpose of these two tasks was to perform activities that include finding, navigating, analyzing and annotating data. In this regard, participants were required to obtain individual values using the visualization tool and afterwards to annotate this data (make notes). In these two particular tasks, we got the highest standard deviation values from the questionnaires.

To further investigate the reasons behind the higher standard deviation values with regards to Tasks 9 and 10, beside the questionnaires, we carried out cross-reference analysis relating the number of occurrences of answers, the timing required for accomplishing the tasks and a calculation of the confidence interval for each question. These results are presented in Table 5.2 and indicate that the number of occurrences for ‘strongly agree’ and ‘agree’ was relatively high. In particular, Table 5.2 presents the number of occurrences for each of the answers, the approximate time (≈) required to accomplish a task and the confidence interval. The sign “/” in this table represents that none of the participants answered, and “0” means less than one minute. There is a difference in the time spent between Tasks 9 and 10 in comparison with the others. The total time spent on Task 9 for all participants was 92 minutes, with an average time of 4 minutes per participant. The total time spent on Task 10 was 80 minutes, with an average time of 3 minutes per participant. Other tasks were performed on average in one minute or less. Furthermore, the confidence interval for Task 9 was ± 0.48 with the range for true population mean from 3.52 to 4.48. This interval was ±0.42 for Task 10 with the range for true population mean from 3.47 to 4.31. These results clearly indicate usability issues of the tool related to the aspects of interactivity, navigation and orientation. Furthermore, they gave us an indication that there is a need to further analyze the data in order to obtain a better understanding of the results that emerged during the user testing. Therefore, we followed up with an analysis of the screen recordings captured during the user testing study and follow-up interviews, with the intention to further strengthen the results and analysis of our study. For further results regarding this user study refer to Paper IV.

Table 5.2: Overview of collected data.



Number of occurrences for each answer						Time		Confidence level 95%	
Task Question	**Strongly Dissagree**	**Dissagree**	**Neutral**	**Agree**	**Strongly Agree**	**Average ≈**	**Total ≈**	**Confidence Interval ±**	**Range for true population mean**
T1 - Q1	/	/	2	7	9	0	5	0.32	4.07 to 4.71
T2 - Q2	/	/	/	9	9	0	9	0.24	4.26 to 4.74
T3 - Q3	/	/	2	9	7	1	17	0.31	3.97 to 4.59
Q4	/	/	2	10	6			0.3	3.92 to 4.52
T4 - Q5	/	/	2	8	8	0	6	0.32	4.01 to 4.65
Q6	/	/	1	11	6			0.26	4.02 to 4.54
T5 - Q7	/	/	6	7	5	1	26	0.37	3.57 to 4.31
T6 - Q8	/	1	2	12	3	1	23	0.34	3.6 to 4.28
Q9	/	/	8	7	3			0.35	3.37 to 4.07
T7 - Q10	/	/	/	5	13	1	15	0.21	4.51 to 4.93
T8 - Q11	/	/	1	6	11	1	21	0.29	4.27 to 4.85
T9 - Q12	/	2	3	6	7	4	92	0.48	3.52 to 4.48
T10 -Q13	/	1	5	7	5	3	80	0.42	3.47 to 4.31
Total	**/**	**4**	**34**	**104**	**92**	**N/A**			

Throughout this study several important issues have been identified related to the experience in conducting a user testing study that can be summarised as follows:

(a) In order to assess the web-based visualization tool (or other related web applications) several usability aspects are identified that can be considered for conducting a user testing study:

1. Application functionality,
2. Navigation (easy to retrieve and to browse content),
3. Interaction mechanisms and satisfaction of the users that use the web-based application.

These three categories are related to the overall design and implementation processes and requirements of a web-based application. These would help verify whether an application allows the users to invoke the available services, navigate the content, and perform specific operations and tasks in a satisfactory manner. More specifically, the overall material developed helped us assess the web-based visualization tool in terms of application functionality (searching, note taking), navigation (use of filtering panel, picture navigation) and interactivity (orientation, browsing of content), and the stakeholder requirements derived from our earlier developments.

(b) Another issue identified in this study is related to data collection techniques that include observations, tasks and questionnaires, analysis of screen capturing, and follow-up interviews. Such techniques were very helpful for obtaining more reliable results, and seemed to be reasonable for acquiring better results in designing and implementing functionalities that addresses the users' needs.

(c) The quantitative data gathered from user testing, and by analyzing the data using descriptive statistics such as calculating the mean, standard deviation and confidence interval are very useful for identifying usability aspects.

(d) Cyclic evaluation process in combination with prototyping processes seems to be a suitable approach for conducting user testing studies related to web-based applications.

(e) Validating different aspects of the web-based application with regards to the application's functionalities, navigation and interaction mechanisms, may result in potential suggestions for the rebuilding of the tool based on these categories/aspects (see Paper IV).

5.4. Evolution of the Software System Across Design and Implementation Stages

During the three years of development efforts three prototypes of the software system were implemented by utilizing service-oriented approaches for supporting TEL activities in the context of inquiry learning. These prototypes of a software system evolved from being a standalone application towards combining several Internet-based services to process and visualize the geo-temporal data collected using mobile data collection tools, as already introduced in the previous sections. In the first development stage, the first prototype has been mainly implemented using static forms for mobile and desktop enabled visualization features and did not provide real time data representation. During the second development stage, and due to the evolvement of requirements, the second prototype resulted in a combination between more dynamic forms for mobile (XForms), desktop and web technologies and included initial cloud services. This combination enabled data collection in both online and offline modes and real time data representation. Finally, during the third development stage the last prototype of the visualization completely relied on a cloud environment (real time and online).

Overall, the prototyping cycles during the three development stages were carried out following the principles of requirements engineering. The development of the prototypes, their different cycles and their features were related to the six phases of cloud application development, as proposed by Hosono et al. [90], as presented in Table 5.3.

Table 5.3: Cloud application development phases, taken from [90].

Cloud Application Development Phases	
Phase 1	Designing application
Phase 2	Implementing application locally
Phase 3	Simulating application locally
Phase 4	Deploying application to cloud environment
Phase 5	Staging it on cloud environment
Phase 6	Operating application on cloud environment

During the prototype development, a high-fidelity principle is used, that is usually user-driven and where the requirements have already been tested in an early stage of the development. The first *four phases* of cloud application development were mapped during the first two prototyping cycles (first and second development stages).

The first prototype comprised of the first *three phases*, whereas the second prototype covered the *fourth phase*. Testing of the prototypes in a local environment and then its deployment in the cloud followed these implementations.

Finally, the third prototype resulted in the deployment on a cloud environment using Google Services. The third prototype launched *phases five* and *six* of the cloud application development, as introduced above. Even though, the efforts made to refine and maintain the system continued while operating the application in the cloud. The prototyping efforts have been carried out as a part of the different stages of the web development cycles, inspired by [83]. Figure 5.9 presents the timeline overview of the different development cycles and stages of the software system by using the prototyping approach.

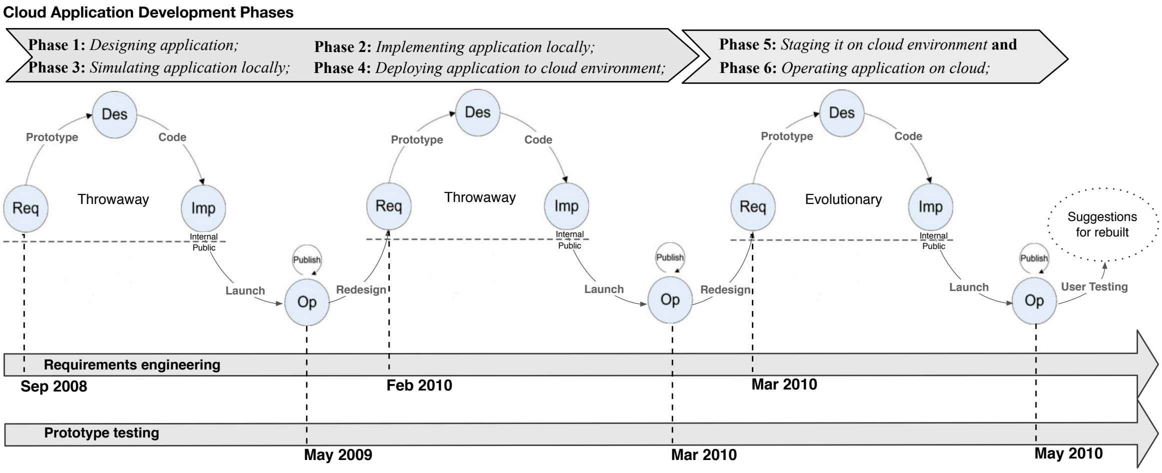


Figure 5.9: Cyclic prototyping efforts across a timeline[6] related to requirements and testing, and cloud application development phases.

This figure illustrates how the prototyping cycles within the different phases of cloud application development are complementary. The requirements engineering, and prototype testing timelines are presented in relation to the last two years of development. Moreover, the development time of the first prototype (Sep. 2008 – May 2009) has been dramatically shortened in the second prototype (Feb. 2010 – Mar. 2010), mainly due to the utilization of open standards for data exchange.

The features of the cloud environment and services made the system more flexible. Initially, traditional desktop-based integrated development environments were employed and development then gradually moved towards a mashup-pattern that combined different service-oriented approaches. One identified issue was that the rapid speed and evolution of web-based technologies affected the development process and the application itself. For e.g., in one particular implementation case Google adopted an open authorization protocol (OAuth) [91]. This was the case that resulted in our system not functioning, hence we needed to follow and implement new authorisation methods into our solution. This means that Internet-based services have advantages but also drawbacks, since a developer always needs to cope

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[6] Note that the timeline is presented in a nonlinear scale.

with the latest technological changes and developments, if the implementation relies on others services. Therefore, five important aspects are concluded and discussed:

(1) There is a need to combine throwaway and evolutionary prototyping in order to cope with the rapid speed of developments with respect to software technologies and techniques offered over the web. Throwaway prototypes can be a valuable that help refine conceptual ideas related to the design of the software system. Evolutionary prototypes are more functional (closer to a final product) and can continuously evolve. This latest feature can represent an important advantage when it comes to maintaining software components and applications that rely on a cloud infrastructure.

(2) The different phases of cloud application development can be matched with prototyping efforts (by also involving users, analysis and rebuilt cycles) in order to be able to closely reflect the users' requirements and their dynamic needs, and to integrate some of them in order to cope with rapid changes in web technologies.

(3) Prototyping cycles may be useful in order to find a balance between the evolution and development of the software system by considering these rapid technological changes (Internet-based services) throughout the implementation process.

(4) Open standards offer a high degree of flexibility in terms of designing mobile forms for various scenarios and data exchange for facilitating visualization, thus enhancing interoperability between different applications. Moreover, in our case open standards clearly reduced the development time.

(5) User testing has been the last stage of this iterative development cycle, which enabled the identification of key functional deficiencies across the three development stages of the software system.

Due to the rapid changes in and with respect to the long term running of the software system, it is not always good to rely on third party functionalities and services. One might consider creating or setting up one's own (private) cloud service or similar, that enables you to have control over different parts of the software system and its components.

During the last three years, three stages of the development lifecycle of the software system have occurred. The developments have evolved and changed rapidly, such as in terms of the design and technology choices and implementation, software and hardware components. Despite the rapid changes of such technologies these developments have not been reflected in the changes in the architecture of software systems. The components identified in Figure 5.3 and Table 5.1 proved to be valid throughout the three iteration cycles. These iterations of Figure 5.3 have resulted in the refinement of the initial system architecture. Figure 5.10 illustrates the component view of the system architecture and potential for expandability with other technologies and external systems.

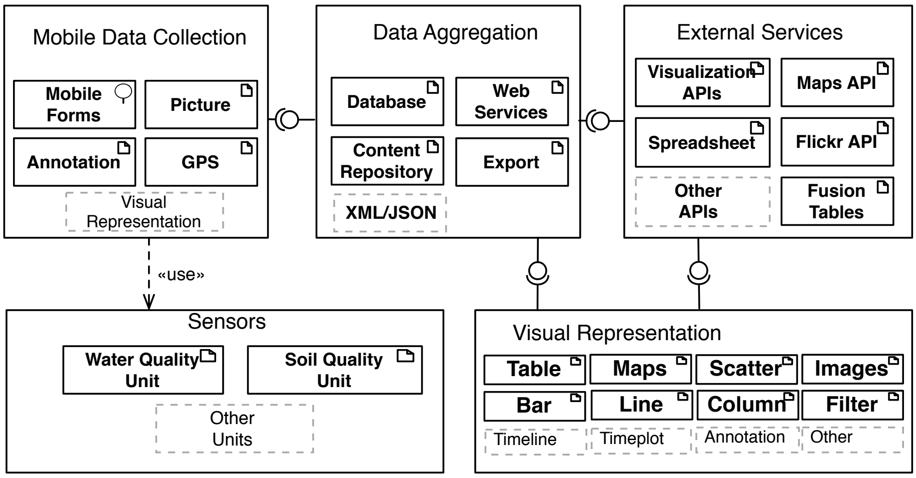

Figure 5.10: Refined initial system architecture including main resources and components.

For describing the flow of steps in the latest software system, Figure 5.11 presents the activity diagram for understanding and verifying the system architecture and its design. A user designs and builds a form for data collection and uploads it to the data aggregation. Afterwards, the designed form is downloaded to the mobile device, followed with data collection related to geo-tagged sensor data and content, and finally its submission takes place. Usually, visualization consumes the aggregated data and processes it for representation and analysis purposes using various options.

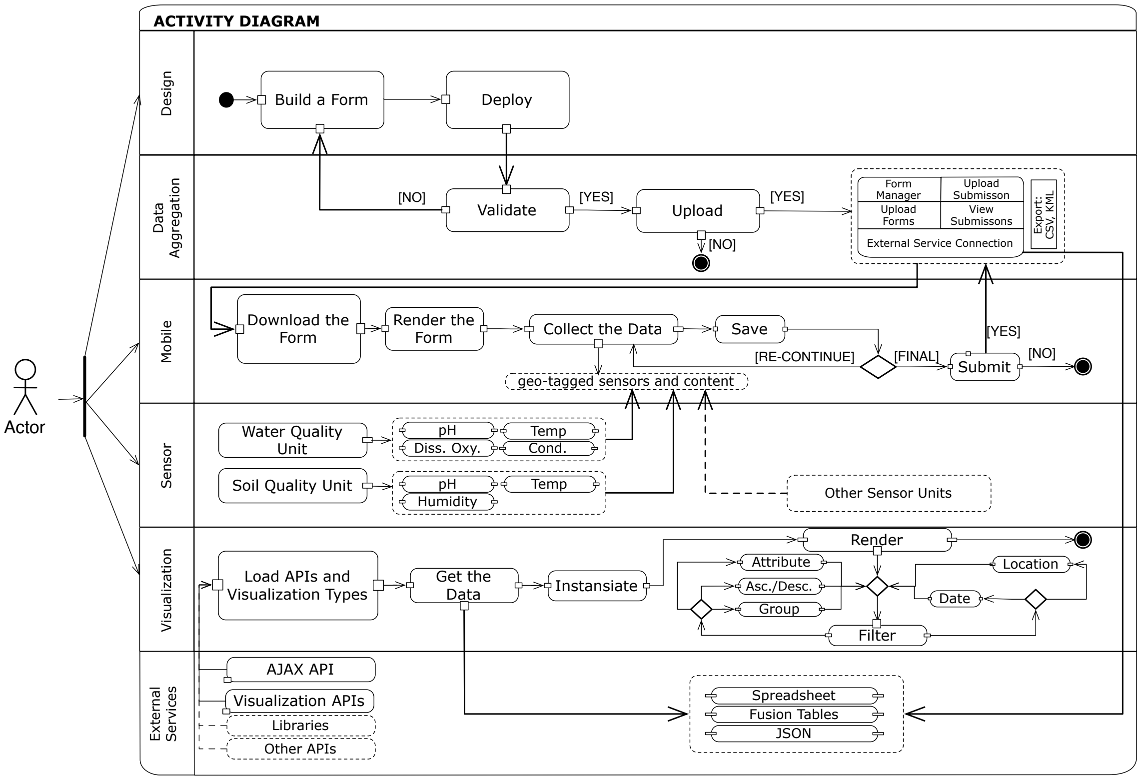

Figure 5.11: Activity diagram.

In the following section, the synthesis of the research findings is presented in the form of architectural concepts that may result in implications for guiding the design and implementation of a software system.

5.5. Architectural Concepts

The three design and implementation stages facilitated the identification of the main features in terms of guiding the design and implementation of the software system. This is achieved by identifying some implications labelled “Architectural Concepts”, in terms of the overall structure of the software system. The idea behind Architectural Concepts is to provide a set of tools for supporting the overall lifecycle of a software development process, such as the requirements, design, implementation, deployment and testing, while coping with rapid changes in technology implementation. To argue that such implications are necessary for one to develop such a software system, we found that the state of the art projects lacked some of the concepts and notions that have been explicitly introduced in this thesis.

As introduced earlier, our design and implementation are composed of diverse concepts, starting from system architecture (an n-tier approach) towards deployment in the cloud, and finally its testing in different settings. Reflecting upon the latest evolution in software technologies based on the web, Object-Oriented (OO) application development combined with scripting languages facilitates rapid application development. An advantage of using both programming paradigm elements (OO and Scripting) concerns its flexibility when it comes to incorporating web-based service-oriented approaches. However, when it comes to the integration of different components and applications, the main challenge with which we have dealt in this thesis is interoperability. Interoperability must be considered while designing and implementing a software system. This becomes particularly evident in software systems that integrate different software and hardware components, such as sensor and mobile devices and web technological applications. One way of dealing with interoperability is by utilizing open standards. Open standards in this research facilitated the development of interoperability among diverse technological resources, by making our system more flexible and expandable. Open standards tackle the issue of the fragmentation of the operating systems, various devices for data collection and browsers by having a more standardised approach for data exchange. In this regard, with open source models you can build “open standards as actual software” by providing “higher security, reliability, flexibility and higher quality if compared to a closed software system” [92].

When it comes to the deployment of the application, one good way is to simulate it locally and afterwards deploy it in the cloud infrastructure, from which the maintenance of the application is much more flexible. Another important issue identified in this research is that during the application development the use of cyclic prototyping process becomes necessary, by following the web development lifecycle. According to Gorton [82], prototyping is typically used for two purposes:

(a) Proof-of-concept: *Can the architecture as designed be built in a way that can satisfy the requirements*?

(b) Proof-of-technology: *Does the technology (middleware, integrated applications, libraries, etc) selected to implement the application behave as expected*?

These two questions in this thesis are answered in two ways:

1. Following the cyclic prototyping approach, the discussion of ideas, designs, requirements and implementation possibilities with stakeholders becomes more easily manageable and understandable. For testing the technical feasibility and understanding whether the technology and implementation behaves as expected, cyclic prototyping (by combining throwaway and evolutionary approaches) offers an easy and communicative way to present the prototype and test it on real time activities and in authentic settings.
2. During the user trials the prototype testing allows requirements engineering to evolve flexibly towards constructing a final product [84], where different iterations and tests are conducted in a cyclic manner, in order to verify and satisfy the stakeholder requirements.

During the prototyping iterations of the application, assessment and testing is another important concept within the software and web engineering research community when it comes to the assessment of web-based applications. As introduced in the foundations chapter, there are two important dimensions for conducting this process: 1) testing of the code and architectural failures while developing it; and 2) usability evaluation of the application that is related to the users' needs and their requirements [36, 70, 71].

Our research efforts introduced several challenges, mainly interoperability issues, open standards, cloud services, cyclic prototyping, and user testing, which we have faced during our development phases over the last three years. These challenges comprise the possible implications towards web and mobile application design and implementation. These implications are formulated in the form of Architectural Concepts, as introduced earlier. Architectural Concepts are characterised by several concepts that might be essential to be considered during the application development phases. These are mainly architectural models, programming paradigms, enabling services, interoperability considerations, deployment and maintenance, development methods, user trials, and finally the assessment of the quality of such an application. Enabling services in the context of this thesis means services such as SDKs, frameworks, Internet-based services, APIs and so on.

These concepts have evolved during the three development stages from the refinement process of the initial system architecture. Architectural Concepts in this aspect represent the implications for supporting the overall lifecycle of a software development process. In Table 5.4 the main findings are listed as key concepts, and several instances and/or approaches of the Architectural Concepts. These concepts are related to the main research question that are valid to identify the main features that may result in implications to guide the design and implementation of a software system for supporting inquiry learning in different contexts.

Table 5.4: Implications.

Architectural Concepts	
Key Concepts	**Instances and/or Approaches**
Architectural models	n-tier architecture, System architecture,
Programing paradigm elements	Object oriented, Scripting,
Enabling Services	Wep APIs, Web Services, SDKs, Cloud Services,
Interoperability considerations	Open standards, Open Source,
Deployment and Maintenance	Local simulation, Cloud infrastructure,
Development methods	Cyclic prototyping, Web development life cycle,
User Trials and/or Stakeholders	Requirements engineering, Prototype testing,
Assessment and Testing	Cyclic evaluation, User testing.

Architectural Concepts could implicate and serve as a guide during the development process of mobile and web-based applications. Following these recommendations, they may enable the designers and developers to address the challenges during their development process, which emerge as a result of rapid changes in mobile and web technologies. Therefore, these would help the system to become better and more robust, and interoperable with other systems. Such a system will become a more standard-based system, which means it is more open to other systems for the easy exchange and integration of data and services. Thus, the development process might be reduced with respect to time and costs. Besides reducing the time for the developers, it allows the re-use of existing services, which requires a shorter time than developing a new one, which in turn also reduces the costs for an organisation. Thus, the infrastructure components of the system will not only be tight to one project or platform, but will make components more reusable. Another important issue in such software developments is that the requirements of the users are continuously considered and tested during the design and implementation process. Therefore, the system might have a greater usability, and the maintenance stage might require less effort. The benefit in terms of the software development process is the constant interactions with users. In this case the software system matures as the usage and testing settings and/or activities change. Furthermore, the developers can verify whether the deadline and milestones of the software system or its modules are met for a specific user activity and/or settings.

These architectural concepts are verified and tested in the context of TEL that supports the user activities in an authentic setting, but that can also be applicable in other domains and fields, since the concepts and approaches introduced are more generic.

6. Conclusion and Future Work

Throughout the different chapters of this thesis, the integration of different technological resources (such as sensors, mobile and web technologies) were elaborated on, while designing and implementing a software system for supporting inquiry learning in different contexts. Below, three outcomes in relation to the goals presented in section 1.1 and challenges in section 2.3 are addressed:

1. A block architecture relying on service-oriented approaches and open standards facilitated interoperability among mobile, web and sensor components and technologies in a software system, as described in sections 4.1, 4.2, 5.1, 5.2, and in Papers I and II.
2. The adoption of cyclic prototyping with incremental development stages helped find the balance between the design and implementation of the system, while reflecting on rapid changes of software and web-based technologies, as described in sections 4.3 and 5.4, and in Paper III.
3. User testing techniques for the assessment and testing of the software system were employed in order to cope with the dynamic user requirements in the field of inquiry learning and TEL, as described in sections 3.3, 4.4 and 5.3, and in Paper IV.

An attempt to answer the research questions presented in section 3.2 will be reviewed and addressed in the following paragraphs. The answers to the research questions are presented in the form of bottom up approach. Before answering the main question, the two sub-questions first need to be tackled. The purpose is to bring the focus of this thesis into the discussion, with several conclusions. The first sub-question to be reviewed was stated as follows:

> **Q1** How to facilitate interoperability among mobile, web and sensor technologies by integrating them in the proposed system architecture?

To answer this question, an important issue to be addressed is that service oriented approaches facilitate interoperability through utilizing open source and open standards into the software system by following the evolution of cyclic prototyping, as described in Chapter 5. Furthermore, they clearly facilitated interoperability among mobile, web and sensor technologies for supporting data collection and analysis in the context of inquiry learning, as described in sections 4.1, 4.2, 5.1, 5.2, and in Papers I and II. During the three prototyping (three development) stages different technological solutions were integrated and implemented. The initial system architecture retained the same blocks and components, while various mobile, web and sensor technologies were integrated incrementally. To conclude, the use of visualization tools showed the benefits of utilizing the interoperability between the different technological resources described in this thesis.

The second sub-question to be reviewed was stated as follows:

> **Q2** How to utilize Internet-based services for visualization purposes and what are the potential benefits of such an implementation?

The three iterations during the development stages and testing presented in this thesis were conducted in a cyclic manner by using a prototyping approach. This approach was motivated by the design and implementation of a system in close communication with the users, including domain experts (teachers) and end users (students). First, the two prototypes consisted mainly of desktop (standalone)-based features. Explorations aimed at seeking more flexible solutions led us to identify cloud services as a potential alternative, where the third prototype was deployed. More specifically, these efforts were followed by the staging and operating of the final prototype in the cloud environment. This led to the more flexible and easy utilization of the data collected from mobile devices and the visualizations offered over the web (enabling services) within the software system, as described in sections 4.3, 5.2, 5.4 and in Paper III.

For identifying the benefits of such implementation, assessment and testing was necessary in this research. The validation of various usability aspects of the system related to application functionality, navigation and interaction mechanisms, may result in potential suggestions for the rebuilding of the system based in these mechanisms, as described in sections 4.4, 5.3, 5.4 and in Paper IV.

In considering the research problem, this thesis was guided by the following main research question, to be reviewed:

> *What are the main features that guide the design and implementation of a software system for supporting inquiry learning in different contexts?*

The main implications identified during the research efforts presented in this thesis were formulated in the form of Architectural Concepts, as described in section 5.5. These implications support the overall lifecycle of a software development process, such as requirements, design, implementation, deployment and testing, while coping with rapid changes in technology implementation. Thus, this software system supported various inquiry learning activities in authentic settings. Some of the Architectural Concepts identified in this thesis corresponded well with the kind of support that inquiry-learning activities require. They provided solid foundations in terms of the possibilities of tackling the requirements for supporting inquiry learning in a flexible manner. These concepts provide recommendations as they can be used to guide the design and implementation of web and mobile applications in order to support inquiry learning.

These concepts might be essential in the software development process throughout different phases of web and mobile application design and implementation. Thus, these implications could provide some potential benefits for academic research as well as for the Information Technology (IT) industry.

This research would contribute to both areas in terms of Architectural Concepts, by considering the latest web technological developments and cyclic prototyping, which enable constant testing, and the flexible gathering of requirements in an incremental manner. Architectural Concepts, especially for academic research as well as for the industry, might serve as recommendations that could contribute to the development process of new software systems or applications. Technological changes affect business, especially IT organisations. For the rapid changes to be smoothly reflected in research and business processes, there must be well-defined processes to ensure the continual refinement of the applications developed. The possible guiding of the mobile and web development, defining how IT organisations should implement technology, can maximise the benefits in terms of the long term goals, costs, time, and to satisfy customers with their product. Following the overall suggested implications of Architectural Concepts could lead to these potential benefits:

- Standard based system
- Constant interaction with users
- Incremental development
- Reduced time and costs
- Expandability
- Flexible change of technologies
- Higher usability
- Easy maintenance

Overall, the results suggest that by following prototyping, web development cycles and cloud application development, the software system becomes more robust compared with the earlier implementations described in section 5.2. These specific implementations, in turn, allow users to collect data, explore, analyze and reflect upon the real-time data they have collected in a more satisfactory manner. The development approach advocated in this thesis, enabled us to design and deploy a software system that is more robust, the components of which are more interoperable, easy deployable and flexible for supporting different user activities. In conclusion, the emerging platforms such as mobile and web developments are becoming integrated into a new platform that is more ubiquitous and flexible, and this pushes the web to act as a software platform. Nowadays, HTML5 and other related technologies show promising results when it comes to uniformity of Web APIs access and consumption. The latest will help to gradually move the web from being a document oriented platform towards a service-oriented infrastructure that relies on dynamic distributed components in the form of Uniform Web APIs.

The idea of this thesis was to discuss some of the main research efforts that have arisen from the last three years of research. The concepts and technology implementations throughout these development stages will further evolve into new concepts, ideas and implementations concerning my future research efforts towards the degree of a PhD.

6.1. Future Research Efforts

The conclusions presented in the previous section offer plenty of opportunities for future research. The focus of future efforts will primarily be on developing and implementing new features and functionalities to support collaborative activities with our software system. From a development perspective, we envision the possibility of enhancing new mobile and visualization tools based on interactive technologies in order to support synchronous collaboration between physically distributed users in indoor and outdoor settings. As identified by previous work, and according to the results, note taking and integrating collaborative data manipulation in the system by using big screen projections are part of the research agenda.

Therefore, the areas to be further explored in our future research efforts are related to mobile and web engineering and geo-collaboration (for geographic visual representations and collaboration purposes). One of the future efforts will be on exploring the possibilities of HTML 5 as an emerging standard when it comes to web and mobile development across diverse platforms and devices. The exploration of integrating interactive technologies (such as gesture-based interaction) into the software system has already been started. One such exploration has already been accepted as a forthcoming publication [93].

To validate the proposed idea for future research, solid scientific and investigation strategies are required. Expanding and validating the initially proposed architecture with new implemented features and components will be the primary focus of our forthcoming efforts. Therefore, some of the approaches used in this thesis will be further explored and used in future research. Finally, we envision conducting the evaluation process with large groups of users for validating and assessing our future technology implementations.

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Appendix A

Publications

PAPER I

Vogel, B., Spikol, D., Kurti, A, & Milrad, M. (2010). Integrating Mobile, Web and Sensory Technologies to Support Inquiry-Based Science Learning. Proceedings of the *6th IEEE WMUTE International Conference on Wireless, Mobile and Ubiquitous Technologies in Education,* WMUTE 2010 held in Kaohsiung, Taiwan, April 12-16th, 2010, pp. 65-72.

Best student paper award

The 6th IEEE International Conference on Wireless, Mobile, and Ubiquitous Technologies in Education

Integrating Mobile, Web and Sensory Technologies to Support Inquiry-Based Science Learning

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Abstract—**Recent advances in mobile, wireless, and sensor technologies provide new possibilities for supporting learning activities that can be spatially distributed and incorporate different physical and environmental sensory data. In this paper, we present our technical efforts in relation to the design and implementation of mobile and web applications that integrate sensory data used to support inquiry-based science learning. In order to test the validity of our solution and its functionality and novelty, we conducted a prototype experiment with high school students in the field of environmental sciences. The initial outcomes presented in this paper point towards the potential benefits of using sensor and mobile technologies with real-time geo-positioned data and visualizations, which may increase students' engagement, enabling them to conduct scientific inquiries and analyses in new ways.**

Keywords: context, visualization, inquiry-based science learning, mobile learning, sensor technologies.

I. INTRODUCTION

The rapid development in mobile, wireless, and sensor technologies provide new possibilities for augmented learning activities. These technology-enhanced learning activities can be spatially distributed and incorporate different physical and environmental sensory data [1]. In addition, sensor-based technology has provided new perspectives about how learning activities can be embedded in different settings and across contexts [2].

However, despite these technological advancements many challenges still remain related to the integration of different technological resources for use in broader educational scenarios. The efforts described in this paper are related to our ongoing research that explores the challenges related to the technological integration of different devices and sensors to support science inquiry learning. Thus, the main research question addressed in this paper can be formulated as follows:

How mobile, web and sensory technologies could be integrated to support science inquiry learning activities in the classroom and in outdoors settings?

This paper focuses on our design and technical efforts in relation to system and software (both mobile and web) development to support science inquiry learning with the help of different portable sensory devices. The paper is organized as follows: section two presents a brief background relating the importance of context in supporting learning and technology design. In order to position our work, section three provides an overview of related research contributions closely aligned with our current efforts. Afterwards, we introduce our proposed system architecture that guided the design and technological development in this research effort. This overview is followed by a description of a learning activity experiment in which the proposed system was used to provide support for science inquiry activities in the field of environmental sciences. The paper ends with a discussion and an outline of our future work.

II. THE MULTIPLE PERSPECTIVES ON CONTEXT

The notion of context and its implications for mobile learning has gained a lot of attention among members of the research community in the last years. A recent study conducted by Frohberg and colleagues emphasize how context can be used for the classification of mobile learning [3]. One of the main conclusions of their study was that "*mobile learning can best provide support for learning in context.*"

In our particular case, this statement supports the idea that mobile learning needs to be designed to promote active science inquiry learning across different educational situations. Mobile probes can augment learner investigations with real-time geo-positioned data and visualizations, which may increase students' engagement, enabling them to conduct scientific inquiries and analyses in novel ways. One innovative aspect of these new learning landscapes is the combination of learning activities to be conducted across different educational contexts such as schools, nature and science centers/museums.

This indoor-outdoor integration of mobile computing has expanded the important feature of *context awareness* into learning environments. From an educational viewpoint, *context awareness* refers to how the pedagogical flow and content in the different learning activities needs to be aware of the situations in which the learners are (e.g., geo-location, proximity to people and objects). From a technological perspective, context can be regarded as any information that illustrates the situation of a group of learners, including location, time, activities, and their preferences [4]. The crucial factor for context awareness is the possibility of capturing this broad range of contextual attributes [5]. These

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characteristics combined together with sensors that provide additional information about the current physical environment can serve as a good basis to support new ways of interactions between the users and the environment and for the visualization of spatially referenced/distributed data [6]. In the following section, we describe some related projects that have addressed the issue of context awareness to support science learning.

III. RELATED WORK

Recently, context sensing [7] has become an important line of exploration in the field of ubiquitous computing. There are a number of ongoing research efforts focusing on the development of context aware applications in the field of technology-enhanced learning. Education technologists in different research projects have explored the potentials of these technologies by combining visualization tools with context aware applications [8, 9, 10, 11 & 12]. A brief technical description related to a selected number of research initiatives that explored the use of sensors, mobile devices and context awareness to support science inquiry learning is provided below.

Hansen and Bouvin's HyCon framework [8] presents a supportive learning initiative with a variety of mobile technologies and software applications. This framework was developed to provide a platform for experiments with hypermedia mechanisms in context aware and mobile environments. HyCon is developed as a layered framework consisting of four layers: a storage layer, a server layer, a terminal layer, and a sensor layer. Furthermore, at the application level this framework aims to support several aspects of mobile learning activities such as field trips and problem-based education. This support is constructed by using different sensors to collect the context information that could be used to link, annotate, and tag different learning resources. In this manner, Hansen and Bouvin suggest that learners gained better learning experiences as a result of context aware features of the HyCon framework.

Another similar approach that addresses the issue of context awareness in inquiry-based learning activities is the ButterflyNet project developed by the Stanford HCI Group [9]. This project is built upon a n-tier architecture that deals with data capture, structure, access, and transformation. Resources in this architecture are visual codes, digital pens, cameras, GPS devices, and audio and video recorders. In the application domain this project supports inquiry learning in biology. An interesting feature of this project is the ability to visualize notes captured with a digital pen during inquiry activities.

Hwang *et al.,* [10] have additionally advocated the use of context awareness systems to support learning in complex scientific experiments. In their project implementation of context awareness, support is based upon a distributed system and includes the help of an expert system. The authors of this paper suggest that adaptive features of such a system provide benefits to the learners while experimenting in complex scientific domains.

The use of sensory information with mobile devices to support learning activities has been reported by Silva and colleagues [11]. In their work, they provide a lengthy list of different research projects that explore the spatial and sensory dimension of the environment with educational benefits. They conclude that it is very important that the use of the mobile technology in learning should be accompanied by an emphasis on space and sensing to achieve an engaging learning environment.

In the Personal Inquiry project, Collins and colleagues [12] have developed and introduced a system that supports location-based inquiry learning across school, field and home contexts using mobile, sensor and web technologies. They present the design of technology-supported inquiry activities and how to develop flexible, re-usable tools to support and bridge sequences of activities. They also discuss how the use of digital maps and the visualization of sensor data can be used for bridging representations across field and classroom activities.

With reference to the above-mentioned work, we have identified a couple of deficiencies in the existing approaches that require further research attention. The main deficiencies that we consider worth researching are: *lack of full utilization of the sensory data to support the inquiry processes*, and *not fully developed tools for visualizing sensory data to support learners' reflections about their inquiry process*. Another interesting research issue is the extensibility of such systems when it comes to different open systems and available APIs (Application Programming Interfaces) on the Web. In comparing our research efforts with the above-mentioned projects and the identified deficiencies, our approach tries to utilize and visualize sensory data to support different learning processes in the cycle of inquiry science [13]. We have designed and implemented a software system to enable wireless and sensor technologies to connect with mobile and other computational devices in order to provide alternative ways to support science inquiry learning. In the next section we present the major components of our proposed system architecture.

IV. OUR PROPOSED SYSTEM ARCHITECTURE

This section presents the overall system architecture, which includes an overview from a high-level perspective to a low-level perspective of a set of hardware and software components. With reference to the deficiencies identified in the related work section and from several basic functional requirements identified during the design phase (see [14] for a detailed description of these requirements), we have developed the system architecture illustrated in Figure 1.

Our proposed system architecture consists of five different blocks. The blocks used to construct this architecture aim to provide some logical divisions of the resources in the system. The architecture organizes available resources into the following blocks: sensors, mobile devices and the transmission of sensor data, repositories, external APIs, and visualization. It provides a complete lifecycle showing how data can be stored, exported, shared, and visualized. Our primary idea is to develop a generic architecture that can be used to support different aspects of inquiry science learning.

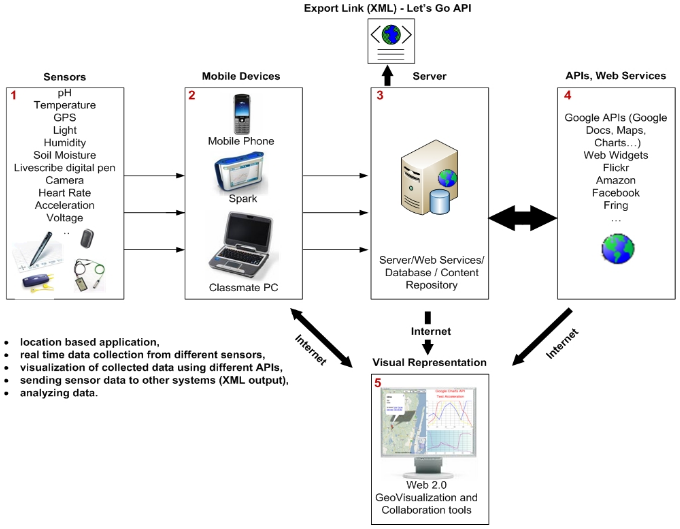


Figure 1. Proposed system architecture

Grigera and colleagues [15] suggest that context-sensing issues need to be addressed from a software engineering perspective and not as a simple implementation issue. Thus, the design of the suggested architecture has been inspired by an n-tier approach. From a software engineering perspective, a n-tier architecture is a client-server architecture [16] in which the presentation tier, logic tier, and data tier are logically three separated processes.

A. *System Architecture blocks description*

- Context sensing is managed through the "*Sensors*" block of the proposed architecture (see Figure 1). The main functionality of this block is to comprehend user context aspects and different environmental data gathered during inquiry science learning activities.
- The "*Mobile Devices*" block is responsible for interfacing sensor devices and serializing their data streams into standard readable formats. This block is also important for annotation and tagging of different user generated content along with the environmental data. Furthermore, another functionality of this block is to transmit these data to the Server block of the architecture.
- The "*Server*" block is one of the most important components of our system, in which we store and organize content and contextual data. Moreover, this block offers extensibility capabilities by providing XML feeds to other systems. This block also offers web server capabilities including a database, content repositories, and web services.
- The next block in this proposed architecture labeled "*Web APIs*" provides the required functionalities for utilizing different Web APIs (such as Google Maps, Flickr, Web based Spreadsheets etc.). These web APIs allow us to mashup several services into a single application that is very important for the next visualization block of this architecture.
- The last block in our proposed architecture is the "*Visual Representation*" block. The main functionality of the visualization block is to visually represent different sensory-based data. Edelson and colleagues [13] advocated the importance of visual representations for supporting inquiry science learning. The representations can help to promote and create spaces for reflection that illustrates the outcomes of the data collected (e.g. geo-tagged sensor data and photos) during different phases of the inquiry science activities.

The implementation of the proposed architecture required the development of several software tools and components. In order to test the validity of our system architecture and the functionality of its blocks, we have designed a prototype experiment to support inquiry-based learning activities in the field of environmental sciences. A detailed description of this learning activity is presented in the following section.

V. LEARNING ACTIVITY DESCRIPTION

The prototype experiment was conducted as part of the LETS GO project. The aim of the project is to design challenging collaborative learning activities supported by mobile and sensor technologies. These combinations of technologies enable the creation of "*mobile science collaboratories*" that can be defined as a set of mobile devices, open software tools, and resources, with online participation frameworks for learner collaboration and inquiry [14]. Our project continues the body of work in inquiry science learning with different mobile technologies [17 & 18]. The design approach we adopt in the project is guided through the use of co-design methodologies with teachers, learners, technology developers, and educational researchers.

The prototype case illustrated in this paper took place in the spring of 2009 in Växjö, Sweden. In this experiment, eight students from a local high school participated in three 2-hours sessions over a 2-weeks period. The subject was woodland ecology and formed part of the environmental science class that the students had elected to study. Additionally, we conducted a scaled-down test case with a local middle school with eight students in a special 1-day session, which is beyond the scope of the present paper. Prior to this study, four initial low fidelity test runs were conducted in California, USA.

The first session required the students to ask questions about the health of the local forest and to create hypotheses about how pH, soil temperature, light, soil moisture, and type might affect the local environment. In addition, the students set up their investigations by getting familiar with the different instruments, scientific sensors and probes, the smartphone for data input and control of the fieldwork, and a digital pen used for note taking. Once the students were familiar with the devices, they began the investigation by heading out to the local forest behind the school. They collected data (sensor data and soil samples) by using the scientific probes, capturing images with the built-in camera in the smartphone, and recording notes with the digital pen. After the fieldwork, the students returned to the lab to process the soil samples and review the data collected. During the second session, the students began to construct new knowledge by analyzing the soil samples and reflecting on and discussing the data collected using the visualization tools. The third session with the students provided additional time to visualize the data with the final soil sessions and to compare the health of trees between locations. This allowed the students to generate new questions about the woodlands. In addition, the students did a small structured brainstorming session to generate new ways to utilize different technologies for more in-depth research on the woodlands.

In the following section, we describe our technical implementation efforts that emerged as a result of the functional requirements identified from the design phase of the learning activity.

VI. DEVELOPMENT AND TECHNICAL IMPLEMENTATION

Functional requirements from the design phase of the learning activity identified the need to integrate geo-location and environmental sensing, visualization, and Web 2.0 mashup technologies, as part of a broader educational scenario. As a result, there was a need to develop different software components and to integrate several hardware resources. The technical overview describing how these components and hardware resources have been integrated is illustrated in Figure 2, which follows our proposed architecture blocks described in section 4.

The learning design requirements required us to provide sensor networks, live mapping tools, data visualization & collaboration tools, and the learning resources, while the software design requirements cover usability, low cost, open standards, multiple application support, and support for different types and contexts collaboration [14]. For the technical implementation of the LETS GO trial, the system overview consisted of four main software and hardware components that have been devised to support students learning science by doing science with inquiry cycles [19]:

- *Smartphone* with built-in sensors (camera, GPS), a mobile client (application) developed by us for users' input including observations and data collection, using third generation (3G) networking for communication purposes.

- *Pasco Spark Device* with built-in interface, the different sensors, and connection options like Bluetooth and USB that are especially designed for inquiry science learning is used for collection and plotting of data using different sensor probes like: pH, temperature, humidity, etc.

- The *Livescribe* digital pen that digitizes the users´ notes and records audio in sync with the pen strokes and is also used for data collection and recording of conversation and discussions during the field investigations for pursuing inquiries collaboratively.

- The final component is the *visual representation* block, which was used to tailor different sensor data and digital content with their location of occurrence; this component has been developed to support post activity learning or lab work. This component is utilized to support analytical thinking (e.g. reflection and predictions) using multiple representations (graphs, maps, data tables, etc) and making scientific arguments from data.

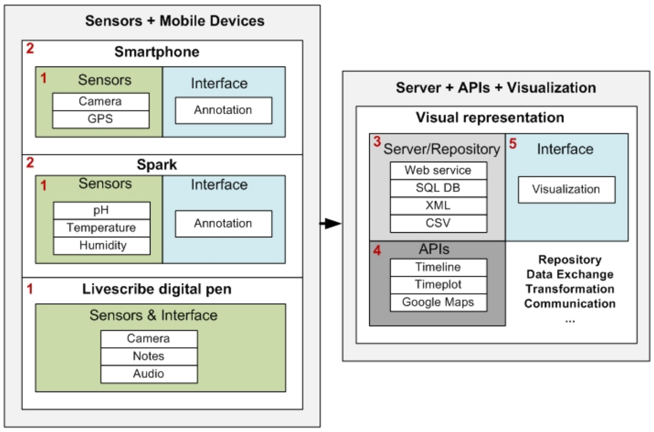


Figure 2. System overview

The visual representation provides the logic by accessing heterogeneous data, transforming them, and representing and visualizing this content to support the learning activity. The interface was developed together with its subcomponents and information visualization techniques were implemented using different APIs.

Note that the numbers 1–5 presented within our system overview in Figure 2 provide detailed relations of these blocks with the system architecture blocks illustrated in Figure 1. For example the smartphone block, numbered 2, is related with the mobile devices block in the system architecture; this numbering is applied to each block in the system overview in order to comprehend each block of the system architecture. In the following sections we give a detailed overview of the technical implementation and the infrastructure and different software components used to support the learning activity in the LETS GO trial.

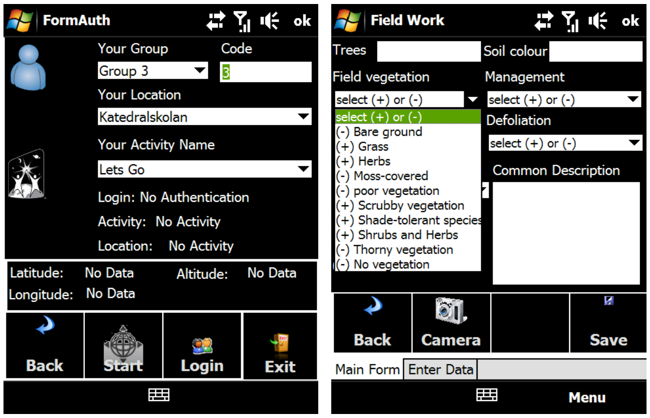
A. Technical Infrastructure

In this section we describe how different software components and infrastructure have been developed and implemented to support the learning activities in the LETS GO project. The communication infrastructure consists of HTTP requests and response commands by integrating multiple web services. Web services have been implemented by making use of HTTP as a main transport protocol to allow requests and responses to pass easily across applications. In addition, we make use of XML and JSON (JavaScript Object Notation) as the data interchange language. An instance of the Microsoft SQL database has also been used as a storage and content repository. Additionally, we have integrated different web APIs in order to support visualization. This infrastructure relied on different wireless communication platforms such as Bluetooth, WiFi, and 3G. In the following section we provide a description of the mobile application and some of its functionalities.

B. *Mobile Client*

One core idea that guided the learning activity design was that field ecology topics are well-suited for geo-gridded data gathering. This generated the need to develop a mobile application to support the process of data collection for the outdoor activities. For the development purposes of this trial, we used mobile devices running Windows Mobile 6.0. The development of the mobile application has been done with C# using Compact Framework 3.5. The mobile application enabled the students to collect sensor data during their inquiry science learning activity. Our application makes it possible to access the GPS and camera sensors through a highly intuitive user interface. Furthermore, this mobile application offers the users the opportunity to annotate sensor data and content created with metadata relevant to their current learning activity.

In order to use this mobile application, the user needs to authenticate his or her identity by choosing the group and activity to which he or she belongs, and to start the GPS for location tracking (Figure 3). The mobile application supports several options for fieldwork and lab work. The mobile application is connected via 3G networks to the SQL database server from where it loads the predefined dataset in the form of drop-down. Furthermore, this mobile application offers support for geo-tagging images with a built-in GPS sensor. The content created in this manner is enhanced with different sensory values and stored as a unique object in the content repository. Besides the automatic tagging from the built in sensors, the application supports users making their own annotations as well. These aspects of geo-tagging and sensory enriched content were very useful for the visualization purposes in the post-activity.



Your Group: Group 3
Code: 3
Your Location: Katedralskolan
Your Activity Name: Lets Go
Login: No Authentication
Activity: No Activity
Location: No Activity
Latitude: No Data
Altitude: No Data
Longitude: No Data

Trees
Soil colour
Field vegetation: select (+) or (-)
Management: select (+) or (-)
select (+) or (-)
(-) Bare ground
(+) Grass
(+) Herbs
(-) Moss-covered
(-) poor vegetation
(+) Scrubby vegetation
(+) Shade-tolerant species
(+) Shrubs and Herbs
(-) Thorny vegetation
(-) No vegetation
Defoliation: select (+) or (-)
Common Description

Figure 3. Mobile client screens shots

C. *Visualization tool*

The sensory data aggregated by the mobile application were used for visualization purposes. As initially described in our proposed architecture, we considered the visualization to be an important component for creating a reflection and collaboration space to be used in the post-activities. For these purposes we developed a geo-visualization tool that enabled different content and sensory data to be visualized tailored to the location where they were collected and measured.

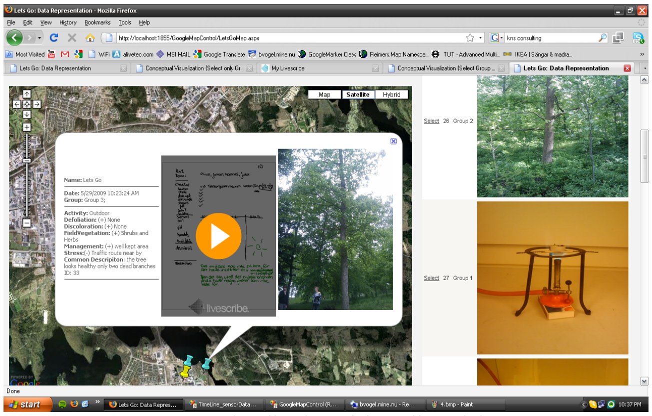
This tool visualizes spatial-temporal sensory data collected during the learning activities. It is a web-based tool and supports different web browsers. The annotations done with the mobile application, digital pen, and spark devices (metadata) are treated with the same significance as the other sensor data sources as can be seen in Figure 4 (caption a). Moreover, this tool offers users various views of the collected data, in the following manner:

- General view (the whole)
- Instant view (positions at any selected date and time) and
- Dynamic view (interaction).

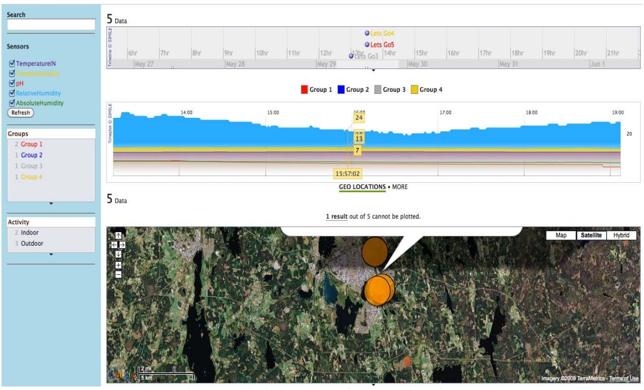
Furthermore, this tool offers the possibility to interactively explore the gathered sensory data using two information visualization techniques (see Figure 4 caption b):

- A timeline is the most frequently used technique for interacting with time-linear visual information [20], and allows the user to explore relationships among historical data. Furthermore, this technique allows users to select date and time intervals for a particular activity. In addition the timeline can also be moved back and forth to dynamically visualize and represent the collected data.

- The time plot technique is used to visualize time series data. In our implementation it is connected to the timeline. This technique visualizes the sensor data collected and provides the possibility of obtaining the individual value of each data. Moreover this visualization technique gives users an opportunity to further analyze the collected data.



(a) Geo-Visualization of the collected data



(b) Spatial-temporal visualization

Figure 4. Visualization tool

These two techniques were integrated with Google Maps APIs in a dynamic way. Using these techniques and approaches, the data collected through the different mobile sensors (pH, relative & absolute humidity, and temperature altogether with GPS), annotations and pictures are integrated and visualized in these visualization tools. Furthermore, the tool allows users to select geographical information in a simple way by retrieving location-based sensor data together with pictures and annotations as one unique object. In the following section we provide an overview of our initial findings during this project.

VII. FINDINGS

The LETS GO trial described in this paper has involved both technical and learning goals. From a technical perspective, the main aim was to validate our proposed system architecture while from a learning perspective the aim was to find novel ways to support inquiry science learning in the field of environmental sciences. The entire process from the design of the learning activity to the definition of the functional requirements was constructed as a series of co-design workshop with different stakeholders including teachers, experts, science educators, researchers and software developers. In the next section we describe some methodological considerations that guided our work, which is followed by a discussion of the initial findings in relation to these efforts.

A. *Some methodological considerations*

The study reported in this paper can be considered as a prototype implementation or sketch. Throughout the entire co-design process, we conducted sets of interviews with the development team, teachers, and researchers. The students filled out three worksheet surveys at the first session of the classroom activity, after the field activity, and then at the close of the second day after the lab work. We wanted to access the students' prior experience with the different technologies and their perceptions of their own knowledge about the health of the forest, and to get some feedback on the use of the technologies. In addition, we videotaped the different sessions for future analysis and some of the researchers used a systematic observation sheet during the field and lab sessions. Additionally, as part of the final session with the students, we used the visualizations as the basis for a joint brainstorming session discussing future uses of the technologies in the science classroom.

B. *Prototype findings*

Due to the technical nature of the present paper, we will focus on functional specifications as a means to assess the study and to expand these requirements for the next phase of the development. Working from the specifications that emerged in the initial design phase of the project, we identified both design and technical requirements [14]. From the design side, we wanted to explore the use of mobile sensor networks, geo-tagged learning content, and to provide data visualization and collaborative inquiries tools for the students. For the technical requirements, we need to achieve a level of usability for classroom use, to support different applications, to utilize open standards, and to keep the costs low. In general we consider that the outcome of the trial validated our proposed system architecture. Different instantiations of this system developed for the purpose of this trial were easily used and well received by students participating in the learning activity.

The students thought that using the smartphone in the field and lab expedited the work. One student in one of the groups reported, *"The tools made the experiment go faster and it was fun to use them in the field. I think we saved a lot of time by feeding the data directly into the phone instead of via paper, like we did before."* The scientific sensors worked well and the students had very little trouble setting up the scientific sensor kits and collecting and analysing the data. Through the worksheets a student reported that the scientific sensor kit was "*easy to use, a better way, and more precise in measurements, along with getting your results right in the forest.*" Additionally, the digital pens additionally were of great interest to the students, especially the audio playback feature, as they could back in classroom listen to the conversation they had in the field while conducting the experiment and solving a number of tasks associated to the problem domain. Figure 5 bellow illustrates different phases of the learning activities and the technology in use.

Figure 5. The different technologies in use

The students all reported that they enjoyed the collaborative work and the different tasks they were assigned, like the sensor operator, digital note taking, and smart phone operator. They thought that the scenario provided them with clear tasks and jobs to accomplish. The visualization tools provide a new window for the students to reflect, discuss, and share different opinions in the group and as a whole.

VIII. DISCUSSION AND FUTURE EFFORTS

In this paper we have illustrated how our initial design ideas and technical efforts conducted in the LETS GO trial can be used to create mobile collaboratories. Our system architecture enables off-the-shelf technologies to be used with the newly developed infrastructure by allowing multiple streams of data to be aggregated and analyzed for use in science learning activities. The system architecture and technical overview presented provide a future roadmap for our development with context sensing and awareness integrated with the smartphones, sensor-based technologies, and digital pens. One of the salient features of our software system is centered on the visualization of the sensory data. However, our current implementation still lacks the proper tools for user interaction with this data that can further support learning activities.

One issue that needs to be considered is the lack of open standards in education technology tools. Each of the devices has, to a large extent, a closed system approach that restricts the development of customized and integrated approaches advocated by the requirements. The scientific sensors system, the digital pen, and to some extent the smartphone required manual synchronization of data before we could provide the visualization tools. In addition, the data visualization tools had some trouble rendering the data in older versions of web browsers that are prevalent in the school IT systems. One of the fundamental technical challenges for the project is to explore how to create software and hardware solutions for educational uses that can be easily integrated into schools, making the potential of Science 2.0 [21] accessible to high school students.

The next stage is to expand our approach to the mobile application, database design, and visualization tool by adding more automatic functionalities; we will take into consideration co-located and distributed collaboration. Given that our system architecture is still in the initial phase, we still need to develop applications (interfaces) for some of the building blocks of our architecture. Our aim is to develop our system toward fully-fledged context oriented architecture that transparently monitors contexts surrounding both clients and services in a given environment [22]. Furthermore, we will explore the possibilities for creating geo-visualization spaces to support collaboration in learning environments. Additionally, we will also explore how to integrate low-cost open source electronics to create sensor network grids for environmental data collection.

ACKNOWLEDGMENT

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PAPER II

Vogel, B., Kurti, A., Spikol, D, & Milrad, M. (2010). Exploring the benefits of open standard initiatives for supporting inquiry-based science learning. Proceedings of the *Fifth European Conference on Technology Enhanced Learning*, EC-TEL 2010, held in Barcelona, Spain, September 28 - October 1, 2010, LNCS, Springer-Verlag, Berlin Heidelberg. pp. 596-601.

Exploring the Benefits of Open Standard Initiatives for Supporting Inquiry-Based Science Learning

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Abstract. Mobile devices combined with sensor technologies provide new possibilities for embedding inquiry-based science learning activities in authentic settings. These technologies rely on various standards for data exchange what makes the development of interoperable mobile and sensor-based applications a challenging task. In this paper, we present our technical efforts related to how to leverage data interoperability using open standards. To validate the potential benefits of this approach, we developed a prototype implementation and conducted a trial with high school students in the field of environmental science. The initial results indicate the potential benefits of using open standards for data exchange in order to support the integration of various technological resources and applications.

Keywords: Interoperability, open standards, mobile learning, ODK, sensors, visualization, inquiry-based science learning.

1 Introduction

Mobile devices combined with sensor technologies provide new possibilities for embedding inquiry-based science learning activities in authentic settings [1, 2]. Nevertheless, these technologies rely on various standards for data exchange what makes the development of interoperable mobile and sensor-based applications a challenging task. Therefore, interoperability remains a key feature to resolve while dealing with diverse data exchange issues across different software and hardware components. Interoperability in these settings would enable multiple applications to interact and seamlessly share data. According to Milrad et al., [3], "*interoperability can provide functions such as media integration and flexible, scalable re-use of learning objects*". Interoperability in the field of TEL needs to achieve two basic purposes: 1) the technical interoperability of data exchange and 2) the pedagogical interoperability of learning content and curriculum units. In this paper, we will focus only on the technical interoperability of data exchange in mobile and sensor-based systems with the particular focus on how to support inquiry-based science learning (IBSL). The main research question addressed in this paper is formulated as follows:

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How can open standards approaches for data exchange be used to facilitate interoperability across heterogeneous devices used for supporting inquiry-based science learning?

In the following section, we present a brief overview of open standard approaches that could be used to facilitate interoperability.

2 Interoperability and Open Standards

A common approach utilized to facilitate interoperability is the usage of open standard formats for data exchange. Open standards approaches deal with the interoperability of data using transparent descriptions, by which different software systems can easily exchange information [4]. According to Fanning [5], there is a close relation between open standard and open source development. One of the main conclusions of his study is that "*A good open source project is based on open standards*". Dinevski [4] argues that with open source models you can build "*open standards as actual software*" by providing "*higher security, reliability, flexibility and higher quality if compared to closed software system*".

Open standards and open source initiatives have gained momentum in the development of mobile applications with the introduction of Google's Android platform (http://source.android.com). Recently the Symbian platform has also become available as open source code (http://www.symbian.org). These recent trends provided new opportunities for the development of mobile applications based on open standards and open source technologies. One of such emerging applications is the Open Data Kit (ODK) that runs on the Android platform. This application is a set of tools for collecting rich data and, it is especially designed to let users own, visualize and share data easily [6]. The key concept in ODK is to support mobile data collection and exchange tools, making it applicable across different application domains such as health, sports, learning and so on.

Open standards are of key importance for supporting interoperability in distributed TEL environments [7]. In our particular system implementation, we needed to provide support for inquiry-based science learning activities. In these settings, there was a need to insure the data interoperability between diverse applications and devices. Thus, we need to consider how to use and integrate open standards technologies while developing software systems for supporting inquiry-based science learning. In the following section, we will present a number of related research initiatives in the field of IBSL that make use of mobile and sensor-based tools.

3 Technological Resources in Inquiry-Based Learning Systems

Inquiry-based science learning activities have been addressed by members of the TEL community in various projects [1, 8, 9]. The main denominator in these projects has been the integration of a wide range of mobile, sensor and web technologies to support IBSL activities. In the Science Created by YOU project (SCY), learners generate their own learning objects [10]. Additionally, these Emerging Learning Objects are reusable and shareable components created with drawing-based modeling and visualization tools.

The SCY system offers intelligent support for dynamic, ad-hoc collaboration, mobile tools and by providing just in time information and scaffolding to support learning. The Personal Inquiry (PI) project supports inquiry activities with flexible, re-usable tools to support and bridge sequences of activities [11]. The PI system supports location-based inquiry learning across school, field, and home contexts using mobile, sensor and web technologies. The project makes use of digital maps and visualization tools used for bridging representations across field and classroom activities. A common denominator in these projects is the lack of a standard that provides seamless data exchange among the devices and applications used in these activities.

In our previous work, we utilized and visualized sensor data to support different learning processes in the different cycles of IBSL [1]. We have designed and developed a software system that integrates data coming from various technological tools and that include a mobile client for data collection and annotation, mobile sensor probes, a digital pen for notes and audio recording, and geo-temporal visualizations. One central aspect we have identified based on our previous developments is the lack of data interoperability between the different tools and technologies. Under these circumstances, most of the technological resources require to some extent manual synchronization of data for providing data processing and representations. These processes are time consuming and generate significant barriers for the seamless integration of these technologies in educational settings. Each of the technologies in use has a closed system approach that restricts further development. In our case, for example a scientific data logger, typically provides data in binary format that need to be appropriately serialized and decoded in order to get the values correctly. In order to tackle this problem, we argue that data interoperability can be supported by the use of open standards in order to provide more flexible and interoperable software solutions and systems. In the coming sections, we present a specific learning activity, the tools we developed and the technical architecture and its implementation in order to illustrate the potential of using open standards to support IBSL.

4 The Learning Activity

The learning activity presented in this section was conducted as part of the Learning Ecology through Science with Global Outcomes (LETS GO!) project [1, 9]. The aim of the project is to design challenging collaborative IBSL activities supported by mobile and sensor technologies. These combinations of technologies enable the creation of "*mobile science collaboratories*" that can be defined as a set of mobile devices, open software tools, and resources, with an open framework for learner collaboration and inquiry [1, 9]. The activities presented in this section have been developed in collaboration with local teachers in Sweden and USA together with a multi-discipline research team through a co-design process [9].

The learning activity reported in this paper has been conducted over a five weeks period in the winter of 2010 in Sweden. Twelve students (16-17 years old) participated in two hours session once per week. As part of the students' environmental science curriculum, they investigated water quality in surrounding lakes. The activities carried out by the students include classroom lessons, field trips and lab work. Overall, there were four different sessions investigating different aspects of the inquiry-based science learning cycle.

Fig. 1. Technologies used during the learning activity

Figure 1 gives an overview of the water quality learning activity that included workshops for the students to get familiarized with the different technologies (see Fig.1 captions a and b). Additionally, students conducted field experiments at a local lake and collected samples for lab analysis (see Fig. 1 caption c). Students discussed the initial questions given to them about water quality and their findings from the field and lab work. Visualization tools and Google Earth, as a 3D representation tool, were used to support the students' inquiry process (see Fig.1 caption d).

5 Technical Implementation

This implementation followed the specifications detailed in our previous work derived from the functional requirements [1, 9]. The learning design requirements demanded from us was to provide access to sensor networks, live mapping tools, data visualization, and collaboration tools. Software design requirements included usability, low cost, open standards, multiple application support, and support for different types and contexts collaboration [1, 9].

For the mobile client side, we have developed an XForm that was rendered by ODK Collect allowing data collection during the learning activity. XForm is a standard based on a W3C recommendation that is used to build web forms for easy exchange of data across platforms and devices using XML as a data format. The XForm used for this implementation was developed using a simple XML editor. The logic and the structure of our XForm were jointly developed with the subject teachers following the IBSL cycle [1, 10]. The mobile application (ODK Collect) has the capabilities to *render a form, survey into a sequence of input prompts that provide navigation logic, entry constraints* in the mobile application [6]. The XForm supports various types of data and content inputs such as text, audio, pictures, video, visual codes and GPS that makes it possible to annotate the collected sensor data and content with location metadata. Another interesting feature of ODK Collect is that it allows storing the data locally (in the mobile device) and synchronization with a server (ODK Aggregate) could be done once the mobile device has Internet connectivity. ODK Aggregate provides the server companion that runs on the Google App Engine and is used to host XForms, as well as storing the collected data submitted from the ODK Collect. For this particular implementation, we made use of the ODK platform for data collection and developed a visualization tool. The use of XForms facilitated data interoperability across diverse devices and applications that comprise our system. The system overview that describes the integration of the components and resources used in this implementation is illustrated in Figure 2.

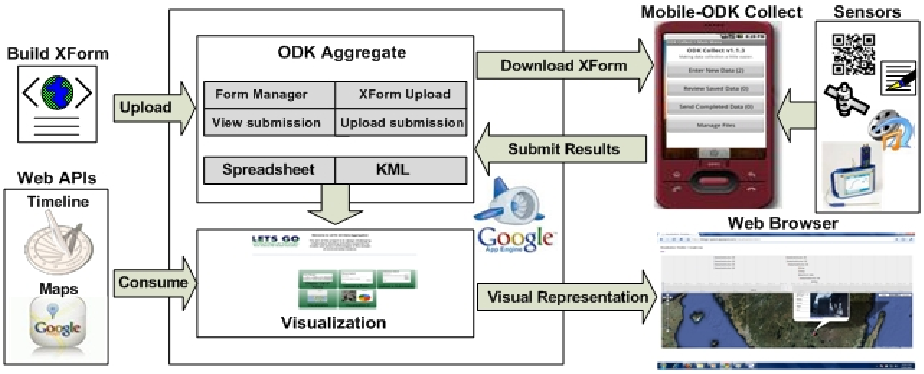

Fig. 2. System overview

The visualization tool was an important component of the system that provided an interactive space to facilitate reflection and collaboration among students that provided a clear overview of the geo-temporal aspects of the collected data [1]. This web-based visualization tool utilizes several web APIs. So far, we have implemented two visualization components that include a timeline and Google maps that uses XML and JavaScript API provided by the Simile project at MIT (http://www.simile-widgets.org/). This tool was integrated with the Google App Engine, as another component of the system. The visualization tool made use of the data collected by the mobile application that were stored as a Google spreadsheet format (.CSV format) in the ODK aggregate. The tool allows users to select geographical data and filter them dynamically using a timeline. Furthermore, the tool visualizes the entire sensor data collected during the learning activities including pH, conductivity, temperature, etc and different annotations and pictures.

6 Discussion and Further Steps

The development and implementation described in this paper demonstrates the growing potential towards the usage of existing open standards to support data collection, data interoperability, analysis and visualization in the context of IBSL. In the activity described in this paper, data interoperability simplifies the integration of data generated by various technological resources and applications. This approach enables rapid development and reuse of technological resources for supporting different learning activities, thus resulting on the seamless integration of data coming from multiple devices. Additionally, this integration has potential benefits for supporting other learning activities. From a practical side, the added value for the classroom is the seamless integration of different sensor data combined with devices that enable powerful visualizations to support the students work. One issue that we will consider in our future work is the full utilization of the visualization component, by incorporating different techniques that provide interactive spaces for discussion, sharing and collaboration. For the next stage of our development, we want to expand our system by incorporating another component from ODK platform, namely the ODK Manage.

This component easily manages the ODK system, by updating the software and forms remotely from the mobile devices, thus further enhancing interoperability issues across different devices. Furthermore, we are in the initial phase of developing a web-based visual authoring tool in which users can design, develop and deploy their own form for mobile data collection tool.

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PAPER III

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An Interactive Web-based Visualization Tool: Design and Development Cycles

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Abstract—**Current advancements in web technologies are enabling to develop new features of interactive systems that rely on cloud infrastructure and services. In this paper, we present our efforts related to the development of three prototypes of a web-based visualization tool that use Google Cloud Services to process and visualize geo-temporal data. The domain in which these efforts are taking place is in the field of environmental science. The need of web-based visualization tools in this area indicates the importance of allowing users in an interactive manner to explore, analyze and reflect on different representations of environmental data. We discuss the development of these prototypes and their features, as well as the different iterations that were carried out during these processes. The outcomes of the design and development processes point out that the users´ feedback generated during the prototyping cycles provided valuable insights in order to further enhance the web-based visualization tool. Thus, our study emphasizes the need of finding a balance between design and development in order to consider how the rapid evolution of web technologies should be taken into account during the design and planning of different cycles of web prototyping.**

Keywords: cyclic prototyping, visualization, web APIs, cloud services, geo-tagged data.

I. INTRODUCTION

Advances in web technologies are enabling cloud applications and services to become easily integrated in an interactive system [1]. According to Hendler [2], the "*Web is an amazing platform for rapid prototyping, application integration, and innovation*." Nowadays, Application Programming Interfaces (APIs), sensor data, geo-tagging and web-based visualization tools play an important role regarding the collection, storage, processing, retrieval and presentation of digital information [1, 3]. In recent years, there has been a significant increase of research studies investigating the use of web technologies to visualize geo-temporal data [4, 5, 6]. The integration of different data sources and web components such as web APIs, web services and cloud frameworks into a web-based application has resulted in the creation of the concept of mashups [7].

One of the main manifestations of the latest developments in the web is the gradual increase of the amount of data and user generated content arising from mobile devices. According to Google's VP Marissa Mayer and HP's Ranganathan, mobile devices have become "*ubiquitous nano-sensors*" that produce an increasing number of data about the environment [8] that can be used to process and visualize information in novel ways. Therefore, as the amount of available data grows, conceptualizing and developing new interactive tools for visualization becomes an important challenge. Visualizing data interactively through the use of different dynamic presentations that rely on graphs, charts, maps and other techniques is often a powerful way to make sense from these vast amounts of gathered data [9]. During the last decade, researchers and developers in the field of visualization have been implementing powerful tools for presenting and analyzing data across different disciplines [10].

In this paper, we present our efforts related to the development of three prototypes of a web-based visualization tool that use Google Cloud Services to process and visualize geo-tagged sensor data collected using mobile devices. The domain in which these efforts are taking place is in the field of environmental science. The specific aim of the paper is to explain how the prototyping cycles of the web-based visualization tool have been carried out following the requirements engineering cycle. We discuss the development of these prototypes and their features in relation to the different phases of cloud application development [11]. Furthermore, we elaborate on those issues related to how rapid technological changes (e.g. Google Cloud Services) have affected the development process of the prototype. Thus, we present the prototyping cycles of the visualization tool across several iterations that include four user trials connected to data collection in field activities. We also discuss how the rapid evolution of web technologies and services has been taken into account during the design and development of the tool. In the next section we introduce our motivation for developing the web-based visualization tool and the challenges associated with this task.

II. MOTIVATION AND CHALLENGES

Visualization is used as a data analysis technique that supports interactive exploration of data on the screen [12]. The idea behind interactive data visualization is to enable users to easily perform visual exploration and analysis of data, to facilitate the understanding of particular phenomenon, and also to communicate findings [13, 14]. The field of Interactive Visualization aims to address those issues related to "*effective integration of visualization and interactive technologies in the field of scientific computing*" [15].

As stated earlier, the evolution of mobile, web and sensor technologies makes it possible that a wide range of data types become available to end users. One simple example is the visualization of geo-referenced data sources using digital

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maps (geographical data like Google Maps). Such kind of visualization represents a type of geo-mashup tool that makes use of different data sources that are presented in a combined view in one screen [7, 15]. Different visual representations can provide different insights to users by enabling them to observe data in context, to analyze these data and to draw different conclusions by using comparisons [15].

Considering the focus of our efforts, there are a number of current technological developments that serve as the foundations for our work. These are enumerated and described as follows:

- **Web APIs.** Geospatial web and digital maps services (Google Maps, Bing Maps, OpenStreetMap's,) combined with web-based visualization techniques and APIs provide intuitive and cost (time) effective solutions for the development of new types of data visualization [1, 2]. These emerging web visualization tools allow users to view data, to interact, and analyze it, as well as to explore it in a broader context [7, 16].
- **Software as a Service (SaaS).** Another area of research and development that has influenced the development of our tool is cloud computing. Cloud computing is defined in the literature as: *"both the applications delivered as services over the Internet and the hardware and systems software in the data centers that provide those services"* [16].
- **Cyclic Prototyping.** The need to discuss ideas and designs possibilities with stakeholders and to assess the technical feasibility of our implementations requires an easy and communicative way to present and test them. Prototyping has shown to provide this communicative way, by allowing requirements engineering to evolve flexibly towards constructing a final product [17]. More specifically, our approach of prototyping is motivated by the development of a web-based visualization tool in close communication with users, including domain experts (teachers) and end users (students). The different iterations and testing are conducted in a cyclic manner.
- **Technology-enhanced Learning (TEL).** Web-based learning tools and applications including interactive visualizations have the potential to increase learners′ engagement and curiosity, thus promoting scientific inquiry thinking. In the scope of our efforts, learning through collaborative visualization refers to developments of "*scientific knowledge that is mediated by scientific visualization tools in a collaborative learning context*." [18].

A number of research efforts have been carried out in relation to visualizing geo-tagged and sensor data using the technologies and concepts described above. Rodrigues and Rodrigues [4] have developed a visualization tool that makes use of maps APIs and Web 2.0 technologies to support asynchronous spatial collaboration between physically distributed users. In another project, GeoJunction [5], the authors propose a web-based geo-visualization tool for exploring geo-temporal data related to public health. The need for supporting collaboration using these technologies has been emphasized by MacEachren and Brewer [6] and their framework for visually enabled geo-collaboration.

Our initial design sessions with end-users that took place in the fall 2008 aimed at exploring the required and desired features [19] of our tool. The outcomes of these efforts in combination with the results of our literature review helped us to identify some challenges with regard to the development of our prototype. Designing and development a web-based visualization tool in the domain of exploration (environmental science learning) indicates the importance of allowing users in an interactive manner to explore, analyze and reflect on different visual representations of geo-temporal environmental data.

The results described in this paper are an effort to try to tackle some of the challenges described earlier and are an evolution of the efforts we conducted in our previous work [20]. During our earlier explorations and developments, we have proposed and implemented a system architecture that consists of five different blocks aiming to provide logical divisions between the different resources of our system. In relation to these divisions, one of the blocks is dedicated to the visualization aspects, while another one is related to the web APIs that are offered by Google Cloud Services. The visualization and web API blocks are the central components of the visualization. The other three blocks are responsible for sensor and data collection and storage purposes and additional information about them is beyond the scope of this paper (see [20] for more detailed information).

The next section describes our approach for the design and prototyping of the web-based visualization tool.

III. DESIGN AND PROTOTYPING

Design and prototyping are used to introduce the evolution phases of an interactive web application through several iterations. In our case, the development of the web-based visualization tool has used cyclic prototyping for enabling us to validate and to test the different versions of the tool based on users' feedback. Furthermore, the idea behind prototyping is to use them as the basis towards the final product specification.

Considering the work of Abou-Zahra [21], the development life cycle of a web application can be categorized according to four main stages: *Requirements, Design, Implementation* and *Operation*. In our particular efforts, these four stages have played a crucial role. During the requirements stage, we have identified some initial requirements that included the need to integrate geo-location and environmental sensing, visualization, and mashup technologies [19]. After the first stage, we developed a prototype and implemented it in order to validate those requirements. For instance, design concepts, navigational features, the general web content composed of text, graphs, pictures and maps presentations were deployed and implemented. The second and the third stages of design and implementation guided these iterations. Then, the final stage of operation intended to maintain and identify additional improvements during testing the prototype.

Furthermore and based on the technological choices for the implementation of the prototype, our development approach was closely aligned with the six phases of the cloud application development, as suggested by [11]. In their work Hosono et al., [11] introduce six phases for cloud application development in order to provide some guidance for design and implementation purposes. These six phases are defined according to the following:

Phase 1: *Designing application,*
Phase 2: *Implementing application locally,*
Phase 3: *Simulating application locally,*
Phase 4: *Deploying application to cloud environment,*
Phase 5: *Staging it on cloud environment and*
Phase 6: *Operating application on cloud environment.*

In our work, we have experienced that there is a need to instantiate these development phases with the prototyping cycles while developing our web-based visualization tool.

For our prototype development, we used high-fidelity prototyping that allows more realistic representation of ideas [17]. It is usually user-driven and consists of developments that lead towards a final product [17], in our case, it is a web-based prototype that intends to become a robust application. The benefit with regard to using high-fidelity prototyping is that the requirements can already be tested in an early stage towards the final product. Several other benefits that can be mentioned are the following: the prototype is fully interactive, it is completely functional, it is user-driven, it has a "*look and feel*" of the final product, and it may save time and money [17].

In prototyping, there are two different development principles (evolutionary prototyping and throwaway prototyping) [17]. The four stages of web development cycles introduced earlier in this section are mapped to our developments that follow these two principles of prototyping:

- **Throwaway prototyping** – *considers creating the basis of a final product, which eventually is thrown away, however it remains valuable to construct further evolving ideas related to the final product.*
- **Evolutionary prototyping** – *considers the evolution of a prototype toward a robust final product.*

We have applied both these principles throughout the development process of the web-based visualization tool. In order to illustrate how this has been accomplished, we describe in the section below the experimental settings of the user trials in which these three prototypes were developed and tested.

A. *Experimental settings*

The prototypes were developed and tested with users in conjunction with a series of user trial activities carried out in the "Learning Ecology through Science with Global Outcomes (LETS GO)" project [19]. These different activities required the utilization of sensor and mobile devices for data collection in the field, and web-based tools for data visualization and analysis in the classroom. The *first* experiment (with 8 students) was conducted in the spring of 2009 in Växjö, Sweden over a period of two weeks and the domain of exploration was soil quality within the subject unit *woodland ecology*. The target groups were students 17-18 years old. The information collected by the students in the surrounding forest consisted of data sets including: pH, temperature, humidity, GPS coordinates, geo-tagged pictures and sounds. The data collected by the students were used later for visualization purposes in the classroom. The use of the tool provided different visual representations of the collected data that allowed students to analyze and to reflect upon the activities they conducted [20]. These settings provided an interesting arena to conduct this first experiment in order to introduce the use of the first prototype. Figure 1 illustrates the use of the visualization tool in the classroom. Implementations aspects related to this experiment are described in more details in section "*B*".

Figure 1. The prototypes in use.

The *second, third* and *fourth* experiments were intended to investigate aspects related to water quality that are part of the school curriculum. These experiments were conducted in the surrounding lakes around the city of Vaxjo. The *second* experiment (with 12 students) was conducted over a five weeks period in the March of 2010 with students 16-17 years old. The *third* (with 54 students) and *fourth* (with 18 students) experiments were conducted during a period of five weeks in the spring of 2010 and the target group consisted of students 14-15 years of age. In all these activities, students measured and collected data related to water quality, including parameters such as pH, dissolved oxygen, temperature, and conductivity. Additionally, students also generated geo-tagged content (pictures, notes and GPS data) during these activities.

These data sets served as samples for lab analysis that represented different visualization instances for the second and third prototype. A technical description of the second prototype is explained in more details in section "*C*", while a detailed explanation of the third one is given in section "*D*".

B. *First prototyping – Throwaway*

The first prototype enabled the visualization of different content and sensory data tailored to the location where they were collected and measured. This prototype used two different information visualization techniques namely timeline and time plot (http://www.simile-widgets.org/) (see Figure 2). These two techniques were integrated with Google Maps APIs in a dynamic way. The technology used for the implementation of this prototype is based on C#, ASP.NET and JavaScript. As a content repository for storing data we used JSON and a relational model – database (MS SQL Server). Throughout the development lifecycle of this prototype, the web-based visualization tool was used and tested with users in real settings as those described earlier in this section.

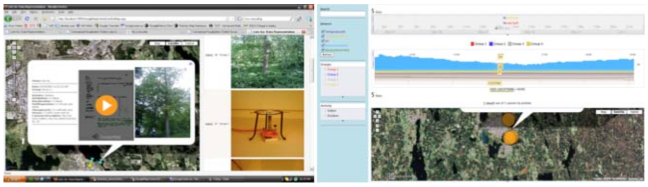

Figure 2. First prototype screen shot.

C. *Second prototyping – Throwaway*

In comparison to the first prototype, the second prototype supported real-time visualization of data sent directly from the mobile clients. While the first prototype was mostly customized and developed for one particular platform and activity (soil quality); changing to a different user activity (water quality) that combine different data sources and devices posed some new requirements that forced us to explore alternative solutions. Hence, the experiments related to water quality created the need to integrate different data sources and formats in order to overcome some interoperability issues posed by the activity and the devices we used to collect these data. Our explorations for seeking for more flexible solutions lead us to identify cloud services as a potential alternative. In the second prototype, we started to integrate and consume initial cloud services. However, the prototype in this case had less functionalities and interactivity than the first one. This prototype allowed users to select geographical data and filter them dynamically using a timeline.

In this prototype, we have implemented two visualization components that include a timeline and Google maps that use XML and JavaScript API provided by the Simile project at MIT (http://www.simile-widgets.org/). As a content repository for storing data in this second prototype, we used a flat model database (Google Spreadsheet).

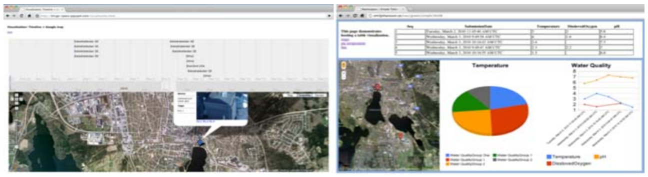

Figure 3. Second prototype screen shot.

D. *Third prototyping – Evolutionary prototyping*

The third prototype also enabled the visualization of different content and sensory data. In contrast to the first and the second prototype, the third prototype can be considered as evolutionary. It utilizes several web based APIs that support multiple representations such as graphs, maps, data tables, charts, scatterplots, and similar, all in an interactive fashion (see figure 4). The technology used for the implementation of this prototype during the development cycle is based on Google Visualization APIs and JavaScript/AJAX. As a content repository for storing data, we continued to use Google Spreadsheet, the same as in the second prototype.

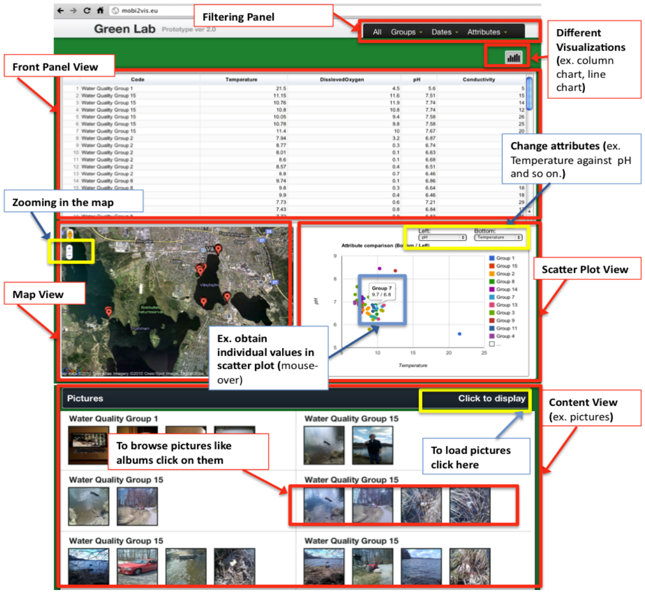

Figure 4. Third prototype screen shot.

This prototype is deployed and relies totally in a cloud environment. Our intention with this third prototype was to create a robust visualization tool that can potentially be easily expanded without making major changes. An additional concern was that it should provide novel visualizations with interactive spaces to facilitate reflection and collaboration among users. Furthermore the features of the third prototype and the variety of visual representations used provided a clear overview on geo-temporal aspects of the collected data. Given the potential offered by this third prototype (implemented using solely cloud services) to evolve towards a final product with easy maintenance and flexible addition of extra features, we continue to explain its components overview. We focus on this prototype, which deserves further elaboration since it is still under the processes of refinement and rebuild.

E. *Components overview – Evolutionary prototyping*

As introduced earlier in this section, this third prototype has been implemented using Google Visualization APIs and AJAX/JavaScript techniques. Different Google Visualization APIs support visualizations over the web that let the user access structured data by visualizing easily with any compliant data sources. This prototype consumes several Google Visualization APIs to provide multiple representations such as graphs, maps, data tables, charts and similar. These multiple representations are embedded within the same prototype in an interactive way. Three core libraries of Google Visualization API[1] are included and loaded to the tool. The data (which previously has been uploaded via the mobile devices) is queried from the spreadsheets in the remote server in order to visualize them. Furthermore, after loading the libraries and querying the data, the chosen

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[1] http://code.google.com/apis/visualization/documentation/using_overview.html

visualization representations (e.g. scatterplot, line chart etc.) are instantiated. Finally, multiple representations are rendered in this prototype.

We have also implemented several filtering mechanisms, according to date, group and attribute. The different visualization formats are very flexible. The data represented in the data table sorts the values in ascending or descending manner. Figure 5 depicts the visualization components that have been integrated into our third prototype.

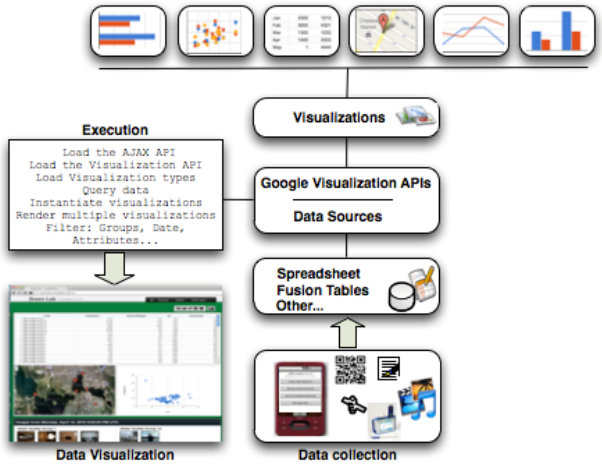

Figure 5. Components overview.

IV. ANALYSIS

In our development cycles, the throwaway prototyping principle used in first and second iterations was a starting point to identify users' specifications and their needs. The outcome of these efforts resulted in the development of the third prototype, which was rebuilt from scratch, although making reuse of the conceptual ideas that emerged from the two initial prototypes. It is important to mention that the first two cycles of our prototyping efforts have been complemented with the initial four phases of the cloud application development, as suggested by [11]. During these phases, we have been able to conceptually design the features of the web based visualization tool, made initial implementations and deployment using different technologies (see Table 1), as well as we tested our tool in a local environment.

The evolutionary prototyping principle used in the third iteration has been conceived upon the lessons learned from the initial two cycles of our prototyping efforts. Nevertheless, we have completely changed the technologies and the implementation in this third cycle. The completion of these efforts launched phases five and six of the cloud application development. The third prototype was completely deployed on the cloud environment using Google services as data center and different visualization APIs. While operating the application on the cloud, we continuously refined and upgraded the web-based visualization tool. Throughout these cycles and phases of developments, the visualization tool became more robust which in turn allowed users to explore, analyze and reflect upon the real-time data they collected in a more satisfactory manner than before.

One of the advantages we have identified in this latest implementation is the level of flexibility provided by using the cloud environment for deploying this prototype. Data sets and different visual libraries consumed by this tool have been offered by different cloud services. The new functionalities of third prototype (such as different visual representations and interactivity) have been enabled by the features of the cloud environment.

There are, however, several interesting features and concerns with regard to throwaway prototyping, as well as evolutionary prototyping. In Table 1, we present an overview of the technologies used while developing these three prototypes. It can be noticed, that there is a clear evolutionary path towards cloud services. Initially, we started by employing traditional desktop based integrated development environments (IDE) and gradually moved towards a mashup-pattern that combined different web APIs. The first prototype has been implemented mostly using desktop enabled features and did not provide real time data representations (mostly offline). The development process of the second prototype resulted in the combination between desktop and web technologies including initial cloud services. This combination enabled real time data representations. The last prototype relies completely on a cloud environment (real time and online).

This shift on the use of technologies for our implementation enabled us to rapidly fulfill one central requirement we had; namely the need for real time data visualization. We consider that the prototyping approach across several cycles is a viable solution to maintain the pace of development in order to cope with the rapid speed of web technologies. Furthermore, we consider that this combined approach was required because the web-based visualization tool was not an ordinary web site, neither an ordinary visualization tool.

Figure 6 below presents an overview of the different development cycles of our web-based visualization prototype. This figure illustrates how we complement the prototyping cycles with the different phases of cloud application development in order to find a solution that fits our needs. This figure presents the requirements engineering, and prototype testing timelines in relation to the last 2 years of the development. The prototyping efforts have been carried out as a part of different stages of the web development cycles, inspired by [21].

Prototyping cycles, as a part of our efforts, represent a good complementary approach to the phases of cloud application development. By prototyping, we were able to follow and cope with the rapid technological developments and at the same time testing our solutions with the end users. This combined approach enabled us to better fulfill the functional requirements when we started to gradually migrate from the IDE to a mashup oriented development.

TABLE I. TECHNOLOGIES USED, FEATURES AND CONCERNS RELATED TO THREE PROTOTYPES

Prototyping	**Throwaway**		**Evolutionary**
Versions	***First Prototype***	***Second Prototype***	***Third Prototype***
Technologies used	C# ASP.NET, JavaScript, JSON, SQL Server, SIMILE, Google Maps.	JavaScript, SIMILE, Google Maps, Google Spreadsheets, Google charts API.	JavaScript/AJAX Google Maps, Google Spreadsheets, Google Visualization APIs, JQuery.
Features	Relational model – database.	Real time data.	
	Visual representations: *Text, Timeline, Time plot, and Maps.* Geo-tagged content: *Pictures.*	Visual representations: *Text, Pictures, Timeline, Maps, and Pie chart.* Geo-tagged content: *Pictures.*	Visual representations: *Text, Data Table, Maps, Scatterplot, Bar chart, Line chart, and Pie chart;* Geo-tagged content: *Pictures.*
Concerns	The prototype was not fully functional. Also, some manual interventions on the data entry were required in order to make the entire functionality of the tool available for the users.	The prototype didn't provide appropriate scaling of visualizations.	Automatic technique for mapping diverse data sets (data types).
	Not real time data.	Flat model database.	

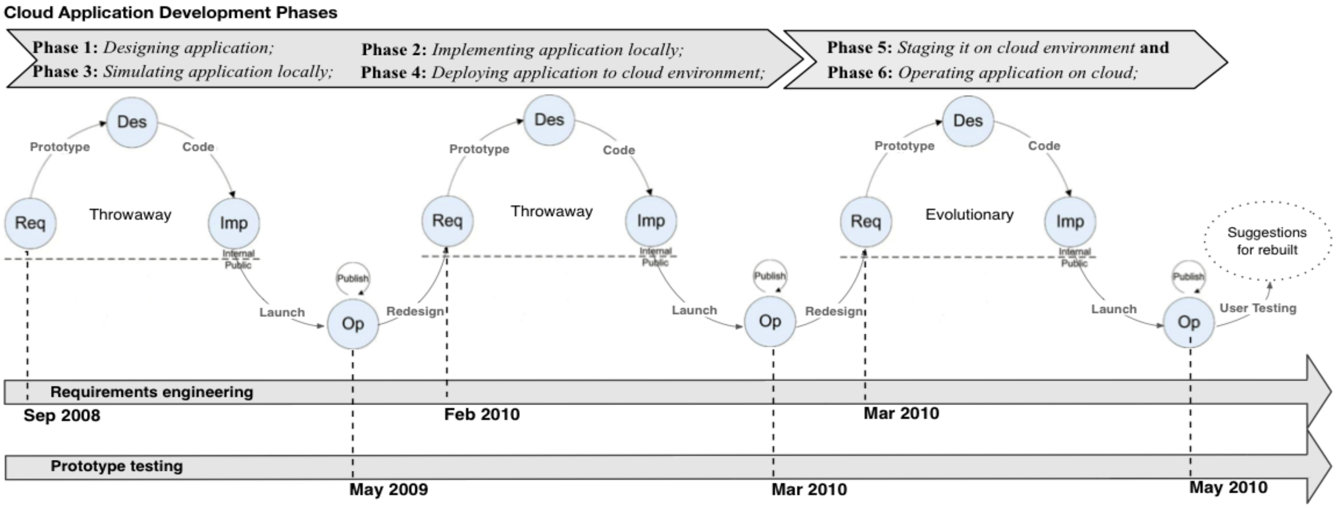

Figure 6. Development cycles of prototyping across the timeline (note that in this figure the dates presented show the start (Req) and the end (Op) of each cycle)

This shift regarding our implementation approach has been guided by the phases of cloud application development, as illustrated in Figure 6. Combining the prototyping efforts with the different phases of cloud application development allow us to match the users´ requirements and to have a fully operational tool that completely relies on cloud services. Our approach is also related to standard software engineering practices such as Agile Unified Process (AUP) [22]. In AUP there is a constant communication with stakeholders, where requirements often change at the beginning of every iteration (where new requirements are added or modified), a case that is closely related to our development cycles, for e.g., see Figure 6.

V. DISCUSSION AND FUTURE WORK

Cyclic prototyping proved to be a useful approach to obtain flexible ways to cope with requirements engineering and for visualizing data. In the efforts described in this paper, we have introduced three prototypes of a web-based visualization tools related to the stages of web development cycles. Furthermore, we have also complemented these development cycles with the phases of the cloud application development. There are a number of important issues that resulted from the overall analysis of the development process as presented in this paper:

1) There is a need to combine throwaway and evolutionary prototyping in order to cope with the rapid speed of developments regarding web technologies and tools. Throwaway prototypes can be a valuable tool that helps to refine conceptual ideas related to the design of the tool. Evolutionary prototypes are more functional *(closer to a final product)* and can continuosly evolve. This latest feature can represent an important advantage when it comes to maintain software components and applications that rely on a cloud infrastructure.

2) The different phases of cloud application developement can be matched with prototyping efforts *(by also involving users, analysis and rebuilt cycles)* in order to be able to closely reflect upon users' requirements and to integrate some of them in to order to cope with the rapid changes in web technologies.

3) Prototyping cycles may be useful in order to find a balance between the evolution and development of the tool by considering these rapid technological changes (*cloud services*) throughout implementation process.

Analysis involving users´ feedback of the web based visualization tool through prototyping cycles generated promising results that can help to further enhance the prototype and its maintenance on the cloud environments. To date, the prototypes have validated the usage and engagement of the users. Throughout the entire process described in this paper, users were actively involved in testing the different features of the prototypes. In the lines below, we briefly describe two interactions that illustrate how working closely with the end users provided valuable inputs for refining the tool. During one of the sessions with the tool, early in the spring 2010, one of the teachers suggested including a data table and chart representations together with maps in the visualization tool, as a way to improve the interactivity of the tool. After the discussions with the teacher about his suggestion, we decided to incorporate and implement this functionality in the new prototype. In another session with students (late spring 2010), the visualization tool was used in combination with an interactive whiteboard. In this way, students were allowed to interact with the tool in a large display being able to navigate the content through visualizations, interactively using digital pen. During this session, we noticed that students started taking notes using a word processor in connection to the content they were discussing. This kind of interaction indicates the potential of introducing collaborative note taking directly in the visualization tool as a possible line of future work.

We will conduct a usability study with university students in relation to our latest (third) prototype, by adopting a web engineering usability perspective in order to obtain users´ feedback that may result in concrete suggestions for rebuilt. In the table below we provide a list of features we plan to develop and implement in our future efforts.

TABLE II. OVERVIEW ON FUTURE WORK

Features	Description
Interactivity and Visualization	More dynamic filtering, different visualization types.
Collaboration	Note taking, integrating collaborative data manipulation by using big screen projections.
User testing	Future iterations by considering cyclic evaluation process for the third prototype.

In our future work, we will continue to refine some features of our visualization tool by using the web development cycles described earlier.

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PAPER IV

Vogel, B., Kurti, A., Milrad, M., and Kerren, A. (2011). An Interactive Web-based Visualization Tool in Action: User Testing and Usability Aspects. In Proceedings of the *11th IEEE International Conference on Computer and Information Technology*, IEEE Computer Society Press, (CIT '11), Pafos, Cyprus, 2011, pp. 403-408.

2011 11th IEEE International Conference on Computer and Information Technology

An Interactive Web-based Visualization Tool in Action: User Testing and Usability Aspects

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Abstract—**In this paper, we present our efforts in relation to the evaluation of an interactive web-based visualization tool developed for supporting environmental sciences learning. The tool enables the visualization of different types of geo-tagged content and sensor data collected using mobile devices. It also utilizes APIs that provide multiple visual representations of the data set. These representations allow users to actively interact with graphs, maps, images, and data tables. In order to test the usability, novelty and interactivity of our web-based visualization tool, we have conducted a study involving university students in the field of teaching environmental sciences. The results and analysis of the user testing indicate that the tool's usability and performance were satisfactory. Outcomes from the user testing have resulted in a number of concrete suggestions for further enhancement and improvements of our visualization tool in relation to application functionality, navigation and interaction.**

Keywords: Usability evaluation, user testing, web-based visualization, geo-tagged data.

I. INTRODUCTION

Visualizing data interactively through the use of different dynamic presentations that rely on graphs, charts, maps and other techniques is often a powerful way to make sense from a vast amount of gathered data [1]. In recent years, several initiatives have been carried out in relation to the use of web technologies to visualize geo-temporal data [2], [3], [4], [5]. In line with these developments, the efforts related to the design and implementation of our web-based visualization tool have been motivated by the following: 1) *Geospatial web* and digital maps services combined with web-based visualization techniques and Web APIs [6] 2) *Cloud computing*, the "*applications delivered as services over the Internet*" [7] 3) *Web-based cyclic development* using prototyping approaches for enabling us to validate and to test the different versions of the tool based on users' feedback [8] and 4) *Technology-Enhanced Learning* as the field of exploration and testing of our web-based visualization tool.

As a result of our research efforts, we have developed three prototypes of a web-based visualization tool. This tool was developed making use of Google Cloud Services to process and visualize geo-temporal data. Its features were carried out in three different iterations following the requirements engineering cycle (see also: Vogel [9]). The specific domain in which these efforts were applied is the field of environmental science learning. The need for allowing users to explore, analyze and reflect on different representations of environmental data in an interactive manner indicates the importance of web-based visualization tools in this domain. The usability evaluation of web-based applications has gained increasing attention in the web engineering community [10]. Usability evaluation is used to test the features of a web-based application and to verify the fulfillments of user requirements [10]. The latest (third) prototype of the visualization tool enables to visualize, analyze and explore different types of geo-tagged content and sensor data collected using mobile devices. In order to address the needs for further improvements of our current prototype, we conducted a user testing of our web-based visualization tool.

II. THE PROTOTYPE

The prototype of our web-based visualization tool was developed as a part of the ongoing research project "Learning Ecology through Science with Global Outcomes (LETS GO)" [9]. In this project, students are using sensor and mobile devices for data collection in the field and the web-based visualization tool for data visualization in the classroom. Students create geo-tagged content and collect data related to water quality, measuring and collecting values, such as pH, dissolved oxygen, temperature, and conductivity.

The web-based visualization tool we have developed utilizes a number of Google Visualization APIs, and it is implemented using AJAX/JavaScript. From a technical perspective, we have relied on Google Cloud Services for our implementation. This approach supports visualizations over the web allowing the access of structured data sets and visualizing them easily with any compliant data sources.

Our prototype uses multiple representations, for instance, graphs, maps, data tables, charts and similar. These visual representations are embedded within the same prototype and can be accessed interactively. Three core libraries of Google Visualization API are included and loaded into the tool. The data is queried from spreadsheets in the remote server in order to visualize them. After loading libraries and querying the data, the chosen visual representations (e.g., scatterplot, line chart etc.) are instantiated and rendered. The tool also supports several filtering mechanisms for visualizing data

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according to date, group and attribute type (kind of sensor data). The data represented in the table format supports sorting of the values in ascending or descending manner. The screen shot of the web-based visualization tool is provided in Figure 1.

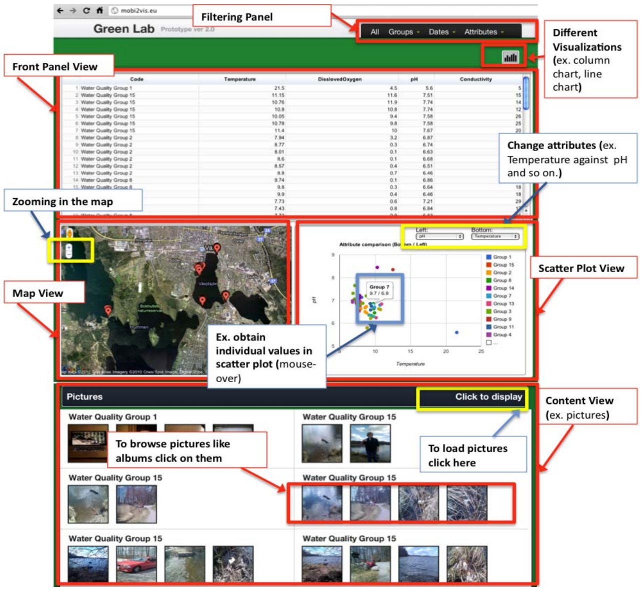

Figure 1. The screen shot of the web-based visualization tool.

III. RELATED WORK

Recently, there have been a number of efforts related to visualizing geo-tagged and sensor data using web-based technologies. Rodrigues and Rodrigues [2] have developed a visualization tool that makes use of maps APIs and Web 2.0 technologies to support asynchronous spatial collaboration between physically distributed users. In another project, GeoJunction [3], the authors propose a web-based geo-visualization tool for exploring geo-temporal data related to public health. The need for supporting collaboration using these technologies has been emphasized by MacEachren and Brewer [4] and their framework for visually enabled geo-collaboration. Throughout these projects, there is a need for conducting usability testing in order to validate novel concepts and ideas that involve the visualization of geo-temporal data sets. Slocum et al. [5] and Nöllenburg [11] suggest that applying usability evaluation to geovisualization tools and applications throughout the whole development process still remains challenging. Furthermore, the authors provide an overview of general challenges related to usability testing of geovisualization tools. Therefore, one important aspects in this field deals with identifying proper ways for conducting user testing of web-based visualization tools that represent geo-temporal data.

There are several approaches that deal with user testing and usability of web-based applications and prototypes evaluation. Fernandez et al. [12] have addressed aspects related to web usability evaluation. In a study they conducted, they present how the usability evaluation of the final user interface can provide feedback for improving usability problems/issues. One of the main results of their efforts is that usability concerns should be taken into account in the process of web development. This latest issue has been addressed also by the work of Shneiderman [13] and Preece [14]. They suggest that usability testing could be used in order to reduce the efforts at the maintenance stages of the web-based applications.

The studies presented above have defined several specific goals that concern usability evaluation as point out in [10], [12], and [15]. The main aspects that have been identified throughout these efforts and that are relevant for our user testing study are listed below:

- *Application functionality,*
- *Navigation (easy to retrieve and easy to browse contents),*
- *Interaction mechanisms and satisfaction of the users that use the web application*

The aspects identified above play an important role guiding the overall process of user testing and development of our web based visualization tool. Therefore, the main concern that guided this study could be formulated as follows: *To verify and understand if the design and development of our web-based visualization tool fulfills the user requirements in relation to application functionality, navigation and interactivity for supporting environmental science learning.* In order to validate usability aspects related to our prototype, we have conducted a user testing study that will be introduced next.

IV. USABILITY STUDY

One of the main objectives of our study is to identify usability issues related to the web-based visualization tool we have developed and implemented. The data collection techniques used in this study includes observations, tasks and questionnaires, analysis of screen capturing, and follow-up interviews. According to [15], the process of conducting a usability study includes a complementary approach that combines heuristic evaluation and user testing methods. A heuristic evaluation approach has been used during the three cycles of prototyping process of our web-based visualization tool as mentioned earlier, where we performed a systematic inspection of a user interface (see also Vogel [9]). This activity is illustrated in Figure 2 where heuristic evaluation represents the first step of the cyclic evaluation process. However, in this study we focus only on the user testing approach that represents the second phase of the evaluation process as suggested by [15].

Throughout this user testing, we have closely followed the cyclic evaluation process of a web-based visualization tool as described in Figure 2. Inspired by the work of Harms and Schweibenz [15], we have modified and extended this cyclic process by including screen capturing and follow-up interviews as additional techniques for collecting data that may help to further identify usability issues.

Developing materials for the user testing follows the second evaluation process in our study that includes *tasks* and *questionnaires, analysis of screen capturing,* and *follow-*

up interviews. The data gathered from the user testing is analyzed, and the suggestions for the rebuilt of the tool are introduced. This is an iterative cycle that continues towards the next version of the tool.

For developing materials and conducting the user testing, a mixed method using quantitative and qualitative analysis has been employed. Quantitative data gathered from questionnaires and tasks have been analyzed using descriptive statistics. The questionnaires were developed using a five points Likert scale (1 = Strongly Disagree; 2 = Disagree; 3 = Neutral; 4 = Agree; 5= Strongly Agree). These values represent the subjective satisfaction of the users with regard to the web-based visualization tool and its functionalities. For gaining in depth insights in these usability issues, we also performed a qualitative analysis of screen capturing and follow-up interviews.

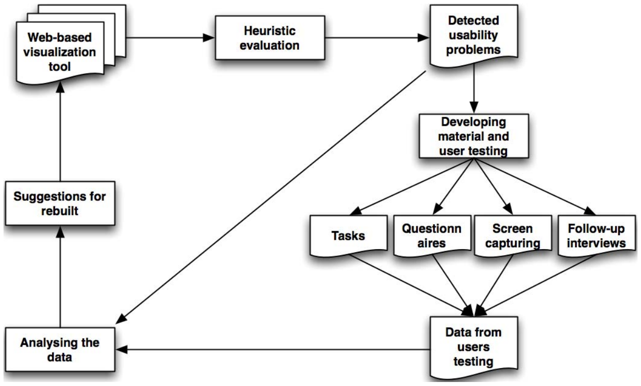

Figure 2. The cyclic evaluation process of a web-based visualization tool based on [15].

A. *Participants, Tasks and Settings*

We have conducted a study involving university students in the field of learning environmental sciences that used the web-based visualization tool. Eighteen participants took part in our user testing. Participants were undergraduate students (teacher students); some of them already with teaching experience in K-12 schools. They comprised a group that varied in ages from twenty up to forty-three years old; eleven of them were females and seven males. Previous to performing the user testing, participants have been involved in a series of learning activities related to the topic of water quality. Activities included an introduction lecture (in the classroom) to the topic followed by a hand on session (in the lab) and a field study in which the students measure water quality and collected sensor data using mobile devices.

In order to carry out the user testing, we developed ten specific tasks presented in Table I. They have been developed in order to identify the aspects related to usability issues of the tool. More specifically, the tasks helped us to assess the tools functionality, navigation and interactivity, and the user requirements derived from our earlier developments.

Each task had its own timestamp marked with start and end time. To enrich the quality of our data, we used a screen capture application on each computer to save the users' activities while performing the tasks. Participants spent approximately 30 minutes for performing all tasks. Additionally, students spent another 30 minutes answering questionnaires. After the initial analysis of the questionnaire and in order to increase the reliability of our results, we have performed analysis of the screen recording and conducted follow-up interviews with the participants. The follow-up interviews started a couple of days after the user testing.

TABLE I. THE TASKS

	Description
1	Show (using the filtering panel) the data collected from your group in the table view format.
2	Identify and browse the pictures taken by your group
3	Using the filtering panel, view the data collected from your group and another one beside yours.
4	In the front panel view, use the following icon 📊 to change the visualization type from table to column chart and then to line chart view.
5	Identify the conductivity values collected by your group only using Attributes in the filtering panel view. Then, present these values using the column chart view.
6	Plot the values of dissolved oxygen and pH for all groups in the scatter plot view.
7	Locate the points where your data has been collected using the zooming feature in the map view.
8	Show only the data collected by your group in the table view. With the mouse, point to the first row and look at that point in the map. Repeat this task for the third sample that was taken.
9	Using the column chart or the scatter plot view, place the mouse over the graphs and then obtain at least 4 individual values from 4 different attributes. Open a new tab in your browser, go to the following URL: http://xyz.com and type those values corresponding to your group
10	Find all the locations where pH was higher than "6.5". After you found the locations, go to http://xyz.com (same form as in Task 9) and type which of the samples (first, second or third, all or none of them) you took was the highest, and then press the submit button.

B. *Data Analysis and Results*

The questionnaire was comprised of seventeen questions. Thirteen questions were related to the tasks performed by the students, while the last four questions were related to the overall rating of the tool. In order to gain better insights from the results of the different tasks, some of them have been covered by more than one question. Based on the collected data (responses to the questions, time to finish each task, number of occurrences of answers), we analyzed the subjective ratings of the collected data using descriptive statistics by getting the *mean*, *standard deviation* and *confidence interval*. To get more reliable results, the desired confidence level was set to 95% for all calculations of the confidence interval. Figure 3 represents the overall results from the questionnaire. The bar chart presents the mean for each task as answered from the participants, and the error bars present the standard deviation for each task. The results suggest that the overall mean derived from all tasks is 4.2 with an overall standard deviation of 0.721. The overall confidence interval was ± 0.33 and the range for true population mean falls overall from 3.87 to 4.53.

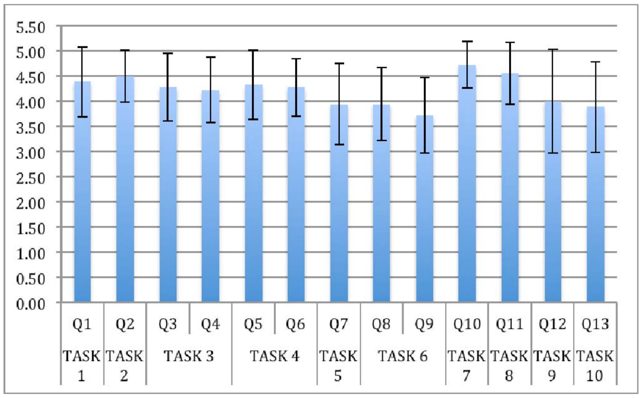

Figure 3. Questionnaire/tasks results

Although the overall results show a high level of satisfaction from the users, we have identified, especially from Tasks 9 and 10, that there were usability issues/problems. The purpose of these two tasks was to perform activities that include finding, navigating, analyzing and annotating data. In this regard, participants were required to obtain individual values using the visualization tool and afterwards to annotate this data (take notes). In these two particular tasks, we got the highest standard deviation values from questionnaires.

To further investigate the reasons behind the higher standard deviation values with regard to tasks 9 and 10, beside the questionnaires, we made cross-reference analyses relating the *number of occurrences* for answers, the *timing* required for accomplishing the tasks and the calculation of *confidence interval* for each question. These results are presented in Table II below and indicate that the *number of occurrences* for 'strongly agree' and 'agree' was relatively high. In particular, Table II presents the number of occurrences for each one of the answers, the approximate Time (≈) to accomplish a task and the confidence interval. The sign "/" in this table represents that none of the participants answered, and "0" means less than a minute. There is a difference on the *time* spent between Tasks 9 and 10 in comparison with the others. The total time spent in Task 9 for all participants was 92 minutes with an average time of 4 minutes per participant. The total time spent for Task 10 was 80 minutes, with an average time of 3 minutes per participant. Other tasks were performed on average in one minute or less time. Furthermore, the *confidence interval* for Task 9 was ± 0.48 with the range for true population mean from 3.52 to 4.48. This interval was ±0.42 for Task 10 with the range for true population mean from 3.47 to 4.31. These results clearly indicate usability issues of the tool related to the aspects of interactivity, navigation and orientation. Furthermore, they gave us an indication that there is a need to further analyzing the data in order to get a better understanding of the results that emerged during the user testing. Therefore, we followed up with the analysis of the screen recordings captured during the user testing study, and follow-up interviews, with a reason to further strengthen the results and analysis of our study.

C. *Screen Recording Analysis*

Screen recordings have been analyzed using a qualitative approach that focused on the identification of critical incidents. As an initial screen recording analysis, we have selected a couple of these recordings. Moreover, we identified slightly different answers/results during the screen recording data analysis than those from the questionnaires. This approach helped us to obtain and to specify the difficulties with regard to particular tasks users may have. The initial analysis of the screen recordings helped us to identify problems related to navigation, functionality, interaction and orientation within the tool. These problems are listed below.

- Students had difficulties using the filtering panel.
- User found difficult to understand whether they needed to tick the checkboxes in order to compare the data between different groups.
- The picture loading functionality was unclear.

TABLE II. OVERIVEW OF THE COLLECTED DATA.

Number of occurrences for each answer						Time		Confidence level 95%	
Task Question	**Strongly Dissagree**	**Dissagree**	**Neutral**	**Agree**	**Strongly Agree**	**Average ≈**	**Total ≈**	**Confidence Interval ±**	**Range for true population mean**
T1 - Q1	/	/	2	7	9	0	5	0.32	4.07 to 4.71
T2 - Q2	/	/	/	9	9	0	9	0.24	4.26 to 4.74
T3 - Q3	/	/	2	9	7	1	17	0.31	3.97 to 4.59
Q4	/	/	2	10	6			0.3	3.92 to 4.52
T4 - Q5	/	/	2	8	8	0	6	0.32	4.01 to 4.65
Q6	/	/	1	11	6			0.26	4.02 to 4.54
T5 - Q7	/	/	6	7	5	1	26	0.37	3.57 to 4.31
T6 - Q8	/	1	2	12	3	1	23	0.34	3.6 to 4.28
Q9	/	/	8	7	3			0.35	3.37 to 4.07
T7 - Q10	/	/	/	5	13	1	15	0.21	4.51 to 4.93
T8 - Q11	/	/	1	6	11	1	21	0.29	4.27 to 4.85
T9 - Q12	/	2	3	6	7	4	92	0.48	3.52 to 4.48
T10 -Q13	/	1	5	7	5	3	80	0.42	3.47 to 4.31
Total	**/**	**4**	**34**	**104**	**92**	**N/A**			

- It was difficult to find specific values in the data sets.
- It was very difficult for them to switch to another tab on the web browser and to write down the notes.
- Students had difficulties in finding the icons for changing the different type of visualizations.
- Finding the pictures related to each group was unclear.
- It was unclear how to obtain individual values from visual representations, such as scatter plot, bar chart or line chart.
- Students had difficulties on how to point to the table view and retrieve the data on the maps.

D. Follow-up Interviews

In order to get deeper insights beyond those issues identified in the previous section we also performed follow-up interviews. It is important to mention that some of the answers received during the interviews were slightly different from those we received from the questionnaire. The follow-up interviews allowed us to further clarify the results in general and helped us to get complementary information in relation to what the screen capture analysis showed. Although the interviews were conducted with a selected number of participants, we gained valuable information that helped us to improve our understanding with regard to potential problems with the tool. Those participants that finished the tasks fastest and those that finished slowest were selected for interviews.

The outcomes from the follow-up interviews provided us with additional insights to supplement the other information sources we had. A number of issues and suggestions for improvement have been identified and they are listed below:

- Tasks that were related to data comparison between different groups using the filtering panel were difficult.
- Some users indicated that they did not actually use the checkbox at all for performing the filtering.
- Finding the pictures with the correspondent groups in the content view panel was considered not an easy task.
- For some of the students, changing the visualization forms from one presentation to another was difficult (e.g., from table view to bar chart or line chart).
- On the map, the marker should include more information. For instance, pictures can be embedded on it implying that each location can have a starting point marked as Test 1 or Sample 1.
- Tasks 9 and 10 were difficult specifically for the note taking (annotation).
- The tool should support other languages in addition to English, so that it is easier to understand which concepts and terms are used.
- The tool should have a free text searching mechanism.

Overall, users reported that some tasks were easy to accomplish (mainly those related to navigation and identifying information), while some of them were very difficult to perform (especially those that required exploring, analyzing and reflecting on different representations of the data sets, as for Tasks 9 and 10). However, in general the students reported that using the tool helped them to visualize the data they collected in the field in novel ways. Overall, the students believed on the benefits of using this kind of visualization as a tool for supporting learning in the subject of study in this particular domain.

V. DISCUSSION AND LESSONS LEARNED

Based on the analysis of the data we collected two important aspects have been identified: 1) Users found the tool consistent and satisfactory for achieving their needs related to environmental sciences; 2) While performing relatively complex tasks, users identified a number of difficulties related to usability issues. The results indicated that overall there was a high level of satisfaction with the tool (mean 4.2, stdev 0.721, and confidence interval ±0.33 with the range for true population mean from 3.87 to 4.53). Statistical results, especially those related to Tasks 9 and 10 pointed out some issues related to the usability of our tool. Data gathered from the screen capturing and follow up interviews strengthened these results and suggested that there were some problems while changing different visualizations, obtaining individual values, annotating the data, and loading the pictures. More specifically, we have identified that the lack of note taking/annotation functionality clearly affected the usability of the tool (as indicated for Tasks 9 and 10). The results of the questionnaires, screen recordings and follow-up interviews indicated that this functionality should be included in the coming version of the tool.

The use of multiple data gathering techniques (questionnaire, screen capturing, and follow-up interviews) has provided clear benefits in terms of identifying usability problems. The combination of these methods provided more reliable interpretation of the data we collected. This mixed approach seems to be beneficial if compared with using only one type of data gathering approach, as we may have faced contradictory results. Such a situation can be clearly identified in some cases in which the answers of the questionnaires did not correspond with the actual experience of the users while using the tool (screen recordings and follow-up interviews).

TABLE III. SUGGESTIONS FOR REBUILT

Suggestions	**Functionalities Rationale**	**Description**
Application functionality	*Search* *Note taking or annotation*	Free text search functionality. Seamlessly integrated and implemented note taking mechanism.
Navigation	*Filtering panel* *Checkboxes* *Pictures*	More visible filtering panel with improved filtering options. Improve pictures loading and filtering.
Interaction	*Changing visualizations* *Orientation or Browsing*	Better visibility and style of the icons. More compact design.

The primary aim of this user testing was to validate different aspects of our web-based visualization tool in order to get suggestions for its further enhancement. These suggestions resulted from the compilation of the overall analysis of the collected data. Table III illustrates and categorizes the different results in relation to concrete recommendations for further enhancement of the tool.

VI. CONCLUSIONS AND FUTURE WORK

Our experience with this user testing study was valuable in terms of identifying usability issues connected to our application. The outcomes of our results indicate that the current version of our web-based visualization tool meets the basic needs of the users in order to perform specific tasks and activities in the field of environmental sciences. However, as the results indicate not all aspects of *application functionality, navigational* and *interaction* of our prototype application are satisfactory. On the other hand, from the description of the tasks and the data represented in Table II, it could be noticed that there is a linear dependency between the complexity of the task, the functionality provided by the tool and the results gained from the questionnaire. In particular, these issues were evident in Tasks 9 and 10, where it was required to explore, search, retrieve and annotate different content and sensor data using multiple representations. The overall analysis for these two tasks (standard deviation, number of occurrences, time completion and confidence interval) provides a strong indication, which affected the usability of our tool. The overall analysis of the data we collected (*tasks* and *questionnaires, analysis of screen capturing,* and *follow-up interviews)* indicates that participants experienced the web-based visualization tool as easy to use, with an overall high level of satisfaction. Users provided also valuable and constructive feedback in relation to further enhancements of the tool, which will serve as concrete suggestions for the rebuilt of the tool. One of the most salient points was that the tool does not directly support yet collaborative tasks, especially those that include note taking and annotations.

From a methodological perspective, we also consider that the process of prototyping and usability evaluation should be combined in an iterative manner in order to provide a better ways for including potential suggestions for improving already during the prototyping process. Furthermore, we consider that the cyclic evaluation process seems to be a suitable approach for conducting user testing studies of web-based visualization tools. This may be a possible answer to the usability challenges in this field, as we have mentioned earlier in Section II. With regard to the reliability of the results, we consider that a mixed method approach that combines different data gathering techniques including questionnaire, screen recordings and follow-up interviews seems to be a viable strategy to provide complimentary data sources that help us to understand how users interact with the tool.

Reflecting upon the lessons learned in this study and the conclusions described above, we plan in our coming efforts to continue to use the cyclic evaluation process for our future developments. The focus of these efforts will be primarily on developing and implementing new features and functionalities to support collaborative activities. Furthermore, from a development perspective we envision the possibility to create new visualization tools based on web technologies to support synchronous collaboration between physically distributed users in indoors and outdoors settings.

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Appendix B

Usability Study - Tasks

USABILITY STUDY
Tuesday, October 26, 2010

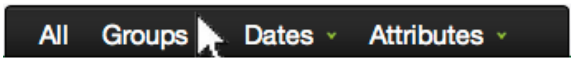
LETS GO Visualization Tool - Usability Study

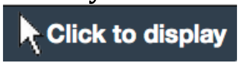
Dear Participant,

The aim of this study is to gain a better understanding of those aspects related to the usability and usefulness of the Mobi2Vis web based visualization tool. The tool has been developed in order to support inquiry based science learning activities that take place in the classroom and outdoors.

Note: Please go to the following URL: http://xyz in order to work with the tool. You should first spend approximately 5 -10 minutes exploring and playing around with the visualization tool before performing the tasks described below. Thank you for your assistance.

Best regards.
The LETS GO Team

TASK 1	
Show (using the filtering panel) the data collected from your group in the table view format.  	
START TIME	**END TIME**

TASK 2	
Identify and browse the pictures taken by your group.  	
START TIME	**END TIME**

TASK 3	
Using the filtering panel, view the data collected from your group and another one beside yours.	
START TIME	**END TIME**

USABILITY STUDY
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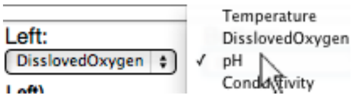
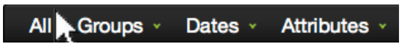
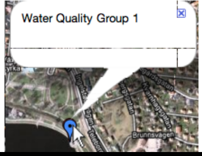
<table>
<tr><th colspan="2">TASK 4</th></tr>
<tr><td colspan="2">In the front panel view, use the following icon 📊 to change the visualization type from table to column chart and then to line chart view.</td></tr>
<tr><td>START TIME</td><td>END TIME</td></tr>
<tr><td></td><td></td></tr>
</table>

<table>
<tr><th colspan="2">TASK 5</th></tr>
<tr><td colspan="2">Identify the conductivity values collected by your group only using Attributes in the filtering panel view. Then, present these values using the column chart view.</td></tr>
<tr><td>START TIME</td><td>END TIME</td></tr>
<tr><td></td><td></td></tr>
</table>

<table>
<tr><th colspan="2">TASK 6</th></tr>
<tr><td colspan="2">Plot the values of dissolved oxygen and pH for all groups in the scatter plot view.
 and after  </td></tr>
<tr><td>START TIME</td><td>END TIME</td></tr>
<tr><td></td><td></td></tr>
</table>

<table>
<tr><th colspan="2">TASK 7</th></tr>
<tr><td colspan="2">Locate the points where your data has been collected using the zooming feature in the map view.
 </td></tr>
<tr><td>START TIME</td><td>END TIME</td></tr>
<tr><td></td><td></td></tr>
</table>

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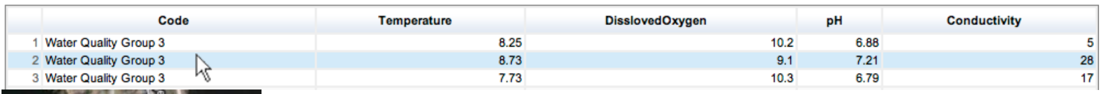
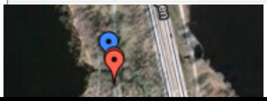
TASK 8

Show only the data collected by your group in the table view. With the mouse, point to the first row and look at that point in the map. Repeat this task for the third sample that was taken.



	Code	Temperature	DisslovedOxygen	pH	Conductivity
1	Water Quality Group 3	8.25	10.2	6.88	5
2	Water Quality Group 3	8.73	9.1	7.21	28
3	Water Quality Group 3	7.73	10.3	6.79	17

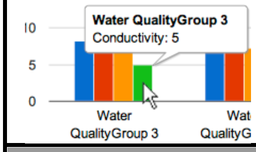


START TIME	END TIME

TASK 9

Using the column chart or the scatter plot view, place the mouse over the graphs and then obtain at least 4 individual values from 4 different attributes. Open a new tab in your browser, go to the following URL: http://xyz and type those values corresponding to your group.

*Note: do not press the “submit” button until you finish task 10.



START TIME	END TIME

TASK 10

Find all the locations where pH was higher than “6.5”. After you found the locations, go to http://xyz (same form as in Task 9) and type which of the samples (first, second or third, all or none of them) you took was the highest, and then press the submit button.

START TIME	END TIME

Appendix C

Usability Study - Questionnaire

Tuesday, October 26, 2010

QUESTIONNAIRE RELATED TO TASKS

LETS GO Visualization Tool - Usability Study

Dear participant,

Please read carefully the statements below before selecting your answer. The data we will collect will help us to enhance and to improve the visualization tool. Thank you again for your assistance.

Best regards.
The LETS GO Team

The values of your answers are based on the scale presented in the table below:

Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

My age is ____ years old and

I am

○ Female ○ Male

TASK 1

1. Showing the data collected by my group in the table view format was easy.

○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

TASK 2

2. Browsing and viewing the pictures taken by my group was easy.

○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

TASK 3

3. Viewing the data collected by my group and another group using the filtering panel was easy.

○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

4. While viewing the data collected by my group and another group the appearance and layout of the tool was consistent.

○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

TASK 4

5. Changing the representation type in the front panel view from table to column chart and then to line chart was easy.

○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

6. Changing the table view to column chart and then line chart was done smoothly without changing the appearance of the rest of the screen.

○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

TASK 5

7. Identifying all conductivity values collected by my group using the Attributes in the filtering panel, and presenting them in the column chart view was easy.

○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

TASK 6

8. Plotting the values of the dissolved oxygen and pH in the scatter plot was easy.

○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

9. While plotting the values of the dissolved oxygen and pH there were not major changes in the layout of the screen.

○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

TASK 7

10. Using the zooming feature in the map view to locate the points where my data has been collected was easy.

○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

TASK 8

11. Locating the point in the map, using the table view with the mouse was easy.

○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

TASK 9

12. Obtaining the individual values from the column chart or scatter plot, using the mouse over feature was easy.

○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

TASK 10

13. Finding all the locations on the map where the pH value was higher then “6.5” was easy.

○ Strongly Disagree ○ Disagree ○ Neutral ○ Agree ○ Strongly Agree

GENERAL QUESTIONS

14. Overall, the filtering mechanisms provided by this tool make the application easy to navigate.

○	○	○	○	○
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

15. The different filtering mechanisms made it easy to find task related information.

○	○	○	○	○
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

16. Overall, this tool was very useful in the context of the learning activity that I needed to perform today.

○	○	○	○	○
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree

17. As a future teacher, I see a great potential of using web based visualization tools for exploring environmental related issues with my students.

○	○	○	○	○
Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree