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Multidisciplinary Collaboration Through Online Virtual Research Environments (VREs): what do VRE users need?

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***Abstract*—Making new data combinations and collaborating with researchers from different disciplines are becoming essential ingredients of scientific research. These activities are increasingly contributing to solutions for multidisciplinary global problems, such as climate change and energy transition. Virtual Research Environments (VREs) can potentially support making data combinations and researcher collaborations by providing a multiplicity of data and services. Many VREs have been developed already and are used in specific research domains. However, there is a lack of insight into what is needed to develop a multidisciplinary VRE in comparison with monodisciplinary VREs. This is currently blocking the development of innovative multidisciplinary VREs. This study aims to investigate the requirements for building a multidisciplinary VRE and to study the key differences between monodisciplinary VREs and multidisciplinary VREs. Our study shows that comprehensive requirements in nine categories need to be fulfilled when designing a multidisciplinary VRE. Lack of considering many requirements and limit focus in monodisciplinary VREs hinder the wide use of current VREs in multidisciplinary research.**

Keywords—VRE; research data sharing; requirements; multidisciplinary Virtual Research Environment; science gateway

I. Introduction

Virtual Research Environments (VREs) have become critical to modern research processes [1]. VREs or Science Gateways, aim to support researchers from multiple disciplines to collaborate [2]. They do so by managing the increasingly complex range of tasks involved in carrying out research on both small and large scale, such as tracking the change of data using information from seafloor scans for undersea archaeology, using data on greenhouse gas concentrations for climate change research, or research on the Internet-of-Things. In a study conducted by Zuiderwijk, Jeffery [3], they state that VREs consist of three major components or layers, namely:1) e-Infrastructures(e-Is) providing Information and Communication Technology (ICT) facilities; 2) e-Research Infrastructures (e-RIs) providing access to data, software and computing resources; 3) the VRE with its users, who can cooperatively work through the VRE to conduct various research activities [3-5].

Many VREs have been developed and used for specific research domains. For example, the *EVER-EST* [6] and the *EPOS* [7] VRE in earth sciences, the *VI-SEEM* [8] VRE in life sciences, climatology and digital cultural heritage, and the *GenePattern* [9] VRE in biological sciences. Requirements for VREs in monodisciplinary research have already been investigated. They include easy-to-use interfaces, adequate data storage, available analysis tools, high performance computing resources [10, 11], secure access mechanisms via the same credentials [11], metadata management [12], help and training support for VRE users [10].

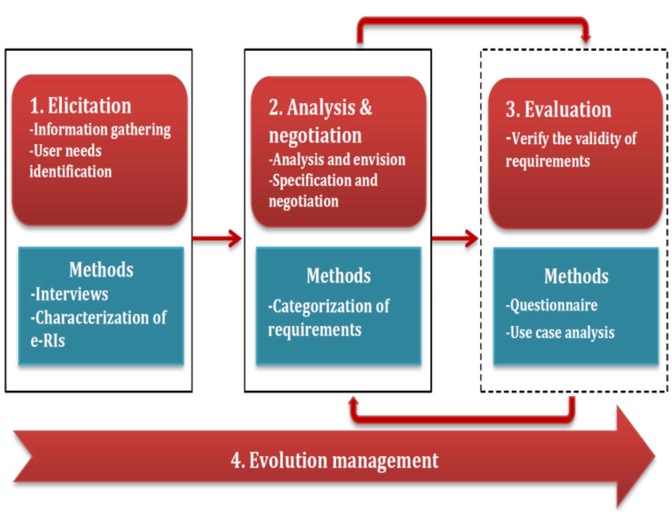
Multidisciplinary research, intending to solve many problems, such as climate change, environmental pollution, and earthquakes monitoring and prediction, needs to combine data from several disciplines and requires collaboration. However, there is a lack of insight into what is needed to develop a multidisciplinary VRE in comparison with monodisciplinary VREs. This is currently blocking the development of innovative multidisciplinary VREs. The objective of this study is twofold: 1) to investigate the requirements for building a multidisciplinary VRE and 2) to study the key differences of current practices of monodisciplinary VREs in comparison with multidisciplinary VREs. To attain this objective, we have investigated VRE requirements using multiple methods, including a literature review, interviews with potential VRE users and developers, and the characterisation of existing research infrastructures.

This paper is organized as follows. Section 2 describes the requirements engineering approach applied in this study. Section 3 and 4 describe the requirements for monodisciplinary VREs and multi-disciplinary VREs accordingly. In Section 5, we compare the requirements between monodisciplinary VREs and multidisciplinary VREs. Section 6 concludes this paper.

II. REQUIREMENT ENGINEERING APPROACH

VREs support research by interconverting between the multiple underlying e-RIs supported by e-Is, while the VRE users neither know nor care about the underlying e-Is [3]. Depending on e-RIs, VREs are on a higher level of hierarchy than e-RIs and underlying e-Is, and provide more advanced functionalities for their end-users which are mainly researchers. The perspective of the user, i.e. the researcher, is essential for developing the VREs. Understanding user requirements is generally recognized as the most crucial and the most difficult stage for the successful development, deployment and evolution of information systems [13-15]. This is also the case for the VREs. Aybuke and Claes [16] state that requirements should include both user needs and needs arising from other stakeholders like organizations, governmental bodies and industry standards. What is common among requirement definitions is that they refer to describing what the proposed information system is supposed to do and how it should do this [13, 16, 17]. However, the understanding regarding "what" and "how" differs per stakeholder, and it is not easy to identify the differences between various requirement classifications in practise [18]. In this study, we adopted the definition of requirement from Aybuke and Claes [16], namely descriptions of how a software products should perform.

Figure 1 The requirement engineering process used in the research



The requirements engineering process concerns the investigation and learning about the problem domain in terms of understanding the actual goals, needs and expectations of the users regarding a system [19]. Browne et. al (2001) stated that this process consists of three steps, namely: 1) information gathering, 2) representation and 3) verification [15]. Maguire et. al (2002) mentioned that the requirement analysis process encompasses 4 steps, namely 1) information gathering, 2) user needs identification, 3) envisioning & evaluation and 4) requirement specifications. Parviaien et. al (2003) stated three phases in the requirement engineering processes, including 1) requirements elicitation, 2) requirements analysis & negotiation and 3) requirements validation [20]. We state that in reality the requirements collection is a continuous and iterative process which needs to accommodate changes from the involved organizations, environment and stakeholders. From these engineering processes we derived four common elements as shown in Figure 1, namely 1) elicitation, 2) analysis and negotiation, 3) evaluation and 4) evolution management. Below we explain how we identified and elicited requirements in this research through each of the steps shown in Figure 1.

Step 1: Elicitation

Requirements elicitation helps to discover and conceptualize system requirements through information gathering and user needs identification. We collected background information from interviews and publicly available documentations of existing VRE research projects. After the user information is collected, analysis can start to identify the real user needs and expectations. In this research we use existing VRE projects and the characterisation of e-RI projects to identify user needs. Interview protocols were created to collect information from the end-users and VRE developers [21]. Ten interviews have been conducted (see Table 1).

TABLE 1 Overview of interviews for requirements information collection

Interviewee #	Role of interviewee	Experience with VREs	Research domain
1	Potential VRE end user	No	Civil engineering
2	Developer	Yes	Earth science
3	Potential VRE end user	Yes	Earth science
4	Potential VRE end user	Yes	Physics
5	Potential VRE end user	No	Physics
6	Developer and potential VRE end user	Yes	Health
7	Developer	Yes	Computer science
8	Developer	Yes	Information science
9	Potential VRE end user	Yes	Library
10	Developer	Yes	Environmental sciences

A VRE allows for connecting existing VREs and e-RIs, we have analyzed the functionalities in the existing VRE projects as a starting point to understand the VRE requirements. Eight ESFRI landmark projects have been selected for analysis. These projects are relatively mature VREs or e-RIs which have been developed or are already in operation now. These VREs focus on a single discipline such as earth science, social science, or life science. A protocol guiding and structuring the characterisation of e-RIs was also created on the basis of six key types of functional elements in an e-RI defined by the ENVRIPlus project [22]. The questions of these three protocols were created using the Reference Model of Open Distributed Processing (ODP) [23]. The questions covered each of the five ODP viewpoints: enterprise (science), information, computation, engineering and technology. The VRE should account for the needs of heterogeneous user groups. In addition, the questions concerning activities of VRE users addressed user activities in line with those mentioned in the literature [24, 25].

Step 2: Analysis and negotiation

Once an initial set of user requirements has been formulated, requirements can be detailed, discussed and agreed by stakeholders in the analysis and negotiation phase, including two main steps:

1) Analyse and envision. When analysing and describing the requirements, it is essential to fully document "the design element or its interfaces in terms of requirements (functional, performance, constraints and design characteristics)" [26]. After describing the requirements, it is also necessary to develop a conceptual prototype to illustrate the requirements and get feedback from the stakeholders. On the basis of the feedback, the requirements are evaluated and may be modified.

2) Specification and negotiation. In the analysis step of user requirements, the following should be discussed with all stakeholders and documented within the specification: identification of the range of relevant users, clear design goals, the requirements with prioritized levels and evaluation criteria to test the requirements whether they will be fulfilled and evidence of acceptance of the requirements by stakeholders. The following methods are used for specification and negotiation: function mapping, requirements categorisation [14].

Step 3: Evaluation

The evaluation of requirements is to check the consistency and completeness of the requirements [20]. This phase is concerned with the examination of the requirement description to ensure that it defines the system in an accurate and comprehensive way. In this research, we have used use case analysis, online questionnaire and several workshops with VRE experts to evaluate the collected requirements. After these activities, we have also designed a VRE system architecture to accommodate all collected requirements.

Step 4: Evolution management

Requirements are the starting point for the system design phase [20]. However, we cannot wait for complete requirements as the content and the priority of the initial requirements may evolve and change during the development process. Therefore, we also keep track of changes in or new requirements. These initial requirements have been used to define the system functionalities when designing the VRE architecture. During the development of the VRE architecture and analysis of use cases, some additional requirements have been identified. These requirements are not new but support requirements identified in step 2.

In this study, we focused on the research results from the step 1 and step 2 while the results from step 3 and step 4 are beyond the scope of this paper.

III. Elicitation of mono-disciplinary VRE requirements

In order to tackle the global challenges and solve complex scientific problems, scientists need to use VREs as shorthand for the tools and technologies. They can conveniently make use of resources and technical infrastructures available both locally and remotely to conduct their research and to interact with other researchers who might be from different countries.

Therefore, VREs need to provide tools and computing resources related to data acquisition, data storage, data processing, and data analysis. According to the e-infrastructure research project ENVRIplus, VREs should meet requirements and provide six types of functionalities, including data identification and citation, i.e. assigning global unique identifiers to data; data curation, i.e. data quality check; data cataloguing, i.e. adding metadata to datasets; data processing, i.e. converting data format and data visualization; data optimization, i.e. data compartmentalization; and data provenance, i.e. tracking the changes of data. We also add collaboration, training and support as an additional category in this table, since researchers are in need of support related to finding collaboration for research projects, i.e. finding the collaborators with specific expertise, writing grant proposal and research project management tools, according to interviewees #1, #8, and #9.

According to the interviewees #1, #3, #4, #5, and #9 (als researchers that are potential VRE end-users), a quickly-accessible, reliable, easy-to-use, low-cost VRE is expected. Therefore, when designing the VRE, it is very important to also consider the non-functional performance-related requirements defined by commonly used software engineering standards in FURPS+ and ISO 25010:2011 such as efficiency, usability, reliability, maintainability, sustainability, compatibility and portability.

In addition, interviewee #6 indicated that all VREs have to carefully deal with data containing privacy sensitive information. Therefore, privacy, security, trust and legal requirements are necessary to be considered in term of regulatory compliance. Privacy and security requirements specify how the use of the VRE should be robust against cyber-attacks in term of enhanced privacy and security. Trust requirements specify the acceptable behaviours of the stakeholders in the VRE, such as users, system developers and service providers. Legal requirements specify that the whole development of VRE should comply with all legislation, especially the new General Data Protection Regulation issued by the European Parliament, the Council and the Commission in 2015.

Research into mono-disciplinary VREs already shows that many challenges exist for the use of VREs [27], including: data context issues (understanding the creation context of research data), data heterogeneity issues (large amount of data generating from various sources), data quality issues (it is not easy to control data quality), privacy issues (datasets containing privacy information need to shared and reused), user experience issues (the expectation of users on the system varies), availability of technology issues. Previous research also shows that for multidisciplinary VREs, even more challenges should be added to this list, since multidisciplinary VREs need to interoperate between a large variety of standards, ontologies and terminologies used by different research disciplines in different countries. According to the information from interviews and the e-RI characterisations, additional challenges concern the availability of data from different sources, data use licensing for different organizations, scalability in terms of connecting High Performance Computing (HPC) facilities, system management responsibility and financial support. Another challenge concerns the access policy. VRE system administrators prefer one certificate per research community in order to lower the effect on user credential management[11], while many organizations cannot easily make agreements on sharing certificates to grant access to VREs.

From the requirements collection work, we have analyzed eight monodisciplinary VREs or e-RIs based on seven functional requirement categories. These VREs provide integrated services and datasets and cross-country access to various resources for research. Researchers from the same research domain can use these resources. Some VREs only provide these services to authorized researchers. Researchers from other disciplines or general public cannot easily access some of these VREs. Some VREs are still in the development phase, although some functionalities in the seven categories are being designed or already implemented. The usability of these functionalities significantly varies. These VREs mainly provide dataset download and limited data analysis tools. The collaboration, training and support functionalities are largely missing in these VREs and e-RIs.

IV. Analysis of Requirements for Multidisciplinary VREs

In this section we describe the requirements for multidisciplinary VRE collaboration, compared to mono-disciplinary VRE use. Table 2 presents a list of requirements for the development of a multidisciplinary VRE, containing nine categories of requirements, namely:

1) ***Data identification and citation requirements*** which define the approaches to provide everlasting and unique references to each research data object;

2) ***Data curation requirements*** which define the needs of processes to assure the availability and quality of data object over the long term;

3) ***Data cataloguing requirements*** which define the needs of easy and quick access to data objects by queries over catalogues;

4) ***Data processing requirements*** which define the needs of providing computational transformation software on data objects;

5) ***Data optimization requirements*** which define the needs of providing computational transformation and processing towards desired effects from the viewpoint of data object creator or users;

6) ***Data provenance requirements*** which define the needs of making logs on the transformation and computational process on data objects;

7) ***Collaboration, training and support requirements*** which define the needs of providing research collaboration tools and manuals for using VREs systems;

8) ***None-functional requirements*** which define the software performance related objectives such usability, stability;

9) ***Security, privacy trust and legal requirements*** which define the needs of system design in compliance with all regulation and improvement measures in terms of improving users' overall trust on the VREs.

TABLE 2 Overview of requirements for a multidisciplinary VRE

Category	**Requirement example**
Data identification and citation	- Ability to assign (global) unique identifiers (e.g. DOIs, ePIC, URIs) to data contents - Ability to assign an accurate, consistent and standardized reference to a data object, which can be cited in scientific publications
Data Curation	- Ability to detect and correct (or remove wrong data - Ability to support manual quality checking
Data Cataloguing	- Ability to associate a data object with one or more metadata objects which contain data descriptions - Ability to select a subset of individuals from within a statistical population to estimate characteristics of the whole population
Data processing	- Ability to convert data from one format to another format - Ability to inspect, clean, transform data, and to provide data models with the goal of highlighting useful information, suggesting conclusions, and supporting decision making
Data optimization	- Large datasets processing - Data compartmentalization
Data provenance	- Data Provenance: Ability to provide "pathways of data" or the history of data information (provenance data) - Data publication information: Ability to provide data publication information (e.g. which data was accessed, which data is not accessible, which query was carried out and when)
Collaboration, training and support	- Notifications: Sending notification when certain information becomes available to the users - Finding collaborators: Ability to locate previous collaborators and potential collaborators
Non-functional (System Performance)	- Usability - Performance efficiency - Reliability - Maintainability - Sustainability
Privacy, security, trust and legal requirements	- Specified service authorization contract - Specific definition regarding software service authorization in compliance with legislation - Secure storage and use of data, especially data containing privacy information

This list contains 148 requirements in 9 categories which have been reported in a project deliverable of the VRE4EIC project [21]. Our requirements provide a comprehensive overview of many perspectives that need to be considered during the development of VREs. The requirement categories mentioned in Table 2 are also important to monodisciplinary VREs, however, the examples of the requirements themselves are specific to multidisciplinary VREs.

V. DISCUSSION

We have analyzed eight e-RIs and VREs to understand the current practices in the development of VREs. Table 3 showed the implementation of functional requirements in these projects. From the table we can see that many projects have considered data-related requirements while collaboration requirements are largely ignored. Although the categories of the requirements have been covered by many existing VRE projects, but the range and details of specific requirements in each categories are not comprehensive enough for developing a multi-disciplinary VRE. Privacy and trust related requirements have not been identified in these projects.

TABLE 3 Characterisation of the e-Research Infrastructures and Virtual Research Environments.

e-Research Infrastructure / Virtual Research Environment	**Requirements**						
	Identification and citation	Curation	Cataloguing	Data Processing	Data Optimization	Data Provenance	Collaboration, training & support
EURO-ARGO	●	●	●	*	*	●	○
ICOS	●	●	●	●	●	●	○
EPOS	●	●	●	●	●	●	*
ELIXIR	●	●	●	●	●	●	○
Lifewatch	●	●	●	●	●	●	○
CESSDA	●	●	●	●	●	●	*
ENVRIPLUS	●	●	●	●	●	●	*
CLARIN	●	●	●	●	●	●	*

● Requirements covered
○ Requirements not covered
* Requirements suggested by the project vision or limitedly covered

A multidisciplinary VRE is ideally open to any researcher. In our study, we found that many researchers are already using some domain-specific resources like research data, software tools or e-infrastructures to support their research activities. However, these resources are only known or open to a small research community. Some of the mono-disciplinary VREs we studied claim to be openly accessible, but they are de facto only open to some researchers due to bureaucratic user registration and approval processes. It is very difficult for researchers from other domains to find these existing VREs since they are not aware of the VRE development in the research domain other than their own science community.

When a new VRE becomes available, researchers do not just move from one e-RI or VRE which they are already familiar with to another. The process of transferring from one VRE to another creates challenges for researchers. Since the usability of existing mono-disciplinary VREs developed based on the requirements in Table 3 significantly varies, the interoperability of those VREs cannot meet the researchers' demands in multi-disciplinary research. In addition, researchers do not want to spend much time on learning how to use new software or work in a new online environment. Therefore, easy access to data from multiple disciplines and to computing resources are crucial. A portal or gateway connected with those resources might be suitable to fulfill this task.

In multidisciplinary research, researchers desire to use a single tool with an easily understandable Graphical User Interfase (GUI) and plug-and-play features provided by different VREs or e-RIs to submit their experiment tasks, data analysis assignments and to monitor the status. They do not want to know the complexity behind simultaneously running these tasks. A powerful workflow engine with an intuitively usable GUI needs to be designed in a multidisciplinary VRE to integrate several mono-disciplinary VREs.

Different research communities use different standards and data models to process research data. Researchers from the same research domain can use their own standards and practices for data processing. In multidisciplinary research, researchers need to combine data from different research domains with interoperable data processing tools. Our research showed that they do not want to encounter errors when they put the data in the VRE system. In the interviews, researchers also expressed their concerns related to the control of their data if shared with other researchers. They want their work and data to be acknowledged and properly referred to when used by others. In a multidisciplinary VRE stored data and data use are more complex compared to a mono-disciplinary VRE, thus better security mechanisms are required without hindering the ease-to-use of the system.

In general, we found that there remains a big gap in the completeness of requirements fulfilled by the existing mono-disciplinary VREs towards multidisciplinary VREs. This is shown in Table 3. A comprehensive multidisciplinary VRE should fulfill the requirements described by in the aforementioned nine requirement categories (see section IV). Multidisciplinary VREs need to be developed in terms of interoperability, a single gateway with an intuitive GUI to easily access data and computing resources, and complying with data protection regulation.

VI. CONCLUSIONS

This research aims to 1) study the requirements for developing a multidisciplinary VRE, and 2) investigate the requirement differences between the current practices of monodisciplinary VRE and the requirements of developing a multidisciplinary VRE. A comprehensive set of requirements needs to be considered when developing a multidisciplinary VRE. Building on the ENVRIplus categorization for e-Research Infrastructure requirements, we categorized functional requirements in the following categories: data identification and citation, data curation, data cataloguing, data processing, data optimization, data provenance, collaboration, training and support. Non-functional requirements were added to this categorization and collected in the categories of performance-related requirements, security, privacy, trust and legal requirements.

Researchers' concerns on losing control of their own research data, lack of interoperability between different VREs and e-RIs and e-Is, as well as lack of comprehensive consideration of various requirements in monodisciplinary VREs limit their adoption for multidisciplinary research. When developing multidisciplinary VREs, we have to take all these requirements into consideration and choose suitable technologies to meet them. However, we have to admit that developing VREs is a rather complex engineering process. Requirements identified in this study may not be implemented at once, but fulfilled stage by stage during the development of mature multidisciplinary VREs.

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