A Multidimensional-Paradigm-Centered Architecture for Cooperative Digital Ecosystems

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Abstract: *Cooperative Digital Ecosystems* are an emerging class of information systems where the main goal is that of *supporting cooperation* in human activities, driven by ICT technologies. Inspired by this main area, in this paper we provide the anatomy and definitions of *a multidimensional-paradigm-centered architecture for supporting Cooperative Digital Ecosystems*.

1 INTRODUCTION

Cooperative Digital Ecosystems (e.g., (Bakhtadze & Suleykin, 2021; Li *et al.*, 2012; Tsai *et al.*, 2022)) are an emerging class of information systems where the main goal is that of supporting cooperation in human activities, driven by ICT technologies. In this context, this paper proposes *a multidimensional-paradigm-centered architecture for supporting Cooperative Digital Ecosystems*, called *KnowExplo*. *KnowExplo* focuses on the definition of models, methodologies and tools in the field of *Open Source ICT technologies* that can be applicable to cooperative digital ecosystems, such as *data*- and *knowledge-intensive environments* (e.g., (Draheim *et al.*, 2021; Kuruppuarachchi *et al.*, 2022; Riasanow *et al.*, 2021)). They play a supporting role in the production, management and dissemination of knowledge performed by *Users*, *Operators* and *Decision Makers*. Recently, there has been a relevant interest about the interaction of such class of systems with emerging *big data trends* (e.g., (Cuzzocrea, 2009; Cuzzocrea & Serafino, 2009; Cuzzocrea & Wang, 2007; Cuzzocrea & Matrangolo, 2004; Cuzzocrea *et al.*, 2003)), like highlighted by recent studies (e.g., (Rrushi & Nelson, 2015; Schultes *et al.*, 2022; Sheng *et al.*, 2016)).

KnowExplo is characterized by an architecture inspired by the *multidimensional paradigm* (e.g., (Gray *et al.*, 1997)), as modern systems have a *multidimensional*, *multi-level* and *multi-resolution nature*. This paradigm is used by actors in an interactive and cooperative way, followed by multidimensional analysis of unconventional data such as *XML documents*, *Web pages*, etc. The main features of the *KnowExplo* platform concern with the aspect of evolution of models and data schemas which do not have a fixed and rigid structure but are *flexible* on the basis of the evolution of interactions among actors. The lifecycle of data- and function-levels is characterized by an *innovative* and *non-conventional* paradigm, and the level of interaction and cooperation with processing models is characterized a *semi-structured* and *reconfigurable* paradigm. In this paper, we also describe the implementation of the target architecture through a *component structure* with different functionalities.

In order to describe the *KnowExplo* platform, several components are introduced. First, the *Information/Knowledge Extraction* component is identified, in order to extract information and knowledge from the primary data sources. Then, the *Ontology Modeling/Mapping* component, which creates appropriate *mapping* with the *multidimensional schemas* of the global repository, called *MD Universal Schema* (MDUS), is identified. In particular, multidimensional modelling of the MDUS schemas and their evolution using Data Mining algorithms, such as *clustering* and *frequent-itemset-mining*, over *Constellations of Facts* are

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introduced. Another goal of the actual research proposal focuses the attention on the *efficient representation* of multidimensional structures in secondary memory, as well as querying and browsing procedures to be implemented within the *KnowExplo* platform.

With these principles in mind, one of the most probing research challenges figured-out by the *KnowExplo* platform consists in the issue of effectively and efficiently presenting data, information and objects from primary sources to actors, being such data useful in cooperative and decision-making processes. This will be also discussed throughout the paper.

In addition to these contributions, several *cloud-computing-based verticalizations* of the proposed platform are described, namely: *Taxation*, *Justice*, and *Social Networks*. Finally, the development environment is presented through a *collection of programmable APIs* and implementation of case studies.

2 THE KnowExplo PLATFORM

The general objective of the *KnowExplo* platform can be summarized in the definition of a set of models, methodologies and tools (with relative implementation and experimentation in the form of case studies and significant verticalizations) that are positioned in the context of *support of Open Source ICT technologies to digital ecosystems that are strongly characterized by a high degree of interaction and cooperation among the actors involved in the stages of production, management and dissemination of knowledge, in the dual form of data and processes*. Due to these specific characteristics, the digital ecosystems of interest by the platform are classified as *data-* and *knowledge-intensive environments*.

Actors of these digital ecosystems can be classified into three large groups: *Users*, *Operators*, *Decision Makers*. *Users* request and perform services/functions available in the reference digital ecosystem; *Operators* act as an intermediary between the *Users* and the services/functions available in the reference digital ecosystem; *Decision Makers* carry out decision-support processes aimed at modifying/restructuring the services and functions available on the basis of the *general progress* of the digital ecosystem, and the achievement of a pre-fixed set of business objectives.

As previously mentioned, in such a scenario, Open Source ICT technologies play an essential role by offering, in fact, an indispensable support to all the activities of production, management and dissemination of knowledge carried out by the actors of the digital ecosystem in a marked way, also including interaction and cooperation. Significant verticalizations of this general scenario are the following: (*i*) *tax management*, where citizens and governance (government companies, regions, etc.) cooperate in the management and payment of taxes; (*ii*) *justice*, where the actors of civil justice (judges, clerks, etc.) cooperate in the management and conduct of civil justice cases and trials; (*iii*) *social networks*, where citizens and territorial authorities (municipalities, mountain communities, etc.) cooperate in managing life and processes of the community.

In order to achieve the described objectives, the *KnowExplo* platform provides the definition of an advanced Open Source platform that is able to embody both the paradigms of production, management and dissemination of knowledge of a markedly interactive and cooperative type, and support paradigms for the representation and processing of data and processes of data- and knowledge-intensive environments. These two different aspects play significant roles within the *KnowExplo* platform, and are also characterized by a relevant inter-relationship, as will be described below.

In order to adequately support the application and functional requirements required by data- and knowledge-intensive environments, the architecture of the *KnowExplo* platform, shown in Figure 1, is strongly characterized by representation, query, processing and delivery models for data, information and objects of the platform's *multidimensional* primary sources. This peculiarity is dictated by the fact that, in modern systems and applications (such as those described by the mentioned verticalizations), data and processes are increasingly characterized by a *multidimensional*, *multi-level and multi-resolution nature*, from which it follows the need for modelling, analyzing and processing data, information and objects that populate these systems and applications according to *multidimensional abstractions*. These multidimensional models and abstractions implemented in the data/function layer of the platform are used by the platform actors as part of their interactive and cooperative knowledge production, management and dissemination processes, in the form of access, query, processing

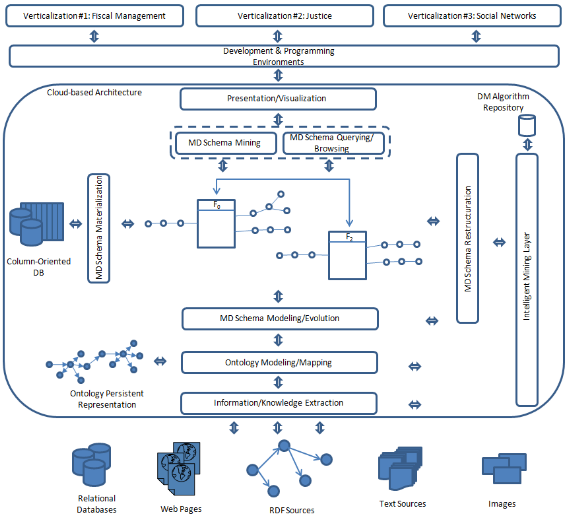

Figure 1: *KnowExplo* platform reference architecture.

and delivery of data, information and objects. Possible applications that derive from the integration of these functionalities of the data/functions level in the interaction/cooperation level are in a great number, and they range from the multidimensional analysis of unconventional data sources (RDF networks, XML documents, data from social networks, etc.) to classification and multidimensional analysis of document corpus (Web pages, etc.). These functions range from the effective management of complex objects coming from intermediate computations of Data Mining processes/algorithms (graphs, trees, etc.) to the use and multidimensional navigation of image databases, and many others. Figure 1 shows the reference architecture of the *KnowExplo* platform.

Models, methodologies and tools for supporting digital ecosystems with a high degree of interaction and cooperation that are intended to be defined and tested within the *KnowExplo* platform are characterized by two fundamental aspects:

- ***Evolution***: this aspect refers to the fact that models and patterns of data and processes through which the actors of the platform interact do not adhere to a fixed and rigid structure over time, but rather they are *flexible* and *can vary their structure* in an adaptive way, based on the evolution of the interactions of actors in the interaction/cooperation level of the platform.
- ***Rich Life Cycle at the Data-Level/Function Frontier – Interaction/Cooperation Level***: this aspect refers to the fact that, in the context of their interactive and cooperative knowledge production, management and dissemination processes, actors of the platform give birth to a rich lifecycle at the frontier between the data/function layer (which is internal to the core layer of the platform - see Figure 1) and the interaction/cooperation level (which is external to the core layer of the platform - see Figure 1). This requires that, on one hand, data/functions layer of the platform must support functionalities of access, querying, processing and delivery of data, information and objects of the platform primary sources in an *innovative* and *unconventional* manner. On the other hand, the interaction/cooperation level of the platform must support *semi-structured* and *reconfigurable* processing models, according to innovative paradigms that enhance the degree of interaction and cooperation between the platform.

These two fundamental aspects define, in fact, the main features of the *KnowExplo* platform architecture.

3 KnowExplo ARCHITECTURE DETAILS

As shown in Figure 1, the reference architecture of the *KnowExplo* platform is characterized by a complex *component structure*, such that each component adheres to a well-established logic and implements a particular and well-separated functionality. To facilitate the description and understanding of the *KnowExplo* platform, an approach that maps *several implementation objectives* (ORs) of the *KnowExplo* framework on this platform is adopted, based on the isolation of the different layers/levels/components that characterize the same platform. Figure 2 shows this mapping.

As it can be argued by Figure 2, every OR is mapped onto a specific set of (software) components of the target *KnowExplo* platform. This nice amenity allows us to achieve a pertinent *separation* during the design phase as well as a solid *software maintenance* at run time.

A description of the various ORs of the framework is provided next, as referred to the *KnowExplo* platform architecture (see Figure 2).

3.1 OR1 – Cooperation with Information Producers

OR1 focuses attention on the following two main activities/components. The first component, called *Information/Knowledge Extraction*, deals with the task of implementing information and knowledge

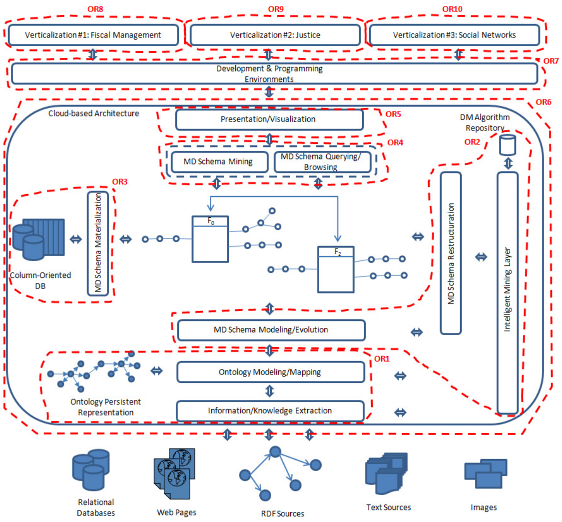

Figure 2: Mapping of the framework ORs on the reference architecture of the *KnowExplo* platform.

extraction functions from the primary data sources that populate the *KnowExplo* platform. It is useful to highlight that these sources can be classified into three major classes: (*i*) *conventional sources*, such as, for example, relational DBs, RDF bases, XML documents, etc.; (*ii*) *multimedia sources*, such as, for example, documents, images, etc.; (*iii*) *complex objects*, such as, for example, trees, graphs, time series, etc. deriving from intermediate computations of Data Mining processes/algorithms. The second component, called *Ontology Modeling/Mapping*, is dedicated to the creation of Ontologies for modelling the knowledge inherent to the primary data sources in the form of networks of concepts and relationships, and creating the appropriate *mappings* towards the *multidimensional schemas* of the global repository MDUS. Furthermore, to ensure effectiveness and efficiency, the ontologies so-constructed are stored and made persistent in a specific layer of the *KnowExplo* platform.

In the *KnowExplo* proposal, the aggregation of these multidimensional schemas in the MDUS pursues an innovative interpretation according to which such schemas that are located in the core layer of the *KnowExplo* platform architecture define the *data universe* of next generation applications and systems that will be based on this platform. The idea behind this approach consists in integrating data, information and objects of primary sources in a global and universal schema that offers the advantage of being able to use the well-known multidimensional abstractions on the sources themselves. As highlighted above, these multidimensional abstractions and the numerous supported applications are then used by the *KnowExplo* platform actors in the interaction/cooperation layer of the platform. Overall, this contributes to improve the representation and mining capabilities of the whole platform, in an effective and pragmatical manner.

3.2 OR2 – Development of the Methodology

OR2 is dedicated to two central aspects within the *KnowExplo* platform. The first aspect concerns with the multidimensional modelling of the MDUS schemas, which is the primary objective of the *MD Schema Modeling/Evolution* component. The second aspect concerns with the evolution of these schemas as a result of data- and knowledge-intensive processes triggered by the actors in the interaction/cooperation level of the platform. In fact, these data- and knowledge-intensive processes, which operate on the data/function level of the platform, can give rise to *inconsistencies* such that the multidimensional schemas of the MDUS are no longer able to capture the (multidimensional) knowledge embedded in the primary data sources (which feed the platform and are processed by the platform actors). This involves in the so-called *evolution of* (*multidimensional*) *schemas*, which plays a central role in the *KnowExplo* platform. The identification of inconsistencies between the knowledge embedded in the primary sources and the knowledge *currently* represented by the multidimensional schemas of the MDUS is implemented by the *Intelligent Mining Layer* component, while the *MD Schema Restructuration* component is dedicated to carry-out the necessary restructuring of these schemas.

As regards the multidimensional modeling of the MDUS schemas, within the *KnowExplo* platform the use of the *Constellations of Facts* is proposed. These latter are multidimensional logical models that have the double positive effect of (*a*) capturing the multidimensional and multi-resolution nature of primary sources that feed the platform, also guaranteeing the necessary *flexibility* that must necessarily characterize functions exported from a knowledge-intensive platform such as *KnowExplo*, and (*b*) effectively and efficiently supporting the activities of navigation, exploration and analysis of data, information and objects of primary sources (note that these operations/functions are then exploited by the actors of the *KnowExplo* platform in the interaction/cooperation level).

More in details, two modalities are envisaged as related to the multidimensional modeling phase of the MUDS schemas. The first is of a classical type, and it involves in a multidimensional *business-oriented* modelling, according to which schemas are edited by a *knowledge worker* on the basis of the knowledge of the target application domain, and a fixed number of *business analysis* objectives. The second pursues the most innovative paradigm of *automatically discovering of multidimensional patterns* directly from the primary sources that feed the *KnowExplo* platform, without the aid of the knowledge worker. It is obvious that, at this level, the Ontologies created within the OR1, and the related mappings, also intervene.

As regards the evolution of the multidimensional schemas of the MDUS, within the *KnowExplo* platform the use of Data Mining algorithms (stored in an appropriate repository - see Figure 1) is proposed, in order to *simultaneously* process data, information and objects of the primary sources that feed the platform and the multidimensional schemes of the MDUS in their *current* modeling. This with the aim of identifying possible inconsistencies between the (multidimensional) knowledge embedded in the primary data sources and the knowledge currently represented by the schemas themselves. As mentioned earlier, this task is the main goal of the *Intelligent Mining Layer* component. Among the various alternatives of Data Mining algorithms that can be useful for this purpose, *clustering* and *frequent-item set-mining* are the ones that best lend themselves to support this important functionality. These possible inconsistencies can be of various types. For example, a clustering algorithm could detect that the current multidimensional partition that characterizes a certain MDUS schema is no longer able to effectively capture the actual clusters that can be discovered in a certain collection of data, information and objects of the primary sources. In this case, *multidimensional schemas must be restructured*, which is the main objective of the *MD Schema Restructuration* component. The restructuring of multidimensional schemas can take place through a wide range of cases, which include, among others: the discovery of a new multidimensional entity (dimension, level, dimensional member, aggregation, etc.), the collapse of two or more existing multidimensional entities into a single multidimensional entity (for example, two dimensional members of a certain OLAP hierarchy could merge into a single dimensional member), adding a new OLAP dimension that was not foreseen in the design/discovery phase of such schemas, the addition of new aggregations that were not considered in the design/discovery phase of such schemas, and so forth. The latter topic is left as future work.

3.3 OR3 – Reorganization and Production of Structures

OR3 focuses the attention on the *efficient representation in secondary memory of the multidimensional structures* stored in the MDUS. This *KnowExplo* platform functionality is implemented by the *MD Schema Materialization* component. This component makes use of *column-oriented open-source database* technology, in order to ensure maximum flexibility during the restructuring phases of the multidimensional schemas of the MDUS. In fact, column-oriented representation is much more flexible than traditional approaches such as, for example, *array-based* (MOLAP) ones. For example, adding a new dimensional level to a pre-existing OLAP hierarchy corresponds, in the case of column-oriented databases, to the simple addition of a new column to the pre-existing ones and to the construction of the necessary low-level references (pointers) that implement the hierarchical relationships between the pre-existing dimensional levels in the reference OLAP hierarchy and the new dimensional level to be added.

3.4 OR4 – KnowExplo Query and Navigation

OR4 focuses attention on two different aspects of the *KnowExplo* platform. The first concerns with the definition of models, techniques and algorithms for *querying and navigating multidimensional structures* (such as *data cubes* and *multidimensional* OLAP *views*) stored in the MDUS, a function to which the *MD Schema Querying/Browsing* component is dedicated. The main purpose of this component is to support essential functionalities within the *KnowExplo* platform, such as those of querying data, information and objects of primary sources through sophisticated multidimensional abstractions, and the navigation of these repositories using successful OLAP tools such as multi-level and multi-resolution browsing, OLAP operators such as, for example, *slice & dice*, *pivoting*, complex OLAP queries such as, for example, similarity queries on multidimensional metric spaces, etc.

The second problem on which OR4 focuses concerns with the definition of models, techniques and algorithms for the *mining of the multidimensional structures* stored in the MDUS. This task is implemented by the *MD Schema Mining* component. The idea behind this component consists in making complex functionalities for the extraction of knowledge from multidimensional structures available to the actors of the *KnowExplo* platform. In turn, these functionalities can be integrated by the actors in their activities of production, management and dissemination of the knowledge in the interaction/cooperation level of the platform.

3.5 OR5 – Presentation and Personalization

OR5 focuses attention on a central issue of the *KnowExplo* platform, namely the presentation and visualization of data, information and objects of primary sources through the multidimensional abstractions offered by the MDUS. These features are implemented by the *Presentation/Visualization* component. It should be explicitly noted that this component is directly interfaced with the interaction/cooperation level of the *KnowExplo* platform actors, and, consequently, the greater number of the application functionalities of the platform are implemented and exported at this level. In this context, the central research theme is represented by the problem of *effectively and efficiently presenting* data, information and objects of primary sources modeled according to multidimensional abstractions to actors who have to elaborate them in order to support their cooperative and decision-making processes.

There are numerous models and techniques that are implemented by this component of the platform. One of these concerns with the "flattening" of multidimensional OLAP data cubes to support their use on mobile devices with scarce computational resources, or to support the definition of OLAP-like interfaces for complex objects, by overcoming the limitations of current OLAP platforms that focus only on conventional data sources. For example, Figure 3 shows a possible OLAP-like interface for the multidimensional and multi-resolution fruition of images.

Figure 3: OLAP-like processing and fruition of images.

3.6 OR6 – Integrated Platform

OR6 focuses attention on the definition, development and testing of the application architecture supporting the *KnowExplo* platform, according to the *Cloud Computing* paradigm. This task is implemented by the *Cloud-based Architecture* component. The choice of the Cloud Computing paradigm is motivated by the fact that this paradigm allows considerable flexibility, scalability and reliability. Therefore, it perfectly adapts to the requirements of the *KnowExplo* platform.

The Cloud-based architecture interfaces both to the core of the platform and to a *layer of programmable APIs* (OR7) and, above all, to the verticalizations to be built on the basic framework offered by the *KnowExplo* platform (OR8, OR9, OR10). OR6 therefore provides not only the definition, development and testing of the core architecture of the *KnowExplo* platform, but also of its interfaces to the layers and external components, according to well-understood software patterns.

As highlighted above, verticalizations play a key role within the *KnowExplo* platform. In greater details, the verticalizations are built directly on the Cloud-based architecture of the *KnowExplo* platform and are concerned with *complete instances* of the general platform in which the *general purposes* components of the platform are "rewritten" through specialized functionalities and procedures on the basis of the particular application case considered by the current verticalization.

Platform verticalizations, which are essentially based on Cloud Computing software architectures, and cover real-life instances coming from modern settings, are presented in the next Sections.

3.7 OR7 – Development Environment

OR7 is dedicated to the definition, implementation and testing of development environments that interface with the functionalities offered by the *KnowExplo* platform through a collection of programmable APIs and support the construction of data- and knowledge-intensive applications that adhere to the paradigms encapsulated in the platform (multidimensionality, cooperation, intelligent use, etc.). *Development & Programming Environments* is the component that implements this layer of the reference architecture of the *KnowExplo* platform.

This component offers both the API collection and development environments which, again, adhere to *KnowExplo*'s paradigms. Thanks to this component, the platform becomes "programmable" and completely *open*, so it can be integrated with other next-generation platforms, systems and applications, as well as interfaced with traditional *legacy systems*.

A secondary but no less important activity of OR7 is represented by the definition and implementation of a series of case studies which, on the one hand, show the operational functionality of applications based on the *KnowExplo* APIs and, on the other hand, serve to test the effectiveness and efficiency of applications built on the *KnowExplo* platform. It should be noted that these topics are also relevant for what regards the issue of *scalability* of big data processing, which is an hot-topic of high interest at now.

3.8 OR8 – Verticalization 1: Taxation

This verticalization (implemented by the *Fiscal Management* component) focuses on the management and payment of taxes through the interaction and cooperation of actors such as citizens, government companies, regions, etc.

3.9 OR9 – Verticalization 2: Justice

This verticalization (implemented by the *Justice* component) focuses on the management and conduct of civil justice cases and processes through the interaction and cooperation of actors such as judges, clerks, law enforcement agencies, etc.

3.10 OR10 – Verticalization 3: Social Networks

This verticalization (implemented by the *Social Networks* component) focuses on the management of civic life of territorial areas such as metropolitan areas, municipalities, mountain communities, etc., through the interaction and cooperation of actors such as citizens, territorial authorities, politicians, etc.

4 RELATED WORK

By inspecting actual literature, there exist several research proposals that are relevant to our research. This further corroborates our feeling about the relevance of the investigated research field. In the following, we overview the most noticeable ones.

(Alam *et al.*, 2017) presents *a digital twin architecture reference model for the cloud-based cyber-physical system*, C2PS, where the key properties of the C2PS are analytically described. The model helps in identifying various degrees of basic and hybrid computation-interaction modes in this paradigm. The C2PS smart interaction controller has been designed using a *Bayesian belief network*, so that the system dynamically considers current contexts. The composition of fuzzy rule base with the Bayes network further enables the system with reconfiguration capability. Finally, authors present a telematics-based prototype driving assistance application for the vehicular domain of C2PS, VCPS, to demonstrate the efficacy of the architecture reference model.

(Vedeshin *et al.*, 2019) highlights the advent of personal manufacturing, where home users, small, medium, and Fortune 500 enterprises use devices such as 3D printers, CNC mills, and robotics to manufacture products locally. Authors propose *a digital ecosystem of personal manufacturing*, which is currently used or being tried by 111 Fortune 2000 enterprises. In this paper, they focus on the creation of the *cloud-based manufacturing operating system*, *3DPrinterOS*, to address an evolving critical problem of personal manufacturing. Therefore, authors introduce a novel software ecosystem architecture to sustain a massive communication load of command, control, and telemetry data to and from millions of manufacturing machines and users. This solution allows users to create and deploy their own applications into *3DPrinterOS* cloud operating system.

To guide the architecture design process in the context of *digital twins*, (Tekinerdogan & Verdouw, 2020) provides *a pattern-oriented approach for architecting digital twin-based systems*. Authors propose a catalog of digital twin architecture design patterns that can be reused in the broad context of systems engineering. The patterns support the various phases in the systems engineering life cycle process, and are described using a well-defined pattern docu-menttation template. For illustrating the application of digital twin patterns, a multi-case study approach in the agriculture and food domain is adopted.

Finally, (Yun *et al.*, 2022) proposes *a digital twin architecture to provide accurate disaster prediction services with a similarity-based hybrid modeling scheme*. The hybrid modeling scheme creates a hybrid disaster model that compensates for the errors of physics-based prediction results with a data-driven error correction model to enhance the prediction accuracy. The similarity-based hybrid modeling scheme reduces errors from the data dependency of the hybrid model by constructing a training dataset using similarity assessments between the target disaster and the historical disasters.

5 CONCLUSIONS AND FUTURE WORK

This paper has focused the attention on innovative Cooperative Digital Ecosystems, an emerging class of systems where the cooperation among different actors is the main aspect to be considered. In order to support the main underlying process, we have introduced and described in details *KnowExplo*, *a multidimensional-paradigm-centered architecture* for supporting these systems. Future work is mainly oriented towards equipping the proposed architecture with emerging big data trends (e.g., (Campan *et al.*, 2017; Cuzzocrea *et al.*, 2014; Li *et al.*, 2022)).

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