Designing and Building a Low-Cost IoT Solution for Natural Disaster Monitoring and Mitigation: An Experience Report

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Abstract: Mitigating natural disasters is a global concern and a social challenge, and new technologies and social inclusion mechanisms have been applied to improve prevention and response to these events. Several initiatives seek to mitigate natural disasters and rely on technologies such as the Internet of Things, crowdsourcing, volunteer training, society involvement, among others. Although there are many initiatives in this regard, building a model enabling real mitigation of natural disasters remains a major challenge. This study aims to present a Natural Disaster Mitigation model, which combines different technologies through the construction of a multidisciplinary group composed of researchers, students, civil defense technicians, and the municipal school network. The goal is to develop and implement a meteorological monitoring network using low-cost technological artifacts installed in school systems in the target cities.

1 INTRODUCTION

Digital technologies like the Internet of Things (IoT) and environmental education have been explored to improve prevention and response to natural disasters. However, to the best of our knowledge, no proposals were found in the literature leveraging such a myriad of strategies and technologies like Project-Based Learning (PBL), IoT, crowdsourcing, meteorological education, and environmental education, applied in the context of protection and defense actions.

The goal of this work is to present a natural disaster mitigation model that combines the construction of IT artifacts with training for the public involved. The idea is to build a set of low-cost meteorological stations leveraging IoT technology, crowdsourcing, robotics training, notions of meteorology, and civil defense techniques. The proposed model was prototyped and implemented by an interdisciplinary group made up of researchers and students from four universities, civil defense technicians, and a group of teachers and students from schools in the municipal education network, using the PBL strategy and the Design Science Research (DSR) method. This paper also describes the methodology used to build and implement the proposed model, the actions taken, and the applied technology, in addition to presenting the results achieved so far and future works.

This article is organized as follows. Section II presents the theoretical foundation of digital technologies and strategies applied in disaster mitigation. Section III depicts the related works, and Section IV describes the proposed model. Section V presents the conclusions, and section VI describes our future work.

2 BACKGROUND

Emerging technologies like IoT have been explored to improve prevention and response to these events. The literature highlights the importance of using the crowdsourcing strategy in collecting voluntary

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geographic information to better understand natural disasters (Tulloch, 2014), especially leveraging the participatory sensing paradigm (Oliveira et al., 2015). Furthermore, studies have analyzed socio-environmental vulnerability and disaster risk reduction, recognizing that natural threats are not unexpected events and that preparation is essential (Freitas et al., 2012). The analysis of the situation of natural disasters in Brazil has also been the subject of study, highlighting the need to understand the interactions between natural disasters and public health (Freitas et al., 2014).

Literature reviews on natural disaster information and surveillance systems are relevant to understanding how technologies can be applied in this context (Sobral et al., 2010). Studies have sought to help plan preventive and mitigating actions, as in the case of meteorological diagnosis of natural disasters (Barcellos et al., 2016).

On the other hand, the theoretical analysis of natural disasters has been explored in several areas of knowledge, emphasizing the importance of risk and disaster management due to the increase in the magnitude and frequency of these events (Machado & Machado, 2019; Kobiyama et al., 2018). The use of IoT technologies for humanitarian logistics and for search and rescue in natural disasters has also been the subject of a literature review (Monteiro et al., 2018). Vulnerability to natural disasters and their nursing implications have also been addressed, highlighting the importance of preparation to face these events (Bandeira et al., 2014).

Meteorological monitoring in Brazilian cities is carried out through a network of meteorological stations distributed throughout the country. These stations collect data on atmospheric conditions, such as temperature, air humidity, atmospheric pressure, wind speed, and direction, among other meteorological parameters. The main institution responsible for this monitoring in Brazil is the National Institute of Meteorology (INMET), which is linked to the Ministry of Agriculture, Livestock and Food Supply.

INMET operates an extensive network of automatic and conventional meteorological stations located in urban and rural areas. Automatic stations collect data continuously and in real time, transmitting the information to processing centers. In addition, there are conventional stations where human observers manually record meteorological data. In addition to INMET, other institutions, such as universities and research centers, also contribute to meteorological monitoring in Brazil. The information collected is used to produce weather forecasts, weather alerts, and climate studies, providing data for various areas, such as agriculture, aviation, water resources management, and natural disaster prevention (INMET. 2024).

Considering INMET's limited resources and the country’s territorial extension, the involvement of various institutions and the very civil society through transversal, collaborative and low-cost alternatives is crucial, aiming to address the challenges related to meteorological monitoring. One of these alternatives lies in the proposal of a natural disaster mitigation model leveraging IoT technology and crowdsourcing, with the use of low-cost meteorological sensors, cloud applications with various collaborative resources, and the direct involvement of the school community and its surroundings, supported by the offer of robotics courses, notions of meteorology and civil defense. With this methodology, microregions can be equipped with low-cost stations, and a clear picture of the meteorological response can be obtained.

Regarding the inclusion of crowdsourcing in our mitigation model, we were inspired by the work of Chaves et al. (2019), who highlight that citizen involvement has been increasingly used in the prevention and management of urban disasters, in addition to the fact that current networked citizens are in direct contact with institutions and companies (Schneider and de Souza, 2015). This scenario thus creates a unique opportunity to leverage the work of crowd volunteers.

3 RELATED WORK

An example that uses the DSR approach and values integrating IoT resources with education is presented by Costa et al. (2022). It describes a proposal to integrate IoT concepts and technologies into the curriculum of a high school technical course in Agriculture, using a technological artifact based on IoT as a teaching tool. In an evaluation with course teachers, interest in applying the proposal and the great potential of the artifact for improving teaching-learning processes was demonstrated.

Several works seek to mitigate natural disasters using software and hardware artifacts. Simoes and De Souza (2016) demonstrate technologies for implementing low-cost stations using the MQTT protocol and the ESP8266 microcontroller. On the other hand, Math and Dharwadkar (2018) propose a cloud-based intelligent system weather station. The storage and processing of data obtained to predict the effect of climate change is done in the cloud, and the system is designed to effectively monitor environmental weather conditions such as temperature, humidity, wind speed, pressure and precipitation. The authors aimed to design a low-cost system requiring less maintenance and minimal human intervention.

Kodali and Mandal (2016) present the way in which a weather station can be described as an instrument or device that provides us with information about the weather in our neighboring environment. The authors also show how it can provide details about ambient temperature, barometric pressure, humidity, etc. Therefore, this device basically detects temperature, pressure, humidity, light intensity and rainfall amount. They further describe that several types of sensors are present in the prototype, through which all the aforementioned parameters can be measured. With the help of temperature and humidity, we can calculate other data parameters such as dew point.

In addition to the resources mentioned above, the study presents the possibility of monitoring the light intensity of the location, the atmospheric pressure in the room, and the amount of rain. The core of the presented prototype is the Nodemcu (12E) WiFi module based on ESP8266 with connected sensors. Such sensors are parameterized so that whenever values exceed a chosen limit, warnings are sent via email and a tweet alerting the device owner to take the necessary measures.

Banara, Singh and Chauhan (2022) present a bibliographical review of an existing meteorological monitoring system, including its sensors, microcontrollers, and means of communication. The chronological review of meteorological monitoring system literature presented by the authors provides a chronological table with publication date, sensors used, parameters used, description, and platform used of fourteen studies.

As previously stated, in the literature, we did not find a model similar to the one proposed by this study, where it was decided to: a) combine the competence of researchers and university students in a set of activities that involved different actors in the mitigation control process; b) bring the municipal school network into the mitigation control process; c) implement meteorological stations in schools; d) include in the project a teaching and training model (for teachers, technicians, students and volunteers involved) addressing fundamental concepts related to the problem of mitigating natural disasters as well as notions of meteorology and civil defense.

4 PROPOSED MODEL

The methodology used in this work was DSR because it aims to build innovative artifacts proposed to solve real societal problems based on the production of scientific knowledge (Dresch et al., 2015). The DSR process is divided into highly interconnected steps that may overlap, allowing the results of some steps to influence the review of a previous step. Development in cycles allows new functionalities to be developed and integrated into previous cycles, according to the evaluation of the results (Goecks et al., 2021).

DSR begins with the stages of identification and awareness of the problem, where the possibility of integrating universities, civil defense and municipal school networks through a disaster mitigation model was discussed. The goal is to reduce the effects of natural disasters and build more participatory, resilient societies with a preventive culture.

From the problems encountered to the final proposal of the model, collective intelligence concepts were used both in generating ideas and in decision support, enabling the aggregation of information, decision-making, the improvement of scientific practice, and work management (Pentland, 2006). Initially, the model was proposed to include only a couple of actors, emphasizing developing a station prototype and the necessary tools for data collection and analysis. However, it became clear that building such a model would require more actors, with a structure being built that encompassed several entities acting through an iterative DSR process.

Although the goal of the proposed model was to serve the school networks of the target cities, it was crucial to give the starting point by building a pilot project. This paper describes the first pilot application of our natural disaster mitigation model, designed for the city of Macaé, in the state of Rio de Janeiro, Brazil. Several activities were carried out collaboratively using an iterative DSR process to develop and implement this network of stations. Figure 1 depicts the core of our proposed model, showing key tasks covering the various entities involved.

- Creation of a multidisciplinary working group involving students and researchers from four higher education institutions with Educational management, Hardware Development Team, Software Development Team, Marketing Team, Robotics Training Team, BI Data Analysis Training Team, Deployment Team, Management and quality team;

- Strategic definition of the points where meteorological stations would be located;
- Low-cost, real-time, Internet-enabled station construction/assembly with IOT technology;
- Development of a tool for collaborative use for the analysis and control of measurements carried out by stations;
- Field testing of the station prototype and computational tools;
- Building a collaborative partnership with interested parties, including Macaé City Hall – (Secretary of education and civil defense), the Universidade Norte Fluminense (UENF) through its meteorology laboratory (LAMET)
- Development of a relationship with the municipal school network providing robotics training for staff and students (construction of a meteorological station), notions of meteorology and notions of civil defense;
- Training civil defense employees in a BI tool to analyze data collected by stations.

Before understanding the process, we describe the entities involved and their relationships (Figure 1).

4.1 Multidisciplinary Working Group

A multidisciplinary group was created with researchers and students from different courses from four higher education institutions distributed in teams, as shown in Figure 3.

The courses involved were Mechanical Engineering, Production Engineering, Pharmacy, Nutrition, Chemistry, Medicine, Information Systems, Mathematics, Electrical Engineering and Meteorological Engineering. The purpose was to use free robotics with the application of active methodologies in solving and testing practical problems (PBL), seeking to contribute significantly to the improvement of learning, in addition to enabling the construction of robotic devices that assist in the learning process and construction of knowledge. Integrating the university with partner institutions will allow it to respond to social, environmental, and organizational challenges in the context of the continued training of professionals in the school network and civil defense.

4.2 Strategic Definition of Meteorological Stations

Macaé is located at latitude S -22º22'33" and longitude W -41º46'30", with 23 kilometers of coastline. The climate is hot and humid most of the year, with temperatures varying between 18ºC and 30ºC, with considerable thermal amplitude caused due to the exchange of winds between the coast and the mountains, which are relatively close. The schools were defined through a study carried out by civil defense looking for important areas for meteorological studies or vulnerable to natural disasters, taking into account that the city has characteristics of mountains and sea. The school community plays a fundamental role in the model, as it functions as a center for collecting and disseminating information.

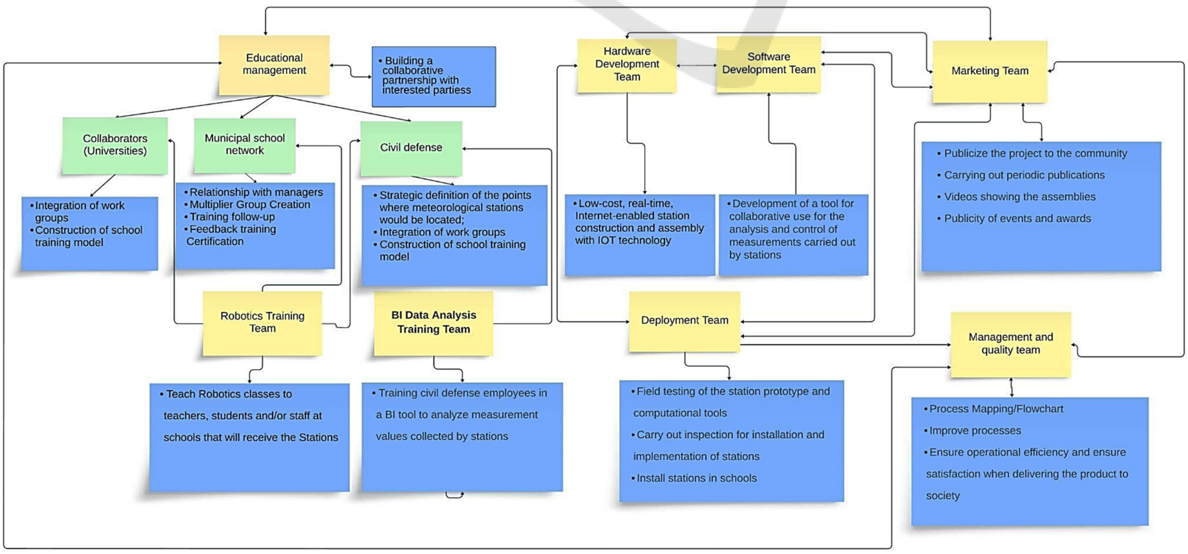

Figure 1: Relationship of the entities that comprise the process (multidisciplinary working group).

Teachers and students are trained to understand and interpret a weather station's construction mechanism and the alerts issued by the IoT system, transforming schools into crucial points of contact for communication with civil defense and the wider community.

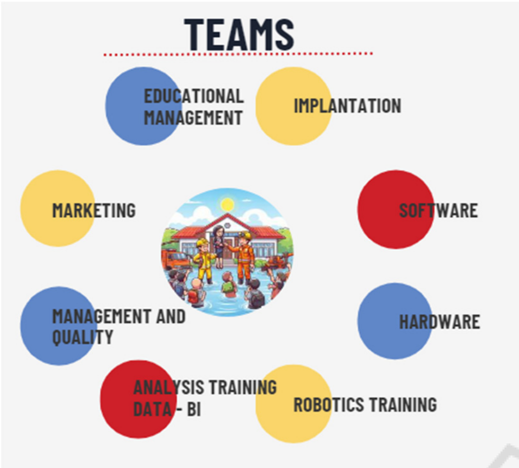

Figure 2: Teams that make up the project.

4.3 Low-Cost Station Assembly with IoT Technology

A low-cost real-time station prototype was developed. It was crucial that the station had the following characteristics: easy to build, weather resistant, insectproof, lightweight, easy to install, and sustainable. We also aimed that the sensors had the following technical capabilities: internet-enabled, consuming little energy, auxiliary power, computationally efficient, easily programmable, with over-the-air (OTA) updates.

Figure 3: Part of the multidisciplinary group

Thinking about functionality and ease of maintenance, which should be carried out in partnership with teams from schools, civil defense and employees, it was decided to build the stations in modules, which were categorized into four groups that include: microcontroller, circuit, sensors for humidity, temperature, wind speed, wind direction, rainfall volume, atmospheric pressure and auxiliary outputs for new sensors, solar power supply and hardware peripherals.

A prototype station was developed based on the ESP32 microcontroller platform with Wi-Fi functionality and using OTA updates. The microcontroller is connected to a custom circuit board, as seen in Figure 4. It acts as the central location to which all electronic and electrical components and sensors are connected, as shown in Figure 5.

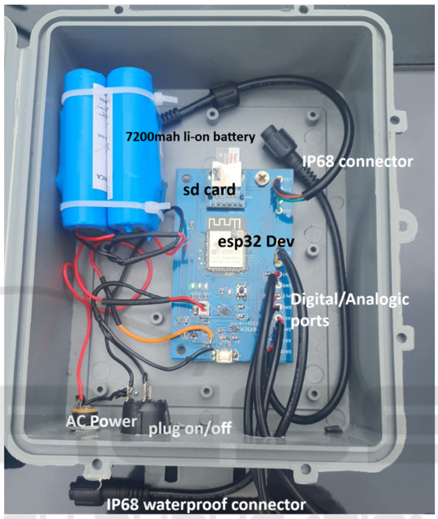

Figure 4: Weather station central.

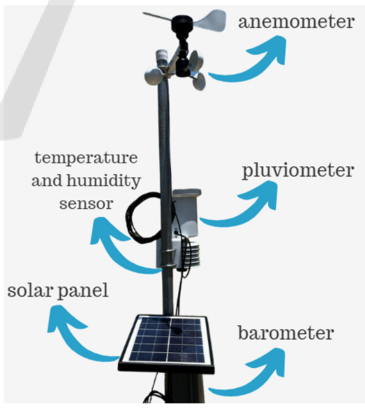

Figure 5: Station components, including sensors.

4.4 A Tool for Collaboratively Analyzing Measurements

The application was developed according to the needs established by civil defense, using a set of programming languages and technologies (such as

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PHP, apache web server, Codeigniter framework, and MySQL database). Figures 6-8 depict various features of the application, such as control panel functions displaying general statistics and event control; visualization of station status and monitoring with color scale on georeferencing; statistical visualization of readings through graphs, control of incidents throughout the city reported by users; registrations for station management.

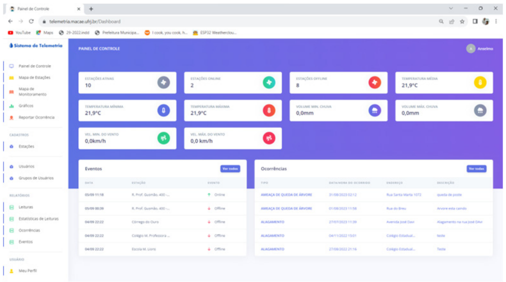

Figure 6: Real-time application main screen.

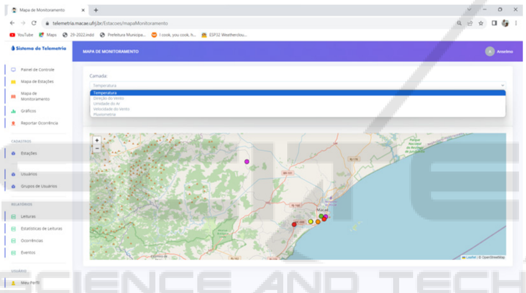

Figure 7: Station map screen per alert.

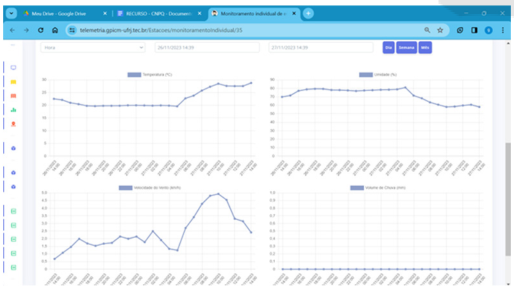

Figure 8: Station graphics screen.

4.5 Field Testing

After prototyping, the stations were produced and programmed with embedded software in C language. A service analysis and configuration tool was also developed using Bluetooth Low Energy (BLE) technology to facilitate the maintenance and installation of stations in schools (Figure 9).

4.6 Collaborative Partnership

A collaborative partnership was developed with interested parties, including Macaé City Hall (civil defense department), municipal education department, and UENF through its meteorology laboratory (LAMET), where we have several researchers and students from different courses.

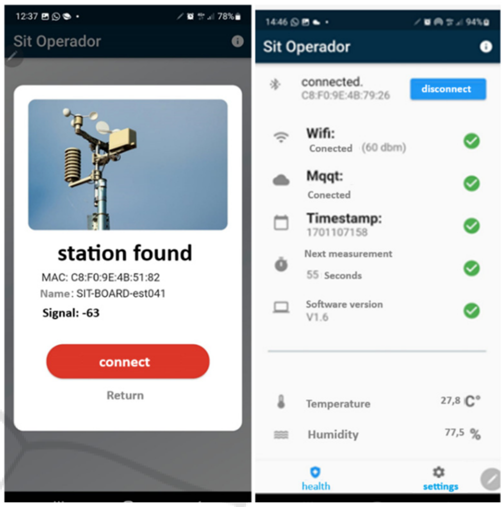

Figure 9: Service analysis and configuration tool using Bluetooth Low Energy (BLE) technology.

Figure 10: Part of the team of project collaborators.

Figure 11: Civil defense monitoring center.

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Such partnership has become fundamental to building knowledge and the feeling of belonging. A monitoring center (Figure 11) was created to support the analysis of collected data and civil defense decision-making with real-time readings.

4.7 Development of a Relationship with the School Network

The participation of school representatives in robotics, meteorology, and civil defense courses is essential for disseminating information and building a sense of belonging with each station being implemented as well as the project as a whole, aiming to mitigate natural disaster actions.

Training in robotics, notions of meteorology, and civil defense techniques was offered to thirty-five schools in the municipal network. At this stage, it was possible to serve a number of forty-nine employees and students from sixteen schools.

In the robotics course, theoretical and practical classes were offered with an ESP32 microcontroller and a set of sensors, enabling the student to obtain robotics concepts through the construction of experiments and the development of a station similar to the one implemented in their school. The goal was to involve the school group in the use and maintenance of it.

In meteorology training, relevant topics were presented, such as the World Meteorological Organization (WMO), global observation system, meteorological radars, frontal systems and extratropical cyclones, meteorological systems, mesoscale convective complexes, extreme events, cloud observation, how to monitor season data, changes climate, renewable energy, weather forecast, air pollution, climate and arboviruses.

The civil defense training was composed of notions of civil defense, disasters and monitoring, a set of prevention, mitigation, preparation, response and recovery actions, national defense system, concepts of prevention, mitigation, preparation, response, recovery and restoration, what is a disaster, types of disasters, Brazilian classification and coding of disasters (cobrade), differentiating floods from overflow, risks in flooded or overflow streets, storms and hangovers.

4.8 Training Civil Defense Employees in a BI Tool

The training aimed to train civil defense employees in data analysis in order to allow the generation of relevant information from data generated by meteorological stations. Google Looker Studio was used as a data analysis and business intelligence tool emphasizing meteorological data. Training was offered in a virtual learning environment due to the dynamics of the technical activity of civil defense agents. Participation in the training was voluntary and we had significant participation, with a 65% completion rate. Training of technicians in the analysis of meteorological data using the *Google Looker* tool was considered to be positive, where 83% of students gave grades nine and ten after being questioned with the following question: *Considering all aspects evaluated, globally, what grade would you give the Course on a scale of 1 to 10?*

5 CONCLUSIONS

The strategy of combining the expertise of researchers and university students in a set of activities that involve several actors in the mitigation control process is neither simple nor trivial, and the results related to the challenge of disaster mitigation must be evaluated in a medium and long term. Part of the challenge was to bring the municipal school network into the mitigation control process and offer the possibility of training in addition to implementing meteorological stations in schools. However, evidence of positive results has already been collected, despite the very recent implementation of the project, highlighting the integration of universities, through their various courses, with the local government and the education department.

In addition, a set of results was achieved in the context of the project in 2023:

- Savings of 4 million Brazilian reais in implementing a low-cost station monitoring system.
- 16 meteorological stations installed.
- 16 schools in the municipal school network had groups trained in robotics, meteorology concepts and civil defense.
- Integration of 42 students from 4 universities in the knowledge construction process, with the exchange of skills between different courses.
- 36 civil defense employees participated in BI training, using the Google Looker Studio tool emphasizing meteorological data.
- Organization of the First Meeting on Climate, Technologies and Accident Risk Reduction, involving the academic community, local government, and society.

6 FUTURE WORK

Future work will include creating sustainability indicators for monitoring and prevention of natural disasters, contributing to achieving the goals of the 2030 Agenda, the Sendai Framework for Disaster Risk Reduction 2015-2030, the National Civil Protection and Defense Policy through Law 12608/2012; promoting actions within the scope of the Innovation Ecosystem established in Macaé; and supporting the development of projects with the potential to generate technology-based businesses.

It is also planned to analyze the collected data, geoprocess it, and adapt or resize the models according to the needs of the Deputy Secretariat for Civil Defense. In the educational area, an adjustment of technical and scientific cooperation is planned and carried out through teaching and/or research, and the development of projects in the area of Protection and Civil Defense aligned with Civil Defense projects in schools.

In a second development cycle, prediction mechanisms will be implemented through the analysis of data stored on servers. BI tools (such as Google Looker) have been applied in the training of Civil Defense technicians, who, in the second development cycle, will be advised by Meteorological Engineering specialists belonging to the multidisciplinary group in the analysis and construction of predictability patterns.

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