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APPLICATION PAPER

Developing FAIR functionality and properties for micrometeorological data

Mark Roantree[1], Vuong M. Ngo[2], Stevan Savić[3], Branislava Lalić[4] and Michael Scriney[1]

[1]Rinn Artificial Intelligence, School of Computing, Dublin City University, Dublin, Ireland
[2]Faculty of Information Technology, Ho Chi Minh City Open University, Ho Chi Minh City, Vietnam
[3]Faculty of Sciences, University of Novi Sad, Serbia
[4]Faculty of Agriculture, University of Novi Sad, Serbia
Corresponding author: Vuong M. Ngo; Email: vuong.cs@gmail.com

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Abstract

The growing demand for reusable micrometeorological data in climate, environmental, and agricultural research, driven by challenges including weather-induced agricultural losses, water use for irrigation, emerging invasive species and disease vectors, deforestation, and increasing urbanization, highlights the need for datasets that comply with the FAIR (Findable, Accessible, Interoperable, and Reusable) principles. FAIR data and metadata should be easily discoverable by humans or machines, accessible under specific conditions or restrictions, conform to recognized formats and standards to be combined and exchanged, and licensed according to community norms, allowing users to know what kinds of reuse are permitted. To support researchers in creating FAIR-compliant datasets, the FAIR Micromet Portal was developed within the CA20108 COST Action. The portal provides a guided, step-by-step workflow for generating standardized metadata, linking datasets with persistent identifiers, and facilitating compliance with the FAIR principles. This paper presents the design and implementation of the FAIR Micromet Portal and describes how its metadata model and workflow satisfy the complete set of FAIR metrics. Using a micrometeorological case study, we demonstrate how the portal enables researchers to create FAIR-compliant metadata with minimal effort while supporting data discovery, interoperability, and long-term reusability.

1. Introduction

The deployment of sensing technologies has changed both the everyday life of human beings and the manner in which data can be acquired across a wide range of scientific and practical domains. Sensors are devices that detect changes in the health and performance of human beings, smart machines, buildings and cities, manufacturing, daily life, and the measurement of the environment and climate. In healthcare, there has been considerable research in the usage of sensors, with a detailed survey in Antunes et al. (2018); many examples can be found on the usage of sensors to drive performance in sport with recent examples of the adoption of machine learning (De Beéck et al., 2018); smart cities (Santana et al., 2018); and in climate, the capture of micrometeorological data using a range of ongoing sensors has been in place for a considerable number of years (World Meteorological Organization, 2021b). A more general recent overview can be found in Javaid et al. (2021).

In this research, we focus on the generation and acquisition of climate data and on accelerating its usage by adopting FAIR principles. The current state of weather-induced agricultural losses, water use for

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irrigation, the appearance of new invasive species and disease vectors (strongly depending on micro-meteorological conditions), new environmental zoning of plant diseases and pests, deforestation, increased urbanization, rural-to-urban migration, and increased urban energy consumption for cooling and heating impose scientific and societal demands for FAIR micrometeorological data.

Recent research (Hsieh, 2022) predicting a significant rise in the acceptance and application of machine learning in environmental science does not address the important issue of available data in data-driven analytics. It is an important motivation for climate-based research to have access to as much interpretable data as possible and in that light, we now highlight the meaning of FAIR: Findability, Accessibility, Interoperability, and Reusability. This means that data and metadata should: be easily discoverable by humans or machines; accessible under specific conditions or restrictions; conform to recognized formats and standards to be combined and exchanged; and be licensed according to community norms allowing users to know what kinds of reuse are permitted. While open data is the ultimate goal, it is important to have in mind that the FAIR concept implies open metadata *only.* Measurement results should be stored in a repository chosen by the data owner, using a DOI as a persistent unique identifier and a preferred license, from closed to fully open with numerous options.

There is a distinct difference between open and FAIR data, related to the degree of accessibility and requirements for usability (Mons et al., 2017). Open data is available without restriction, while FAIR data may have specific conditions for access and usage. Open Government Data refers to the information collected, produced or paid for by the public bodies and made freely available for reuse for any purpose (European Union, 2023), with a license specifying the terms of use. These principles for Open Data are described in detail in the Open Definition (Open Knowledge Foundation, 2015). Public sector information is information held by the public sector. The Directive on the re-use of public sector information provides a common legal framework for a European market for government-held data. It is built around the key pillars of the internal market: free flow of data, transparency, and fair competition. It is important to note that not all of the public sector information is Open Data.

A recent report (PwC EU Services, 2018) on the cost of non-FAIR research estimated that the lack of FAIR data costs approximately €10.2 billion annually, equivalent to 78% of the annual Horizon 2020 budget or 3% of total EU research expenditure. This report, targeted at research funders, data and related infrastructures and research organizations, identified the impact of research activities as most significant but also highlighted its impact on collaboration and innovation. In general, increased time and cost are repeatedly cited as the main negative impacts. This report provides detail on the different cost indicators: time, cost of storage, license costs, research retraction, double funding, interdisciplinarity, and potential economic growth. As the research presented in this paper emerges from EU Cost Action CA20108, an interdisciplinary action with climate researchers from different domains, data engineers, and machine learning researchers, an interesting finding was that the cost of its effect on *interdisciplinary* research was difficult to estimate. However, findings indicate that reproducibility is hampered if data is not FAIR; lack of access to data and the poor quality of data restrict interdisciplinarity; and the benefit of accessing "disparate data from other disciplines" is lost for these teams. Central to reproducibility is the provision of metadata so that practitioners may obtain greater context from a given dataset. Several standards exist for the provision of FAIR data, such as the Dublin Core Metadata element set (DCMI, 2018) and standards for publishing such data, such as FAIR Data Point (FDP) (da Silva Santos et al., 2023).

This cost to research of non-FAIR data can potentially be exacerbated when dealing with high-value data. For example, in the high-value datasets identified by the EU (EUR-Lex, 2022), the meteorological thematic category includes datasets on observational data measured by weather stations, validated observations (climate data), weather alerts, radar data, and numerical weather prediction (NWP) model data with the granularity and key metadata attributes listed in Table 1.

1.1. Motivation and contribution

Developing a FAIR repository for climate science data is a multidisciplinary effort involving climate scientists who generate data; data engineers with skills to create federated digital assets; and machine

Table 1. *FAIR metrics and interpretation*

ID	Original principal	Metric interpretation
Findable		
F1.1	Data assigned globally unique ID	Essential (directly or indirectly)
F1.2	Metadata assigned globally unique ID	Preferable (directly or indirectly)
F2	Data are described by rich metadata	Should support different levels
F3	Metadata explicitly includes the unique ID	Should be a metadata attribute
F4.1	Data are searchable	Directly or indirectly
F4.2	Metadata are searchable	Directly or indirectly
Accessible		
A1.1	Data retrieved using standard protocol	Query Portal or high level language
A1.2	Metadata retrieved using standard protocol	Query Portal or high level language
A2	System is open, free, universally implementable	Should be open and free to read and search
A3	System includes authentication/authorization	Requires authentication for *creating* metadata
A4	Metadata is accessible past the lifetime of data	Metadata and data are equally valuable
Interoperable		
I1	Metadata uses a formal, accessible, shared, broad applied knowledge representation language	Accepts XML, JSON, CSV, etc.
I2	Vocabularies follow FAIR principles	Standard metadata or ontology
I3	Metadata includes qualified refs to other (meta)data	Expose your API and metamodel
I4	System supports importing/exporting of metadata	Exportable as XML, CSV, etc.
Reusable		
R1	Metadata are richly designed with a plurality of accurate and relevant attributes	Facilitate rich metadata descriptions
R2	(Meta)data have a clear data usage license	Articulate usage requirements
R3	(Meta)data associated with detailed provenance	Description of data generation & manipulation
R4	(Meta)data meet domain-relevant community standards	Must meet quality criteria

learning researchers who provide expertise on tasks such as gap filling, predictive modelling and exploiting deep learning models for more complex machine learning tasks. One of the main goals of the CA20108 cost action (COST Action, 2021) was to design and build a knowledge portal that is fully compliant with the FAIR principles for scientific data management. In terms of environmental sciences, this is endorsed by the findings in McGovern et al. (2022), who highlighted issues related to training data: understanding and interpreting data for use in machine learning experiments is crucial. Recently, the FAIR Micromet Portal (FMP) was developed to capture metadata for FAIR datasets (Roantree et al., 2023). Its purpose was to provide detailed metadata descriptions for shareable micrometeorological data using the WMO standard (World Meteorological Organization, 2021a). While storing Network, Site, and Sensor metadata locally, the system passes climate datasets to Zenodo, receives back the DOI, and thus creates a permanent link between the FMP and the storage platform Zenodo. In this way, the user exploits the (metadata) search functionality of the FMP to obtain both detailed descriptions and links to data on the

Zenodo platform. A comprehensive review of open repositories (Stall et al., 2023) confirms Zenodo's suitability for this type of storage but does highlight the limitations of a current 50GB limit on datasets. This limitation is overcome by the FMP as it permits any number of Zenodo uploads for a single network site. Central to FAIRNESS within FMP is the Findability and Accessibility of the provided datasets. Using the metadata provided, users are able to search and filter relevant datasets using the defined minimum metadata required for each dataset on the platform.

There are numerous Environmental Observation (EO) platforms with the purpose of providing accessible data and real-time datasets, and trying to partly or fully contribute to the FAIR concept. Some well-known operable EO platforms with a focus on climate data are Copernicus (CDSE authors, 2023), (European Commission, 2023), (ECMWF Open Data, 2023), (University of Münster, 2023), and (Earth System Grid Federation, 2016). In the micrometeorological domain, established long-term networks such as the International Soil Moisture Network (ISMN), FLUXNET (focused on carbon, water and energy fluxes), and the Integrated Carbon Observation System (ICOS) provide valuable observational data. However, these networks generally operate through long-term institutional or project funding and use relatively standardized hardware, data structures, and metadata. In contrast, the FMP offers flexible metadata and data-quality frameworks to handle the diverse, long-tail micrometeorological data generated by varied monitoring and modeling campaigns. To the best of our knowledge, no existing micrometeorological repository combines the FAIR-oriented functionality and metrics proposed by the FMP. Thus, FMP complements established networks by supporting the publishing, evaluation, and reuse of heterogeneous micrometeorological data.

At present, users can perform searches either directly through a web browser interface or programmatically via dedicated APIs. These APIs support querying across the following fields and have been fully implemented and deployed within the Fairness Portal https://fairmicromet.eu/networks/894abd82-c49c-4b5e-8506-f600362cb4da. This dual-access approach ensures both usability for non-technical users and flexibility for developers who require automated or large-scale data retrieval.

- Country
- City/region
- Local environment
- Seasonality (year round, summer only, winter only)
- From date for measurements
- End date for measurements

Given that research clearly demonstrates that FAIR data has far greater impact than data which is not FAIR, it is therefore of considerable value to the research community if there is an automated or easy-to-use method for ensuring that data is FAIR. In essence, create a system where researchers can simply "file and forget," confident that their data meet the FAIR principles and contribution more effectively to science. To achieve this, it is first necessary to understand and interpret the FAIR principles to help validate any proposed solution. Reusability and heterogeneity tend to be conflicting, rather than complementary properties. Thus, to enable a "file and forget" scenario, where data are often heterogeneous, reusability must be enabled firstly through standard metadata descriptions and secondly, data must be searchable and findable. In this paper, we begin with an interpretation of the FAIR principles and articulate what is required to meet the threshold for each principle. We then use a case study from an urban micrometeorological network and perform a step through the creation of FAIR metadata through the FMP, first introduced in Roantree et al. (2023), as essentially a form of software wizard, a user interface that takes the researcher through a sequence of small steps, in the creation of FAIR metadata. In the remainder of the paper, the term FAIRNESS is used to refer to the FAIRNESS CA20108 Cost Action and FMP refers to the FAIRNESS Micromet Portal, a system devised to deliver micrometeorological data FAIR compliant.

Paper structure. In Section 2, we provide a detailed discussion of the FAIR principles and our interpretation of these principles in order that appropriate metrics can be devised. In Section 3, we

describe how the FMP meets FAIR requirements; In Section 4, a discussion is presented; and finally, in Section 5, we draw conclusions.

2. Is my data FAIR?

Since the original FAIR proposal (Wilkinson et al., 2016), there have been a number of papers which sought to explore and interpret the different metrics (Berman and Crosas, 2020); some authors suggested extensions and a tighter interpretation of the thresholds for compliance (Schultes et al., 2020; d'Aquin et al., 2023); while there has also been a recommendation of how FAIR systems should be implemented using the concept of a FDP (Benhamed et al., 2022). There have been a number of efforts at testing micrometerological data for FAIR compliance, including our own case study (Lalić et al., 2022). What is clear is that some of the metrics and their proposed thresholds are inexact and open to interpretation. Thus, we begin with a discussion on the principles themselves, our interpretation of these, and how metrics can be devised from the principles to determine FAIRness. For simplicity, our discussion refers to a globally unique identifier as a Digital Object Identifier (DOI) but accept any equivalent form of globally unique ID.

2.1. Findable

There are six *Findable* principles presented at the top of Table 1, as F1 to F4, extended slightly from the original specification (Wilkinson et al., 2016). We adjusted F1 to clearly articulate 2 distinct requirements: F1.1 requires that data has a DOI; F1.2 requires that metadata has a DOI. Our interpretation is that F1.1 is mandatory while F1.2 requires a DOI in our interpretation. Our added stipulation to F2 (rich metadata description) is that different levels should be supported: (at least) a minimum level of metadata descriptions and advanced level(s) to support more sophisticated descriptions. Our interpretation for F3 is that the metadata should contain an attribute to capture the DOI. For F4, we again treat the two requirements separately: F4.1 and F4.2 advocate that data and metadata respectively are searchable. This may be facilitated directly through the system or indirectly using a separate (FAIR) system.

2.2. Accessible

Table 1 contains five *Accessible* principles extended slightly from the original specification, where A1 is now articulated as A1.1 and A1.2, where we again distinguish between access to data and metadata. Our interpretation is that this requires either a high-level query portal or a standard protocol such as a RESTful API publishing data in standard formats (XML, JSON, etc.). For A2, the term "universally implementable" is ambiguous, so we interpret that to mean "easy to use" and assume A2 to require the system to be free to read and search. For A3, we assume that authentication/authorization is required for the *creation* of FAIR data (otherwise it contradicts A2), but searching should require no such access to *open and free* data (A2). Our interpretation of A4 is that it is delivered through F1.2, which delivers an independent permanent DOI for metadata, and we interpret this principle as meaning: metadata and data are equally valuable.

2.3. Interoperable

Data interoperability is an important concept to understand as it is fundamental to the process of data integration. Its strategies are well understood now (Batini et al., 1986) and in more recent times, methods have been devised to integrate data from both structured and semi-structured data (Scriney et al., 2019), a crucial feature as not all micrometerological data will have a single fixed structure. In Table 1, the three original *Interoperable* principles are extended here with a fourth principle (I4) to further enhance interoperability. In the original specification (Wilkinson et al., 2016), I1 required that both data and metadata adopt the same formal representation. However, here, we restrict that formality to the metadata, as one cannot make assumptions about the data, which often requires a form of data *wrapper* to deliver that level of formalization. Our interpretation is that metadata should be available in one of a small number

of very popular standards, e.g., XML, JSON, or CSV. I2 states a requirement for a common vocabulary which we interpret as the adoption of a standard metamodel or ontology, such as (World Meteorological Organization, 2021b). Considerable detail is required when integrating data from unrelated, heterogeneous sources. In climate science, there are recent examples of single-use bespoke solutions (e.g., Brambilla et al., 2019), but integration generally requires a (meta)data model to describe data, and in the FMP, the WMO guide provides the design and structure for metadata. I3 highlights an important feature of interoperability: the ability for two heterogeneous metamodels (or ontologies) to communicate, which we interpret as exposing or publishing details of each FDP (also highlighted in Benhamed et al. (2022)). We have added I4 as we believe that exporting metadata is a crucial feature in supporting I3, as we are in agreement with the FAIR analysis provided in d'Aquin et al. (2023) and Peters-von Gehlen (Gehlen, 2022).

2.4. Reusable

The four *Reusable* principles are broadly in line with the original specification, with some minor articulations. For R1, we restrict the rich description to metadata (and do not concern ourselves with data). For R2 and R3, we assume that usage requirements and a record of data creation and manipulation (for example, gap filling) are recorded. For R4, we assume a guarantee of minimum criteria (for example, key metadata attributes cannot be left blank).

2.5. Summary

In previous work presented in Lalić et al. (2022), a case study detailed the application of a FAIR test for micrometerological data using metrics very similar to those presented in Table 1. Conducted before the development of the FMP, it identified the *Interoperability* metric as the most difficult metric on which to achieve full conformance. Using a validation method of Yes, No, Partial for each test: *Findable* metrics scored 2 *Yes* and 2 *Partial* responses; *Accessible* metrics scored 2 *Yes* and 2 *Partial* responses; *Interoperable* metrics scored one *Yes* and 3 *Partial* responses; and *Reusable* metrics scored 2 *Yes* and 2 *Partial* responses. Thus, it is important to distinguish between data that has full FAIR compliance, partial FAIR compliance, and is not FAIR compliant. The outcome from this test was that full FAIR compliance is quite difficult to achieve, although partial (and potentially high levels of) FAIR compliance are quite achievable.

3. The FAIR micromet portal

In this section, we describe important features captured in the development of the FMP. In particular, we observed many of the insights into how FAIR principles are interpreted (Jacobsen et al., 2020) in terms of a physical deployment such as the FMP. We begin with the capture of metadata for the micrometerological data stored and accessible through the FMP. The procedure for uploading data, described in Roantree et al. (2023) is that metadata is recorded in the FMP while the actual data is transferred immediately to Zenodo, creating the DOI that is subsequently captured in the FMP, as seen in the top right of Figure 1. The micrometerological data used in the earlier FAIR assessment provides a good case study for validating how the FMP conforms to FAIR principles while also ensuring that data meets and complies with the more difficult metrics. Data were generated as part of the Novi Sad Urban Network (NSUNET) system, where each site was equipped with multiple sensors and a variety of electronic and hardware devices (Milošević et al., 2022). The project's objective was to provide conditions for progressive urban climate research, for example, contributing to the thermal pattern differences of various urban surroundings. Metadata captured at the Network level is shown in Figure 1 and Figure 2.

The *Network* is regarded as the highest level of *abstraction* and thus requires a relatively short metadata record. Figure 1 shows the capture of institution, project, network code, contact email, county, city/region, local environment, seasonality, start date, end date, and reference. These maps are generated by the FMP

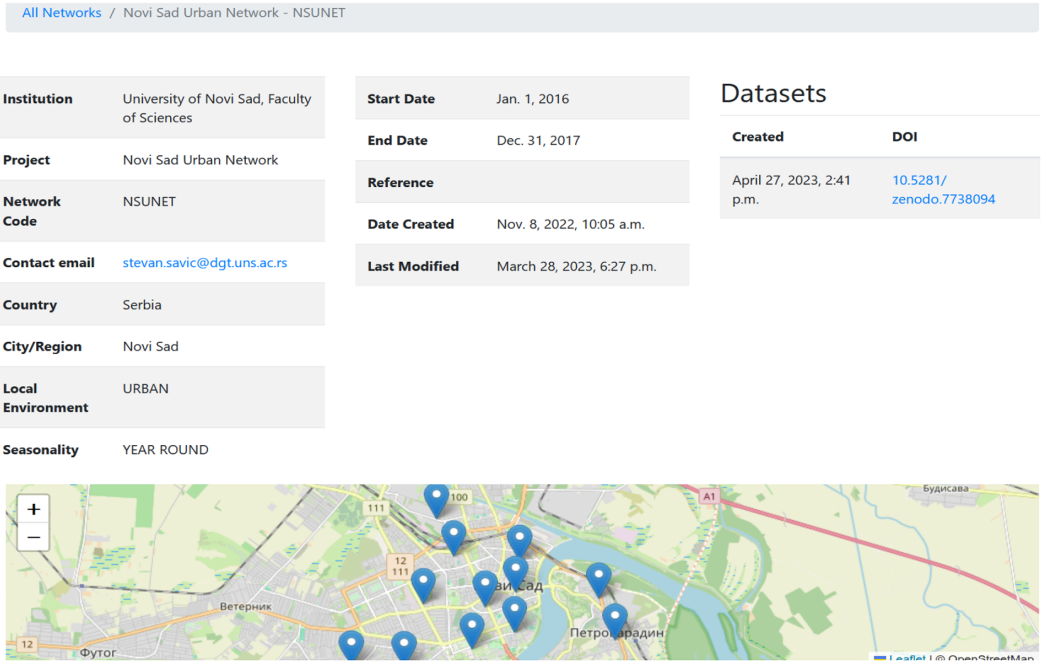


Figure 1. *Network metadata. © OpenStreetMap contributors 2017. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.*

Name	Latitude	Longitude	Altitude (M)	Time Zone	Macroscale Environment	
s2-3	45.261388	19.848888	78.00000	UTC	Residential Area (Multi-Story Buildings)	View
s3-2	45.233333	19.809722	79.00000	UTC	Residential Area (Houses)	View
s5-2	45.25	19.816111	75.00000	UTC	Boulevard	View
s5-3	45.2625	19.826388	78.00000	UTC	Residential Area (Multi-Story Buildings)	View
s5-4	45.238055	19.832777	81.00000	UTC	Residential Area (Multi-Story Buildings)	View
s5-5	45.253055	19.8475	80.00000	UTC	Residential Area (Multi-Story Buildings)	View
s5-6	45.2425	19.847222	78.00000	UTC	Residential Area (Multi-Story Buildings)	View
s6-4	45.233611	19.791944	76.00000	UTC	Residential Area (Houses)	View
s6-8	45.251388	19.875555	76.00000	UTC	Residential Area (Houses)	View

Figure 2. *Network metadata (sites).*

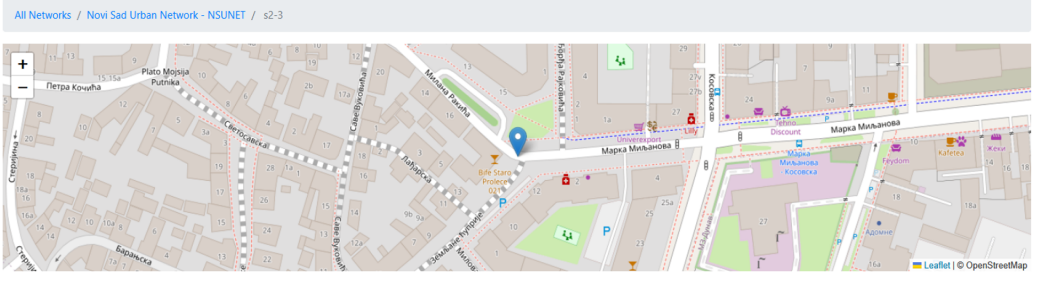
using two software libraries: the Leaflet library is free to use through the BSD-2-Clause license (LeafletJS, 2023), and OpenStreetMap is open data, provided through the Open Data Commons Open Database License (OpenStreetMap Contributors, 2017). The system creates the attributes: Date Created and Last Modified, and DOI creation dates. The *Site* is also at a high level of *abstraction*, requiring a relatively short metadata record. Figure 3 shows the capture of name, latitude, longitude, altitude, time zone, and macroscale environment. The Sensor requires the most descriptive metadata as it contains many parameters and settings and comes with a wide variety of functions, all of which require a description. Figure 4 shows the capture of variable, type, description, temporal resolution, start date, end date, sensor height, values, value notes, sky view factor, height/width values. For both Site and Sensor metadata, the system creates attributes for Date Created and Date Modified.

4. Case study based validation

In this section, we validate the FMP system against the FAIR principles using the NSUNET case study, as this data is freely available on Zenodo (Savić et al., 2023a) with a dataset description and statistical summary presented in (Savić et al., 2023c). We begin with a discussion on FMP system functionality to understand how it automatically provides compliance with a large number of FAIR metrics. We then examine FMP metadata capture in detail to highlight how greater levels of FAIR conformance are obtained, followed by a discussion on NSUNET metadata and its conformance with FAIR principles.

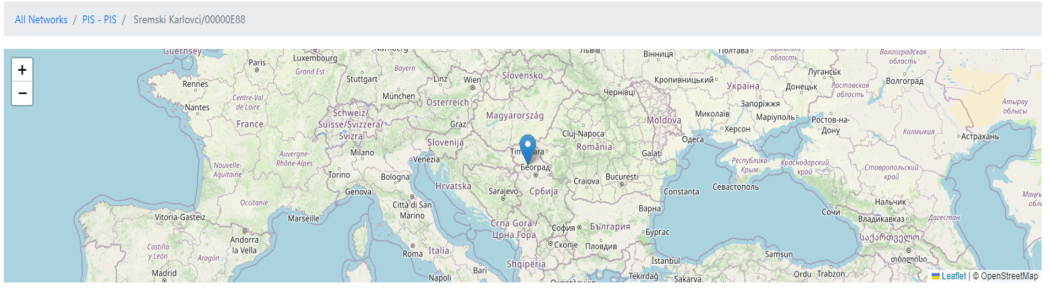
4.1. FMP metadata structure

In Table 2, we can see the different FAIR metrics that are automatically delivered by the FMP system, once the user provides a description for each attribute. By providing storage for metadata descriptions of climate data, the requirements for F2, A4, and I4 are met: data is described by rich metadata; metadata is accessible past the lifetime of data (Zenodo DOI), and importing/exporting of metadata is facilitated. The



Variable	Type	Description	Temporal Resolution	Start Date	End Date	Sensor Height	Values	Value Notes	Sky View Factor	Height/ Width Values	
Air Temperature (Ventilated)	ChipCap 2 sensor, fully calibrated and developed by the General Electric Measurement & Control Company, and located in a ventilated radiation protection screen with dimensions of 200x240 mm. The accuracy of the temperature sensor was ±0.3 oC.	Sensors measured the air temperature values every minute and every 10 minutes measured data was sent to the server (Uni of Novi Sad, Faculty of Sciences). 1-hour datasets were extracted for the period 2016-2017 and QC.	1 h	Jan. 1, 2016	Dec. 31, 2017	4.1 m	MEASURED/ RAW	Dataset from this station is QC with 0 outliers and 0% of missing data. The whole procedure of QC is on this link: https://drive.google.com/drive/folders/1tvDpMMvN10JQni4o6X3SlqI5bJ5yls3r?usp=sharing		It is a small square 41 m with 50 m surrounded by multi-story residential buildings.	View

Figure 3. *Site metadata. © OpenStreetMap contributors 2017. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.*



Variable	Type	Description	Temporal Resolution	Start Date	End Date	Sensor Height	Values	Value Notes	Sky View Factor	Height/Width Values	
Air Temperature (Ventilated)	PT1000 1/3 Class B: https://metos.at/portfolio/hygroclip-relative-humidity-and-air-temperature-sensor/	Sensor with screen: Accuracy with standard adjustment profile: ± 0.1 °C: Resolution: 0.01 °C:	1 h	Jan. 1, 2011	Oct. 28, 2022	2 m	CALC/INDICES	Values are not (yet) treated/controlled: Hourly and daily mean values are calculated from the total number of measurements		Vineyard - open sky	View
Precipitation	Double tipping bucket rain gauge: https://metos.at/portfolio/rain-gauge/	Sesnsitivity: 1 tip per 0.2 mm: Maximum Rain: 12 mm/minute: Accuracy: ±5%	1 h	Jan. 1, 2011	Oct. 28, 2022	2 m	CALC/INDICES	Values are not (yet) treated/controlled: Hourly and daily mean values are calculated from the total number of measurements		Vineyard - open sky	View
Air Relative	ROTRONIC Hygromer® IN-1:	Accuracy with standard	1 h	Jan.	Oct.	2 m	CALC/INDICES	Values are not (yet)		Vineyard -	View

Figure 4. *Sensor metadata. © OpenStreetMap contributors 2017. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.*

Table 2. *FMP functionality and FAIR conformance*

Function	Description	Metric
Storage	WMO metadata	F2, A4, I4
Search	Open search by attribute	F4.2, A1.1, A1.2, A2, R2
Data model	WMO standard	I1, I2, R4
Username/password	For write only	A3
Zenodo	Open data storage	F1.1, F4.1, A1.1, R2, (F1.2)*

FMP's Search option means that both metadata and data (link to Zenodo) can be retrieved (F4.2, A1.1, A1.2, A2) with a clear usage policy (R2). By adopting the WMO description for climate data and measurements, I1 and I2 are achieved, but so is R4 (meeting a domain standard). The authentication screen ensures compliance with A3 while the adoption of Zenodo's technology ensures that F1.1 (globally unique IDs), F4.1 (searchable data), A1.1 (standard access), and R2 (open data usage policy) are met. In addition, Zenodo could be used for metadata storage; for this case study validation, the FMP was used to export metadata for the entire NSUNET network, which was stored on Zenodo and subsequently provided with a unique DOI (F1.2). In summary, conformance to 15 of the 19 FAIR principles is provided through FMP functionality.

4.2. NSUNET case study and discussion

The full metadata record used in this evaluation is openly available (Savić et al., 2023b), with extracts provided in Tables A1 and A2 in Appendices A and B of the Supplementary Material, respectively. In Table 3, we show each metadata variable used to describe climate datasets and highlight the four variables

Table 3. *FMP datasets and FAIR conformance*

Network metadata	Metric	Site metadata	Metric	Sensor metadata	Metric
institution	F2, I3, R1	name	F2, I3, R1	variable	F2, I3, R1
project	F2, I3, R1	latitude	F2, I3, R1	type	F2, I3, R1
network_code	F2, I3, R1	longitude	F2, I3, R1	description	F2, I3, R1
contact_email	F2, I3, R1	altitude	F2, I3, R1	temporal_ resolution	F2, I3, R1
country	F2, I3, R1	time_zone	F2, I3, R1	start_date	F2, I3, R1
city_region	F2, I3, R1	macroscale_ env	F2, I3, R1	end_date	F2, I3, R1
local_ environment	F2, I3, R1			sensor_height	F2, I3, R1
seasonality	F2, I3, R1			values	F2, I3, R1
start_date	F2, I3, R1			value_notes	F2, I3, R1
end_date	F2, I3, R1			sky_view _factor	F2, I3, R1
reference	F2, I3, R1			height_width_values	F2, I3, R1
date_created	F2, I3, R1, R3	date_created	F2, I3, R1, R3	date_created	F2, I3, R1, R3
date_modified	F2, I3, R1, R3	date_modified	F2, I3, R1, R3	date_modified	F2, I3, R1, R3
DOI creation dates	F2, I3, R1			photo	F2, I3, R1
is_public	F2, I3, R1				
DOI	F2, F3, I3, R1	DOI	F2, F3, I3, R1		

that were missing from the previous discussion on FMP functionality and compliance. The F3 metric is delivered by the DOI variable; I3 is covered by the many variables that contain references to other metadata; R1 is delivered by the totality of the metadata captured; and R3 provides some detail of provenance (dates, ownership, and the totality of metadata).

While the validation supports the position that FMP usage ensures that scientific data is FAIR compliant, it relies on underlying technologies (e.g., Zenodo) to cover some of the metrics. While this does not necessarily require that data be open (minimal data uploaded to Zenodo still provides lifetime DOIs), it highlights that there are *degrees of FAIR compliance.* What this suggests is that while two datasets may be FAIR compliant, one of these datasets may be easier for users to find, search, and use. For this issue to be tackled, it will require more FAIR respositories, more scientists engaging with the process, and ultimately, a data flow process that becomes embedded as part of research data creation or acquisition and subsequent management.

The other issues that arise are whether or not FAIR data is actually interoperable. In other words, data can deliver on all four Interoperable metrics but still have low levels of interoperability. This is because true interoperability requires a fair higher level of data engineering, for example, to integrate two datasets from unrelated projects. Some efforts have used quite an extensive set of metadata descriptions to deliver data integration, for example, the research in Frémand et al. (2023) adopting the CF metamodel (Eaton et al., 2023). This far stricter level of FAIR conformance (many mandatory metadata descriptions) leads to higher levels of interoperability but comes at a price. That price is related to resource overhead and acceptance of additional effort by the scientific community. This tradeoff requires a deeper discussion with scientists around the longer-term benefits and significant impact of highly interoperable FAIR data. However, it may also require funding agencies to separately fund this additional overhead while simultaneously making FAIR data processing activities a mandatory part of the funding process.

4.3. Mapping to FAIRSFAIR: A broader evaluation

As part of a broader and more objective evaluation, we used one of the evaluation tools, FAIRSFAIR, described in Peters-von (Gehlen, 2022). This assessment is described in detail in Devaraju et al. (2020), with metrics presented in Table A3 in Appendix C of the Supplementary Material for ease of reference. For this exercise, we took all 15 metrics from the FAIRSFAIR evaluation and, rather than discussing how each metric is fulfilled, we mapped each individual metric to one or more attributes in the FMP schema. For reference, the entire schema is shown in Figure A1 in Appendix D of the Supplementary Material, with five key tables shown in Figure 5 together with mappings from each of the FAIRSFAIR metrics.

In summary, the five Findable metrics denoted by FsF-F (in Table A3 in the Supplementary Material) are (mapped to) captured by *doi*, *zenodo_link* (ksp_sitedataupload), *institution* (ksp_network), *date_created*, *date_modified*, *doi*, *zenodo_link*, *created_by_id* (networkdataupload) attributes and in the case of FsF-F4-01M by relational database metadata (data definition tables). Both Accessible metrics denoted by FsF-A are captured by *doi*, *zenodo_link* (ksp_sitedataupload). The Interoperable metric FsF-I1-01M (metadata is represented using a formal knowledge representation language) is captured by the fact that all data is created and manipulated by SQL. As the WMO model captures semantics for micrometeorological data, the FsF-I1-02M metric is satisfied. The FsF-I2-01M metric (metadata contains links between data and related entities) is captured through a combination of tables as foreign-primary key relationships. There are five Reusability metrics: two are satisfied by virtue of using a relational database model to capture metadata: FsF-R1-01 MD and FsF-R3-02D; one is satisfied by virtue of the WMO standard model (FsF-R1.3-01 M); and the remaining two metrics are captured by FMP attributes *doi* and *zenodo_link* (ksp_sitedataupload) and *project* (ksp_network). Note that while project is used to capture license information, the user is not explicitly requested to enter license information. The next version of the FMP will make that more explicit.

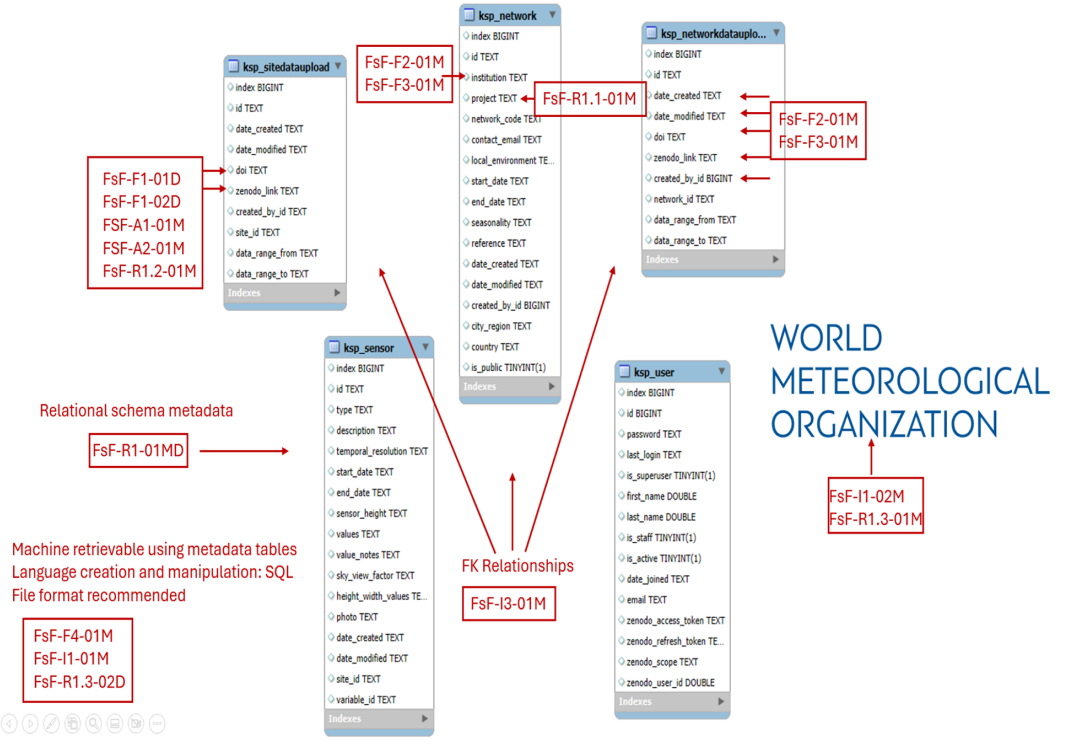


Figure 5. *FsF metric to FMP schema mappings.*

5. Conclusions and future work

In this paper, we articulated the motivation for making scientific data FAIR with a particular focus on climate research data, where long-term reuse, interoperability, and trust are critical. Achieving FAIR compliance in practice requires not only well-defined principles but also easy-to-use, robust tools that enable scientists to associate their datasets with a form of *FAIR Certification* without imposing excessive technical overhead. Our contribution demonstrates how the FMP can effectively deliver such certification for climate research data. Using an extended set of FAIR metrics, we show that 15 out of 19 metrics—almost 80%—are automatically satisfied by the system itself. This result is significant, as it implies that once researchers register high-quality data descriptions (FAIR metadata) within the FMP, a substantial level of FAIR compliance is inherently achieved, reducing both effort and potential for error. As part of the validation of this approach, we illustrated how the remaining FAIR metrics can be addressed through established WMO metadata standards, using a real-world case study of an urban micrometeorological network in Novi Sad comprising 12 observation sites. This case study confirms that the combination of FMP infrastructure and domain-standard metadata provides a comprehensive and practical pathway to FAIR certification for climate datasets.

Future development of the FMP will be organized at two complementary levels in order to deliver platform extensions in the meteorological domain and beyond. First, the platform will be extended to assimilate measurements from physical sensors that are currently not introduced into the system (leaf and soil wetness, for example) and virtual sensors. Data associated with virtual sensors could be obtained using different a physics-based approach, machine learning, or a hybrid of these approaches, such as PINNs Viet-Cuong et al. (2024). Additionally, micrometeorological data of future weather, obtained by downscaling of NWP model outputs on a microscale, would be a significant addition to FMP and important for the broader community. An important feature describing the dataset, which will be added in

future metadata as mandatory, is a standardized method used for gap filling if this procedure is applied. Second, the application of the FMP concept from the micrometeorological domain is equally important. In meetings with research from both agronomy and epidemiology domains as part of the European Cost Action CA20108, it was concluded that there is a significant need for standardization Lalic et al. (2026). In the case of agronomy, it is the result of a combined lack of uniform metadata definition and certain reservations regarding data sharing. In the case of epidemiology, the problem is even more complex because sharing any information related to human health is an extremely sensitive topic.

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Competing interests. The authors declare that they have no competing interests.

Data availability statement. Metadata used for the case study evaluation is openly available at https://www.zenodo.org/record/8237900 (Savić et al., 2023b). Both the cleaned hourly air temperature datasets from the NSUNET system and the raw 10-minute interval data (original data) are openly available at https://www.zenodo.org/record/7738093 (Savić et al., 2023a).

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