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Master Thesis

Improving the Availability of Contextual Data with Machine Learning-Based Interpolation

Ian Maurice Buck

ian.buck@studium.uni-hamburg.de
Study Program Information Systems
Matr.-Nr. 6911467

First Reviewer: Prof. Dr. Janick Edinger
Second Reviewer: Philipp Kisters

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A distributed system is one where the failure of some
computer I've never heard of can keep me from getting my work done.
– *Leslie Lamport*

Abstract

Many science-based applications need continuous or gridded input data in order to work properly. This paper investigates how single data-points can be combined to create a continuous data layer, in which missing data points are interpolated. An example for such an application would be the prediction of temperatures coming from single sensors and weather-stations, that can be combined to detect Urban Heat Island (UHI)s. UHIs are weather phenomena that get amplified among other things by the ongoing densification of urban areas to create more living space, typically accompanied by the removal of green areas that can help with the dissipation of heat. These heat islands, in which the temperature is significantly higher than in surrounding areas, pose a threat to the health of the urban population, especially to the elderly, children and people with existing health conditions. Traditionally, UHIs are detected using Land Surface Temperatures (LST) captured by satellites, that usually have the downside of low spatial and temporal density. This paper proposes an alternative approach by creating a machine-learning model that is able to interpolate missing data between data-points coming from citizen-owned sensor networks that are combined with mobile sensors, which can be attached to rental bikes, buses or e-scooters, to gain temporary insights into otherwise unobserved areas. The model combines data streams of sensor readings with historic data and creates a fine-granular continuous data-layer, in this case for temperature, which allows for an accurate localization of UHIs.

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List of Abbreviations

LST Land Surface Temperatures

UHI Urban Heat Island

1 Introduction

In 2023 56% of the human population already lives in urban areas with the number projected to continuously increase to 68% by 2050 ¹. Combined with the ongoing climate change and urban densification, cities are facing many new challenges. With the removal of vegetation in favor of living space and the sealing of surfaces with heat-absorbing materials such as asphalt or concrete for streets and highways [GRGTDW20], rising temperatures lead to new phenomena that pose risks for the urban citizens. A recent phenomenon is the appearance of so called urban heat-islands (UHI). A heat-island is a local occurrence of significantly higher temperatures than surrounding areas that pose a health risk, especially for the elderly, children or citizen with prior health-issues [MBG15].

In order to detect UHIs, Land Surface Temperature (LST) is commonly used. While allowing for a cheap analysis of large areas without the need of ground weather-stations, this approach comes with certain downsides, such as low temporal and spatial resolution and restrictions such as only being able to measure temperatures when no clouds interfere with the microwaves sent from the measuring satellite [ZPL15]. This spatial and temporal resolution, of f.e. spatial resolution of 0.01° longitude and 0.01° latitude (equal to roughly 1.11km by 1.11km) and temporal resolution of monthly average surface temperature as offered by LST data provided by the European Space Agency (ESA) Climate Office's data set [GVP], is not enough to effectively analyze the urban microclimate. Another candidate that comes to mind are weather stations. They usually provide hourly, for current values sometimes even 10 min interval readings of temperature, rain and wind, but don't offer the necessary spatial resolution. Lastly, there is the possibility of deploying sensor networks to closely monitor the climate of the city, but this approach can be quite cost intensive for a large amount of sensors over a long time period [CMY⁺15]. An alternative that is less costly would be to instead rely on citizen-owned sensor networks from the existing Smart Home and Internet of Things (IoT) infrastructure, like Sensor.Community ² and Netatmo ³, which offer a temporal resolution of 5 min for temperature and wind, hourly for rain, while also having a comparably high spatial resolution. This approach has the desired temporal resolution and has been shown to work well in [MFG⁺17], but there might be areas, such as industrial zones, where citizens are not able or not allowed to install their personal sensors. In order to also gain insights in such previously unobserved areas, we propose the usage of mobile sensors

¹<https://ourworldindata.org/urbanization#by-2050-more-than-two-thirds-of-the-world-will-live-in-urban-areas>

²<https://deutschland.maps.sensor.community/>

³<https://weathermap.netatmo.com/>

that could be installed on buses, bikes or e-scooters to gain temporary snapshots and improve the spatial resolution even further. As research related activities commonly rely on continuous or gridded data fields, there needs to be a way to convert these single data points from the different sensors into a continuous data-layer.

In this paper, we propose a solution to this problem by training a machine learning regression model, that allows for the interpolation of missing data-points. Based on sensor readings, from the sensor networks and mobile sensors, of commonly collected weather information, such as temperature, humidity, rain, pressure, wind, and possibly other variables such as vegetation indexes [AR20], the model then creates a continuous data-layer that allows for a holistic view of the observed variable, in this case temperature.

To do (??)

1.1 Objective

current situation: abundance of data (data quality unknown), but different data sources at different places with different formats, making it hard to work with different sources at the same time - smart city example -> heat island detection - sensor networks (stationary + mobile) - LST satellite data (lack of spatiotemporal resolution, not suited for micro-climate) - vegetation indexes (in geoinformation systems/portals) - etc. - currently these sources are used independently from each other, but how can they be integrated? - hybrid approaches have shown that combining different approaches (smart city stationary + moving sensors) to give better prediction quality than singular approach (reasons: unobserved areas) - statistical models offer not enough flexibility/are too cumbersome to work with (and probabilities are not known) - ML is a good fit to analyse patterns and rules - but effort to retrain models for each application expensive - how can ML be used to integrate the different types of data? - how can data availability of contextual data be improved by leveraging ML approaches for different topics? - for the heat map detection, what you need is a fine-granular temperature map, that allows for outlier detection - either train your own model on a huge dataset - or access a temperature map -> this will be discussed, how to use ML for this and improve data availability by using interpolation - additional topics to briefly discuss (mainly apply by implementing ML models) - what work needs to be done before using the data in ML (preprocessing, transformation, outlier detection etc.) - one way of preparing data is to interpolate missing data to create continuous gridded features (focus of this work) - how ML can we improve the interpolation quality of features? -> turn sparse features into denser versions with interpolation, interpolation based on other features present

Methodology

In order to validate these things, we need high quality data-sets with many different features, but there are not many available, even though for certain things (atmosphere etc.)

there are OpenData sets available. Goal is: implement a temperature map based on ML that interpolates missing data based on historical and current data. Compare prediction quality of different type of models (DL, random forests etc.) based on cross-validation (simulate missing data by leaving data points out on purpose) -> experiment with different intervals, densities etc. -> could also compare to Krigin (as a typical geostatistical approach for temperature interpolation) Subgoal: In order to achieve this, we also need high quality data-sets to train and validate the model -> source them from OpenData platforms

1.2 Structure of this work

Research methods:

- literature research as foundation
- heat island detection - smart cities -> sensor networks vs LST - what type of other data is available? geoinformation, vegetation, for micro-climate: shades of bigger buildings?
- - prototyping
- implement pipeline to pre-process different types of data
- feature extraction
- implement ML model
- deploy ML model

- create/search for fine granular data sets
- add new contextual data to existing data sets
- discuss different types of data (gridded vs continuous vs data points) and methods for each
- train ML models with different methods (deep learning, random forests etc.) and different features enabled

- cross validation of results
- discuss validation techniques and indicators (RSME, MSE)

The rest of the thesis is structured as follows. Chapter 2 begins with an analysis of related work, where important literature is discussed, that forms the foundation of this research. In chapter 3, the focus lies on describing the service architecture, that shows how a machine learning model can be deployed in different contexts to improve data availability. Which machine learning approaches can be used to interpolate missing data and how they differ from each other is discussed in chapter 4. In Chapter 6, the different ML approaches are compared and cross validated with each other based on the different model that are trained on the obtained data-sets. Finally, chapter 7 discusses the findings of this thesis and gives an outlook into future work and research directions.

2 Related Work

In the following chapter we lay the foundation for the research conducted in this thesis. We start off with an introduction of the topic of urban heat island (UHI) detection, which is one of the motivating factors behind this work. UHI research is part of the discipline of modern climatology and relies on many different sub-disciplines like meteorology, thermal dynamics, geology and many more. After discussing traditional ways to detect UHIs, such as using remote satellite data, we discuss newer approaches, especially in the context of smart cities, that focus on collecting air temperatures in urban environments. Measuring data in the urban environment comes with many challenges [Oke06], that can lead to missing or wrong observations for given places. In order to improve data availability in the urban climate context we compare traditional interpolation techniques based on (geo-)statistics with more recent machine-learning based approaches, that could be used in this highly complex urban setting. This interpolated data could be used to improve interpolation or prediction models and give additional insights into the influences of urban environments, f.e. in the context of UHIs and their detection and analysis. Finally, in order to compare traditional geostatistical models with ML-based models, we need comprehensive data-sets of urban climate data. An overview of available data sources is given in section 2.3 together with an introduction to the OpenData movement.

2.1 Urban Heat Islands (UHI)

UHIs have been the center of a lot of attention for quite some time in the scientific community. As early as 1833, with the research of Luke Howard in London which observed higher temperatures inside London than in surrounding areas [How33], UHIs have seen a steadily increase in scientific contributions. The term *Urban Heat Island* was first introduced in the 1940s [BP47]. The recording and investigation of UHIs has seen mayor steps since the begin of modern climatology, also known as the Sundborg's era beginning with Sundborg's 1951 classic heat island study of Uppsala [Sun51]. UHIs occur in many cities around the globe [PPC⁺12] in different climatic zones, during different times of day and in different intensities.

Shared UHI Challenges

Some shared challenges are: 1. Define what *urban* means in the context of UHIs [SO09]. The term urban is widely used to identify areas that are more densely populated than the surrounding rural areas. Having this distinction between urban and rural [Low77] helped researchers to better define the UHI magnitude (cite), but this simple distinction also lead to problems [Ste11]. The problem lies in the fact that there is no clear border between urban and rural areas, but a fluent transition. Especially for larger metropolitan areas, like Tokyo, the urban area could span 10s to 100s of kilometers, making the collection of reference rural temperatures hard. The reference rural temperature has a direct influence on the UHI magnitude, which is ‘the most widely recognized indicator of city climate modification in the encironmental sciences’ [SO09]. As a solution, different classification into local climate zones were proposed [SO12, SO09], that classify areas based on surface roughness, building densities, building heights etc. 2. Measuring the influence of other local urban or meterological phenomena on the temperatures collected. The urban climate is extremly complex, due to many different influences, such as antropological energy,... (cite, todo find the influence factors). Additionally, the urban climate is also influenced by surrounding regional/meso-scale climate phenomena such as storms, valleys, mountains, large waterbodies, costlines and more (cite).

2.1.1 UHI Classification

UHIs can be classified in many different ways. Typically, there is a horizontal classification, defining the superficial extension of the UHI from micro-, to local- to meso-scale, and a vertical classification, defining in which vertical layer of the urban area the heat island is observed. To better understand these scales and the anatomy of the planitoyr/urban boundary layer, figures 2.1 to 2.3 show a detailed view of the meso-, local- and micro-scale of the urban climate, as illustrated by Oke 2006 [Oke06].

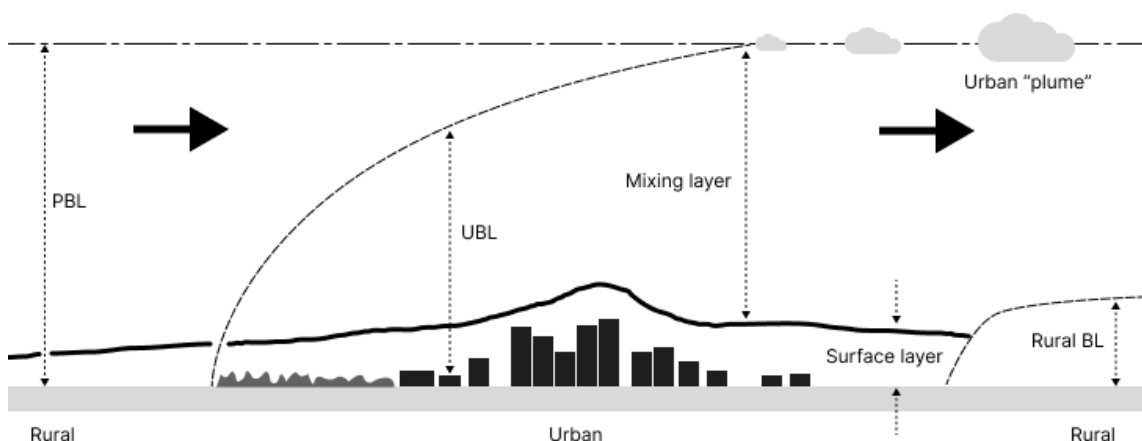


Figure 2.1: Mesoscale view of the urban climate, redrawn from [Oke06]

The mesoscale, as depicted in fig. 2.1, spans the whole urban environment of a city,

typically tens of kilometres. There are several boundary layers, that comprise different scales. The planetary boundary layer (PBL) [Wyn85] is the lowest layer of the Earth's atmosphere and spans from the surface to a height of several hundred meters up to several kilometers. It is characterised by the turbulent mixing of air, forming wind currents, that are mayorly influenced by the underlying surface.

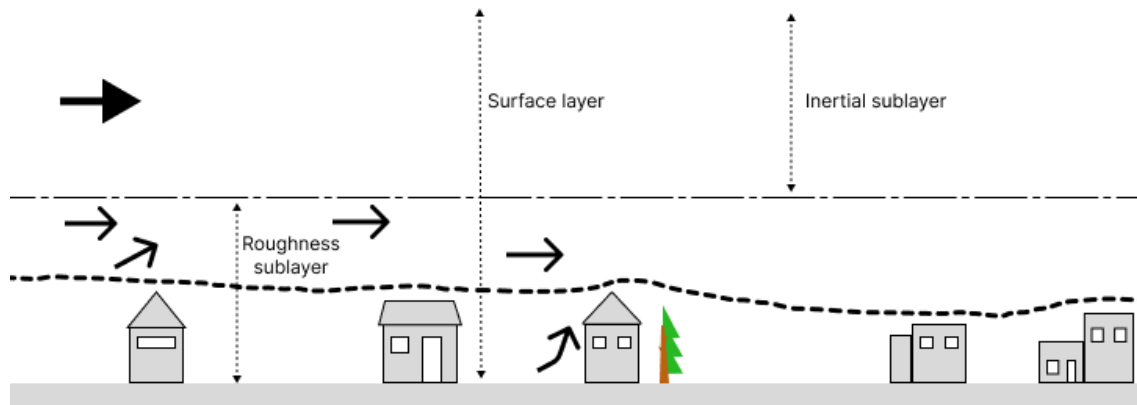


Figure 2.2: Localscale view of the urban climate, redrawn from [Oke06], (Todo finish)

The localscale is situated closer to the surface and contains landscape features such as topography, but does not yet include microscale effects. At this layer, the underlying microclimatic effects in form of fluxes mix together to form a more average and representative view of the source area, typically at the scale of one to several kilometers. This layer is monitored by weather stations that are located at/or slightly above the canopy height. Todo: more infos

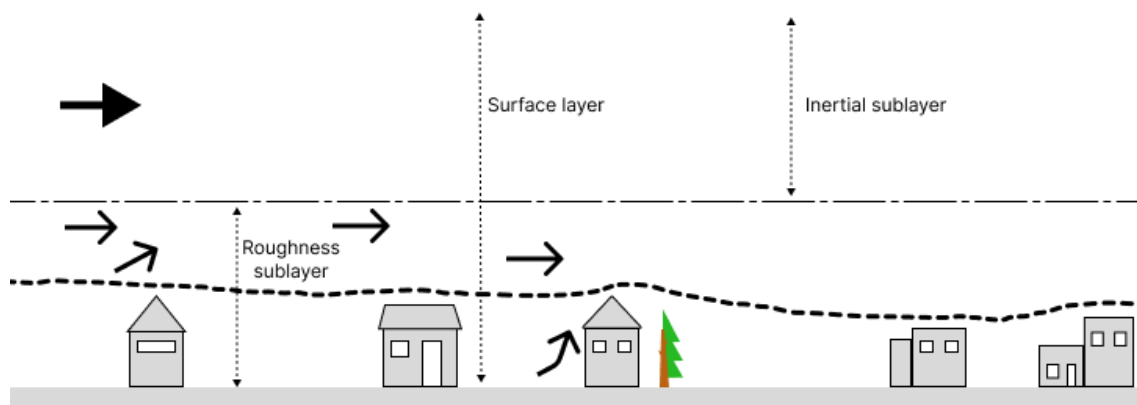


Figure 2.3: Microscale view of the urban climate, redrawn from [Oke06], (Todo)

The microscale deals with the characteristics of each individual surface area. On of the main measurements on this layer is the surface temperature, which is primarily influenced by solar radiation. It is important to note, that surface and air temperatures are correlated, but this correlation varies greatly based on other surrounding influences such

as wind velocity or humidity [SB92]. todo: more

Vertically UHIs can be divided into three major types [Oke76, OMCV17], namely Boundary Layer Heat Island (BUHI), Canopy Urban Heat Island (CUHI) and Surface Urban Heat Islands (SUHI), that correspond with the boundary layer they can be monitored/measured in. todo: more

2.1.2 Canopy Urban Heat Island (CUHI)

The canopy UHI is measured in the canopy boundary layer several meters above ground slightly below or on the average roof layer of the surrounding buildings, as seen in fig. 2.3. The primary measurement in the canopy is air temperature, which is used to measure the urban heat island intensity (UHII) [Oke73], the most commonly used way of describing the heat island magnitude [KB21].

Since the beginning of modern climatology, major progress has been made in this research field, but methodologies and scientific rigor in CUHI research still seems to be lacking, as discussed by Stewart in 2011 [Ste11]. Stewart found, that over 54% of CUHI research was lacking proper methodologies or had other shortcomings such as a lack of site descriptions, where sensors were placed, or the disregard of non-urban factors such as local weather phenomena. In response, progress has been made in recent years by improving methodologies and ensuring correct measurements of climate-related data and study design and execution through various guidelines [Oke06], especially in urban settings, that require special care due to the huge amount of possible influences on local recording sites.

Todo: more

2.1.3 Surface Urban Heat Island (SUHI)

The surface temperature is measured directly at the surface of an object and is the main indicator of the surface urban heat island (SUHI). Surface temperature, in contrast to air temperature, typically is measured via remote sensing technologies like LST via satellites. Well-known satellites include MODIS, Landsat ... (todo list all), that all carry different types of instruments and sensors, that are able to take various measurements. Through the use of satellites, the spatial coverage is great, but raster sizes usually range from one kilometer to a hundred, so the spatial resolution is not that great compared to denser sensor networks. Additionally, these satellites are not geostationary to cover a wide range and therefore only take measurements during a handful of times a day (todo: number of fly overs with example). Another downside is that satellites in many cases need clear-sky conditions to measure surface temperature at ground level, as their sensors are not able to penetrate the cloud surface. As a solution, some technologies such as LIDAR

(todo check if true) offer the approximation of the underlying surface temperature below clouds by measuring the out-going radiation of the surface. todo: List of measurement types (microwaves etc.) with disadvantages

Surface and air temperatures can vary greatly, therefore a SUHI does not necessarily also imply a CUHI.

2.1.4 UHI Detection in the Context of Smart Cities

Smart Cities are ‘urban areas that exploit operational data [...] to optimize the operation of city services’ [HEH⁺10], by collecting near-real-time data from physical and virtual sensors, integrating those data sources into an enterprise computing platform and performing complex analytics on them. With current urbanization trends (60% of ppl living in cities 2060) and the ongoing global and urban warming (cite), research into smart cities has gotten a lot of attention recently (cite). One of the driving factors behind smart cities is next to progress in digitisation of cities the availability of cheap smart sensors (cite), that enable a good spatiotemporal surveillance of factors in a smart city.

- goals and pillars - architecture - challenges
 - classification of UHI detection into the smart city framework

In the context of UHI detection,

- testbeds, sensor networks (citizen owned)
- cross over to pollution detection

2.2 Interpolation of Missing Data

In the context of urban environments, there are many measurements such as surface temperature, which are measured by sensors that have certain weaknesses. In the case of LST data collection, clouds play a mayor part and prevent surface temperature to be measured. In many LST data-sets (ref), measurements for cloud areas are simply defined as having no value. As many applications and algorithms need continuous input data to work as expected, in this work we take a look on how interpolation, especially with the help of ML, can help solve this problem. In the context of LST data, this could mean interpolating the missing data either based on surrounding data (cite) or by integrating many different features such as air temperature, humidity, heat flux etc. in a ML model (cite).

- moving sensors for better spatial coverage into unobserved areas

Interpolation vs. Extrapolation

In this work, we focus on interpolation of missing data. Interpolation is the process of calculating/guessing missing values between given values. This could be a missing value in a time-series or a missing cell in a data grid (cite). In contrast, extrapolation is

the prediction of values based on previous values, like predicting values based on historic time-series data, as in the case of weather forecasting. Due to time constraints, we only focus on the interpolation part, though extrapolation could also play an important role in smart cities by predicting UHIs and warning citizens about potential future heat-related risks.

2.2.1 Regression Analysis in Statistics

Fundamentally, regression analysis has its roots in mathematics, more specifically in the field of statistics. todo: more

- foundation of other research fields, based in statistics/mathematics
- linear regression (least-squares) - multiple regression models - hierarchical regression
- special cases - piecewise linear regression - inverse prediction - weighted least squares
- logistic regression - poisson regression

2.2.2 Interpolation in Geostatistics

- spatiotemporal (kriging) - time series prediction vs interpolation of missing data - based on GIS - pipeline: fit measured data points to grid, interpolate missing squares downside: cannot find local maximas/minimas

2.2.3 Interpolation with Machine Learning Models

- ML regression

2.3 Access to data sets

As part of this thesis, the collection of own data via sensors or other means is not feasible due to time and resource constraints. However, there are many online sources and portals/catalogues that give access to a wide variety of data-sets.

2.3.1 OpenData Movement

- portals - official: - EU: <https://data.europa.eu/data/datasets?query=temperature&locale=en> (combines many governmental and local catalogues) / <https://data.europa.eu/data/catalogues?locale=en>
 - USA: <https://data.gov/> - UK: <https://www.data.gov.uk/> - private: <https://www.kaggle.com/>
 - strategies: - self procurement (test beds -> Helsinki Testbed (climate research mesoscale), UK Birmingham Testbed (climate + smart city),)
-

2.3.2 Available Data Sources and Portals

2.4 Applications and Research Areas (needed?)

- focus on temperature interpolation/climate research
 - climate research - high area coverage, low spatio and temporal resolution (5km by 5km squares) - based on LST data (from satellites) -> not the same as air temperature
 - micro-climate research - bad/costly area coverage, high spatio and temporal resolution - Urban heat islands - Pollution (fine dust pollution)
 - connection to smart cities - integrating many heterogenous data points - detection climatic anomalies - notify/warn residents
 - important key words
 - current status quo
 - important authors and current work
 - > identify research gap - convert single data points to continuous/gridded data - improve density of data to gain insights and improve visibility -> identify areas with low prediction quality
-

3 System Architecture

The main goal of this work is to apply ML-based interpolation techniques to the topic of UHI detection to improve data availability and compare different interpolation techniques that are based on traditional (statistical) and ML-based approaches. ML-based models first of all need a lot of data to be trained and validated with, and after deployment need access to relevant real-time data, if near real-time capabilities are desired. In the context of smart city, such ML-based interpolation models could be used to improve data availability by interpolating missing/unavailable data such as LST readings under cloudy conditions, and be incorporated into a service that other services, like a UHI detection service, could further rely on, without the need to implement interpolation techniques themselves. This could reduce costs to develop such depending services, as they no longer need to deal with missing data themselves while also improving interpolation results with well-trained and designed models. First, we need to take a look at how such a service fits into existing smart city architectures.

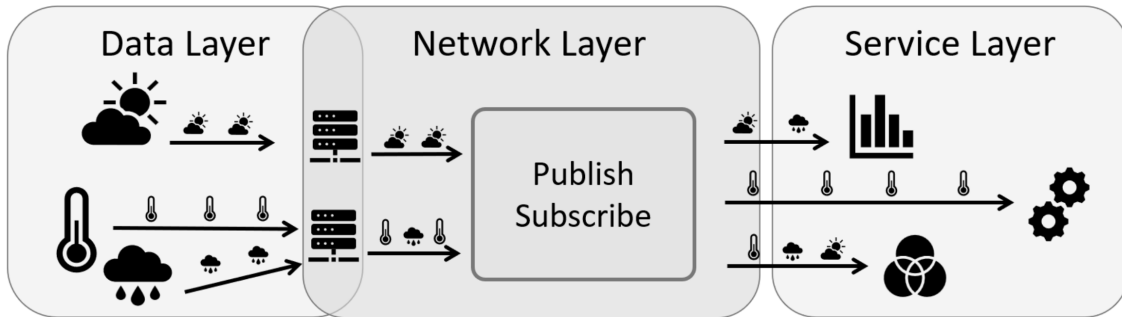


Figure 3.1: In the data layer (left), a wide variety of environmental data is collected with the help of multiple sensors. These are connected to their citizen-owned local base stations, which manage access rights and forward collected data to subscribed services (right) via the decentralized publish-subscribe in the network layer (center).

3.1 Architecture Layers of Smart Cities

The most generalised architecture of a smart city consists of four layer, the sensing layer, transmission layer, data management, and application layer [SKH18]. In this work, we focus on the sensing layer, dealing with topics such as correct sensor placement and underlying sensor footprints, and the application layer, which accesses available data via

data management services to provide additional services to the city and its citizens. For the data transmission and data management layers, there already exist different technologies and service offerings, that aim at solving the underlying problems, e.g. network bandwidth, network availability, sensor discoverability, handling the massive amounts of data that is already or will be collected in the future, and many more. For the communication and discovery of sensor nodes, one solution could be SkipNet [HDJ⁺02], an overlay network focused on discoverability while also protecting privacy, with which the data transportation layer could be designed as a peer-to-peer (P2P) network. Other research focuses on the data accessibility and discoverability, by making data accessible for everyone, not only for economic partners in a closed-off system. Examples would be the Smart Networks For Urban Citizen Participation (SANE) initiative [BJK⁺19], which... Figure 3.1 shows the architecture of the SANE system.

3.1.1 Sensing Layer

The goal for the sensing layer is to monitor the surrounding environment and capture key data for further analysis and decision making. It consists of many different types of physical and virtual sensors. The first group of sensors are the physical sensors, which are placed directly inside the environment. Wireless sensor networks (WSN) have seen a lot of attention for many different applications such as ‘military sensing, physical security, air traffic control, traffic surveillance, video surveillance, industrial and manufacturing automation, distributed robotics, environment monitoring, and building and structures monitoring’ [CK03]. The challenges for WSNs primarily depend among other things on the deployment. An ad-hoc WSN has energy and bandwidth constraints due to the usage of batteries as power sources. In contrast, sensors that are permanently installed, either stationary or on a moving target, and connected to a constant power source don’t have this constraints. This approach could be used for smart cities to reduce waste and guarantee representative measurements via correct sensor placement. In the case of stationary sensor networks though, the initial deployment and following maintenance cost can be substantial [CMY⁺15].

In recent years, low-cost sensors (LCS) in combination with sensor networks have enabled fine-granular real-time monitoring of urban environments, although the quality of individual low-cost sensors can be questionable [CDS⁺17]. In general, LCSs can improve data availability and support analysis, but do not substitute well-calibrated reference instrumentation [LPS18].

Stationary Sensor Types

There are many different types of environmental features that can be measured directly inside an urban area. The types of measurements that can be observed are among others: air temperature, humidity, atmospheric pressure, reactive gaseous air pollutant (CO, NO_x, O₃, SO₂), particulate matter (PM), greenhouse gases (CO₂, CH₄), precipitation,

solar radiation, wind speed and direction, anthropogenic heat, noise, sky-view factor, heat fluxes and many more. Correlations between these features can vary greatly based on surrounding factors. In order to better understand these correlations, many empirical studies have studied the influence of meteorological factors on features such as PM [TMJ10]. Additionally, many fields of statistics have specialised on topics such as statistics in climatology [VSZ02], geostatistics [TYU86] and more.

All sensor readings that are taken by physical sensors are singular data points. Additionally to the type of measurement taken and the actual value observed, physical sensor readings include the physical location of the sensor, e.g. latitude, longitude and altitude, the type of sensor used to take the measurement, and the sampling rate. For air temperature, the sampling rate could be an average temperature measured over five minutes, whereas precipitation might be measured by collecting rain for certain periods of time and then measuring the amount of rain collected. The sensor type is important, as different types of sensors can produce different qualities of measurements, e.g. LCS compared to calibrated reference-grade high cost sensors, and perform better or worse based on the meteorological conditions, e.g. worse performance at low temperatures, high humidity etc. Due to the placement directly inside the environment, (near) real-time observation and high temporal resolution are generally possible, but might be influenced by factors such as network availability. The spatial resolution highly depends on the number of sensors deployed and the correct placement of the sensors. The correct placement has a direct influence on the footprint of the sensor [LF14] and the representativeness of the measurement taken for the underlying and surrounding area [Oke06].

One downside of the placement directly in the environment the sensors are observing, is the exposure to environmental influences such as heat, humidity, or pollution, that can decrease the lifetime of a sensor and may require more frequent maintenance or replacement.

- discussion premium vs low-cost sensors - discussion static data incorporation -> NDVI from geoportal via data management layer
- P2,5: highly depends on air flows - humidity: needs to be replaced more often due to pollution - temperature

Remote Sensing

In comparison to stationary sensors that are installed directly in the environment they are observing, remote sensing describes the process of observing a target environment from afar [CW11]. In climatology, remote sensing is used to collect meteorological data via satellites, planes or balloons by either capturing image data, that can be used to identify things like cloud and land coverage, by measuring passive radiation, or by actively sending out microwaves or using LIDAR to detect features such as surface temperature, e.g. LST data. Remote sensing comes with its own set of advantages and challenges.

The major upside of sensors moving way above ground is the high spatial coverage, that

allows for meso- and planetary-scale analysis of weather phenomena. Another upside is the great data availability, as many satellite providers, such as ESA..., publish their satellite data. This creates many research opportunities, and many services directly rely on these measurements (todo list).

Remote sensing also comes with some downsides. The primary downside is the low spatio-temporal resolutions. Weather satellites usually are not orbit-stationary and move around earth on a predetermined orbit. As a consequence, satellites only pass over each individual area a couple times a day, making real-time applications for currently unobserved areas impossible. Additionally, the spatial resolution can be too low for micro-/local-scale analysis, with typical LST resolution spanning from 1 km² to tens or even hundreds of km² per data point/grid field. In the atmosphere, there is also a lot of environmental noise, like radiation, that can have a negative influence on the measurement accuracy. Another disturbing factor can be clouds or other types of particles like rain, that absorb radiation/microwaves sent from the sensors, traditionally making measuring under cloudy/rainy conditions either impossible (example) or less accurate (example), by instead relying on outgoing radiation from the surface. These restrictions highly depend on the sensor used, as different sensors use different technologies, e.g. microwaves with different wave lengths or higher resolution sensors.

Modelling of the Sensing Layer

A model is an abstraction of the real world that helps us analyse and understand complex problems. In the context of UHI detection, we can use model climate on a bigger scale, or the micro-climate inside a city, to better understand and capture influences. In this work, we focus on ...

One major consideration in this context, what type of data is used to validate and train the ML models. The options in this case are either climate models which simulate data, or capturing/collecting real-world data. Due to the complexity and limitations of simulation, this work only focuses on collecting real-world data.

3.1.2 Data Transportation Layer

Todo (small)

3.1.3 Data Management Layer

How to handle such large amounts of data Connection to other APIs Dealing with the heterogeneity of data modeling uncertainty of data

Integrating Static Data

Next to sensor readings captured for a given area, there are also other types of information that could be useful for ML applications. Alonso and Renard [AR20] used these

additional indexes to predict air temperature:

- Vegetation Index
 - Normalized Difference Vegetation Index (NDVI)
 - Soil Adjusted Vegetation Index (SAVI)
 - Enhanced Vegetation Index (EVI)
 - Tasseled Cap Transformation greenness (GVI)
 - Density of low vegetation
 - Density of medium vegetation
 - Density of high vegetation
 - Water Presence Index
 - Modified Normalized Difference Water Index (MNDWI)
 - Normalized Difference Water Index (NDWI)
 - Moisture Index
 - Tasseled cap Transformation Wetness
 - Normalized Difference Moisture Index (NDMI)
 - Bare Soil Index
 - Normalized Difference Bareness Index (NDBaI)
 - Bare Soil Index (BI)
 - Enhanced Build-Up and Bareness Index (EBBI)
 - Density of bare soil
 - Radiation Index
 - Spectral radiance
 - Emissivity
 - Tasseled Cap Transformation Brightness
 - Building Index
 - Normalized Difference Build-Up Index (NDBI)
 - Urban Index (UI)
 - Index-based Build-Up Index (IBI)
 - Building Density
 - Topographic
 - Slope (°)
-

- Exposure
- Curvature
- Urban morphology
 - Sky View Factor
 - Standard Deviation (STD) of Building Height (building height variation)
- Land use
 - Distance to railway tracks
 - Distance to points of tourist interest
 - Distance to subway entrances
 - Distances to fountains
 - Water area

These types of data can be sourced either directly via satellites like LiDAR or Landsat 8, or via geoportals that publish such data, like the State Office for Geoinformation and Surveying Hamburg ¹ on a regional basis or the EU Inspire Geoportal ² on a continental basis.

Integrating External APIs

Currently, there exist some cities that already operate open-source sensor networks that usually act as a middleware to upload and retrieve sensor data and offer additional functionalities like alert or notifications. A detailed list of case studies is provided in 3.3. Next to city specific initiatives, there exist also independent sensor network platforms or initiatives. These are either operated by vendors of f.e. IOT devices, or by open-source communities. In the following, one vendor and one open-source community project is portrayed in more detail:

Netatmo: Netatmo ³ is a French Smart Home Company that was founded in 2011. It has a large smart home assortment including cameras, door bells, smoke detectors, thermostats and weather stations among others. In the context of collecting meteorological data, the smart weather products are of particular interest. These include a smart weather station that collects air temperature, humidity and air pressure, an anemometer that collects wind speed and direction, and a rain gauge. The sensor specifications, as reported by the vendor himself, is reported in Table 3.1.

Complementary to its smart products, Netatmo also operates a weather platform and

¹<https://geoportal-hamburg.de/geo-online/>

²<https://inspire-geoportal.ec.europa.eu/>

³<https://www.netatmo.com/>

Measurement	Unit	Measurement Range	Precision	Recording Frequency
Temperature	°C	-40°C to 65°C	0.3°C	averaged over 5 min
Humidity	% (RH)	0 to 100%	3%	-
Air Pressure	mbar	260 to 1160 mbar	1mbar	-
Noise	dB	35 to 120 dB	-	-
Wind Speed	m/s	0 to 45 m/s (160 km/h)	0.5 m/s	every 6 sec, averaged over 5 min
Wind Direction	°	0 to 359°	5°	every 6 sec, averaged over 5 min
Rainfall	mm/h	0.2 to 150 mm/h	1mm/h	every 5 min (bucket is emptied)

Table 3.1: Netatmo Sensor Specifications (Vendor reported)

a developer portal. The weather platform offers a weather map ⁴ containing the measurements of connected weather stations across the whole world for air temperature, precipitation, and wind speed and direction. The developer portal ⁵ offers a way to programmatically access all sensor measurements via a REST API. In this work, we later use this REST API to collect sensor data, as discussed in Chapter 5.

Next to commercial vendors, there also exist OpenSource projects which operate and develop sensor platforms independently:

Sensor Community: Sensor.Community ⁶ is an open-source community driven project that aims to collect Open Environmental Data. The project is part of the initiative OK Lab Stuttgart ⁷, which is run by a group of volunteers that ... 13.500 sensors world-wide, open source

- BME280 - SHS

Most of the solutions have in common, that ... - accounts, request quotas, historical data?

But, they also differ at... - no common REST standard, no shared accounts, sensor descriptions (placement)

3.1.4 Application Layer

The application layer contains services which utilize data provided by the data management layer to provide services for the city and its citizens. As part of this layer, services could be build that aggregate data streams coming from the data management layer and use ML to improve the data quality by detecting outliers, reducing bias, interpolating missing data etc. The improved data could then be published and other services that would otherwise rely on the raw data streams and potentially need to implement their own outlier detection or interpolation of missing data techniques, instead simply subscribe to the externally managed service. This could lower the barrier to entry for developers with less available resources, financially or domain-knowledge wise, and generally

⁴<https://weathermap.netatmo.com/>

⁵<https://dev.netatmo.com/apidocumentation>

⁶<https://sensor.community>

⁷<https://codefor.de/stuttgart/>

allow developers/service providers to allocate their resources to other areas like user experience (UX) and usability compared to the maintenance of complex ML-based services. In the context of this work, we focus on the topic of UHI detection. In this context, there could be a UHI detection service that ingests real-time data streams from the data management layer and notify citizens if an UHI is detected in or predicted for a particular urban area. As the main challenge for UHI detection lies, next to the definition of urban and rural reference areas, on the gathering of a comprehensive temperature map that allow UHI detection algorithms to work, in this work we primarily focus on creating and evaluating an air temperature map service, that enables the detection of CUHIs and could also be used as a foundation for other services in a smart city, like plant watering systems, smart healthcare and more.

3.2 Applications for Machine-Learning

The data management layer publishes historical data and real-time data streams for application service to ingest. Generally, ML can be used for the following tasks in different variations:

- Classification

In this context,

This section is about where ML could be used (Land cover,)

- comparison to NLP -> pipeline vs singular model (NLP pipeline vs ChatGPT)

applications: - all-in one solution (all features included) -> huge DL model with billions of parameters (ChaptGPT) - not feasible in this thesis - pipeline solution (use ML models incrementally and build upon results) - similar to NLP - feasible for specific topics - bottom-up approach (use ML to increase the amount of available data)

- types of ML utilisation - outlier detection - classification - regression - interpolation of missing data - prediction of future data

3.2.1 Parallels to Natural Language Processing

NLP pipeline (stemmer, lexer, etc.) vs single model (ChatGPT) - neural network with billions of parameters

3.3 Smart City Case Studies

Many european cities, like Amsterdam, Barcelona, London and Stockholm, have developed their own smart city strategies and platforms. In the following, we take a closer look at the steps each city has taken:

Barcelona, Spain: Barcelona operates the ‘Sentilo’ platform ⁸, an open-source smart city platform that aims to break down informatioal silos inside the city to provide unified access to the data available. It currently contains more than 27.000 sensors ⁹. It offers a modular and extensible architecture, high performance and scalability, alerts, stats, triggers, a simple REST API to send and receive sensor data, and is cross-platform by being build with Java, Redis and MongoDB.

Amsterdam, Netherlands: Amsterdam utilizes sensors to run an extensive smart lighting system, that

London, England: More infos

Stockholm, Sweden: More infos

More honorable mentions from outside the EU:

Singapore: more infos

San Fransico, US: more infos

⁸<http://www.sentilo.io/>

⁹<http://connecta.bcn.cat/connecta-catalog-web/stats/> (*Accessed: 23.03.2023*)

4 Machine Learning Model Design

In recent times, the area of machine learning has seen big advancements in terms of model size and complexity. Especially in the area of generative AI, e.g. text and image generation, models such as OpenAI's ChatGPT [Ope23] have generated significant hype for the possibility of use of AI. As a result, the question arises what benefits AI can bring to other areas of application, such as sensing applications in the context of smart cities. In this chapter, we will discuss the usage of AI in the context of smart city, more precisely in the context of data enrichment via interpolation, and outline possible advantages and disadvantages compared to traditional (geo-) statistical methods.

First of all, we need to clarify what is meant by artificial intelligence (AI), machine learning (ML) and deep learning (DL). AI is a broad term that is used to describe the ability to perform tasks, that are usually associated with human intelligence. ML is a subfield of AI, that focuses on the ability of a system to learn from data without being explicitly programmed to do so. Finally, DL is a subfield of ML, that uses artificial neural networks, which imitate the structure of the human brain, to learn from data and perform various tasks.

In this work, we will focus primarily on DL models, as these offer the possibility to learn complex patterns and dependencies, which could be beneficial in the complex context of smart city and temperature interpolation. The universal approximation theorem states, that a feedforward network with a single hidden layer containing a finite number of neurons can approximate any continuous function [HSW89]. This statement emphasizes the power of DL models. However, it does not state how many neurons are needed to approximate the function and gives no indication on how to train the network. In practice there is lot of trial and error involved when designing DL models.

Additionally, we will also take a brief look on traditional ML models, such as linear regression models, as these are usually very easy to implement and can be used as another baseline for comparison, which trade speed of setup and execution against complexity and potentially less accuracy.

In the following, we will first discuss fundamental model assumptions given by the data layer. Afterwards, we will discuss the potential design of a ML model for temperature interpolation, including the architecture as well as potential input features and possible pre-processing steps. The model is then implemented and later evaluated in chapter 6.

4.1 Model Assumptions from the Data Layer

The data-layer exposes a variety of single data-points for various features for different locations for current and past points in time. As meteorological research and analysis activities are usually in need of gridded or continuous data [SKP⁺20], the goal of this chapter is to design a model that is capable of turning these single data-points into a gridded data layer of air temperature where each cell has a specific air temperature value. Features other than air temperature could further improve the prediction quality, like how [AR20] suggests that in their study the Normalized Difference Vegetation Index (NDVI) and Modified Normalized Difference Water Index (MNDWI) have a strong impact on their estimation model. Therefore, we discuss how additional features can be included in the model.

This model should then be deployed inside the *service-layer* and act as a building block for further temperature related research and analysis, as air temperature is an important variable for research in agronomy, meteorology, hydrology, ecology and many other fields of application and could be used for UHI detection in the context of smart cities. The general idea and architecture behind the model should not only be applicable for air temperature, but also other types of output features.

4.1.1 Incorporating Geolocation Data

As discussed in chapter 2, there is a dependency between air temperature and other meteorological features and the location of the sensors. The closer a sensor is to another sensor, the more correlated the sensor readings should be. This relationship is however greatly influenced by the type of feature and the location of a sensor. As explained in [Oke06], the sensor placement in the urban environment is a complex task, as the urban environment is highly dynamic and sensors can be influenced by highly local phenomena, such as air temperature by heat vents or solar radiation by buildings and surface materials. For this model, we assume that the sensors are placed in a way that the sensor readings are representative for the area they are placed in, even though in practice this assumption might not hold up, especially for sensors placed by non-experts.

Each sensor reading from the data-layer has a location associated with it in the form of longitude, latitude and altitude (if available). This information can be used to calculate the distance between sensors and subsequently the correlation between sensor readings. However, how exactly the distance between two locations is calculated is not trivial. As the earth is a sphere, the distance between two points on the surface is not a straight line. Depending on the application, different distance metrics can be used. For a small area, such as the city of Hamburg, the euclidean distance could be sufficient, as the curvature of the earth for a small distance is negligible. However, for larger areas the geodesic (haversine) distance might be more appropriate. In this work, we are focussing on a single city including its surrounding area, therefore the euclidean distance should have a

sufficient accuracy while also simplifying the calculation. As the city of Hamburg does not have big differences in elevation, the altitude is not considered in the distance calculation.

- area $n \times m$ grid of data points, each grid cell with $n \times n$ size (depending on the resolution), 4D space with location as x and y coordinates (euclidean distance -> but only for smaller areas such as city of Hamburg and surroundings), time as z coordinate and feature values as w coordinate.

4.2 Supervised Learning

There are multiple learning approaches when it comes to machine learning, especially in the context of smart cities. The main directions are supervised learning, with classification and regression, unsupervised learning with clustering and dimensionality reduction, and reinforcement learning [UATMG20]. As interpolation of missing data is a form of regression, in this study we use a supervised regression approach to train our ML models. In supervised learning, an AI network is trained with input and target values to create a mapping function. In the context of smart cities, the input values come from the data management layer and consist of historical sensor data, such as humidity, solar radiance, or air temperature, combined with static data as shown in section 3.1.3. The target variable in this context is air temperature, but the approach can be applied to any other feature, such as humidity or solar radiance.

4.2.1 Dealing with Uncertainty

- The model has a lot of uncertainty - model uncertainty in input data? (depending on sensor type, sensor age, placement...)
 - dealing with bias - dealing with variance -> problem of over-fitting

4.2.2 Supervised Regression Models

Linear Regression Models

Most simple type of regression. Expect a linear dependence between dependent and independent variables. Downside, if the dependence is non-linear - linear regression

Polynomial Regression Models

able to fit non-linear dependencies

Ridge Regression Models

addresses overfitting to training data

LASSO Regression

enforce sparsity in the learned weights

Bayesian Regression

Neural Network Models

input layer -> hidden layers -> output

The advantages of Multi-layer Perceptron are: - Capability to learn non-linear models.
- Capability to learn models in real-time (on-line learning) using `partial_fit`.

The disadvantages of Multi-layer Perceptron (MLP) include: - MLP with hidden layers have a non-convex loss function where there exists more than one local minimum. Therefore different random weight initializations can lead to different validation accuracy. - MLP requires tuning a number of hyperparameters such as the number of hidden neurons, layers, and iterations. - MLP is sensitive to feature scaling.

- Loss functions/optimizers: Stochastic Gradient Descend, Adam, L-BFGS
- random forest regression ...

4.2.3 Evaluation Metrics

- Mean absolute error, mean absolute relative, mean squared error, r-squared, root mean squared error (RMSE)

4.3 ML Model Deployment

Deployed as a service. Input ingested -> continuous data map as output all 5 min or so (could also be smaller depending on use-case -> trade-off between cost and accuracy)

4.3.1 ML Model Retraing

Need to retrain model from time to time, e.g. if the accuracy drops below a certain threshold.

- dealing with coordinate systems: - projected coordinate system (e.g. UTM) instead of long lat alt values (important for interpolation)

4.4 Machine Learning in Geostatistics

Idea/Hypothesis: ML outperforms traditional geostatistical models (in certain scenarios) as it is able to capture more complex interdependencies between features and isn't necessarily bound to the (mathematical) assumptions of geostatistical models.

On important point to mention, is that different meteorological features have different interpolation techniques, as they have different (physical) properties. For example, temperature is a scalar value, while wind speed and direction are vector values. Relative humidity on the other hand is a relative value that is bound between 0 and 1. For precipitation it gets even more complex, as rainfall is highly connected to cloud coverage and movements. In the following, we will take a look at commonly used existing interpolation techniques for different meteorological features and discuss data preprocessing steps.

- Dealing with sparse data - Dealing with extreme weather events (e.g. heat waves, blizzards, etc.) - how can a ML model be trained if no such data exists for a given area?

-> transfer learning

4.4.1 Temperature Interpolation

- difference between air and surface temperature

- surface temperature -> solar radiation, surface roughness, emissivity, soil moisture, soil temperature, vegetation cover, snow cover, and surface slope

- air temperature -> surface temperature

4.4.2 Wind Speed and Direction Interpolation

prob not easily archivable with ML -> depends on high/low pressure areas

4.4.3 Relative Humidity Interpolation

Data preprocessing: scale to $[0, 1]$ does not seem to work well with kriging, maybe just nearest neighbor approach/linear, or the input values are just not accurate

4.4.4 Precipitation Interpolation

DeepLearning Lecture - sequence modeling design criteria - handle variable-length sequences - track long term dependencies - maintain information about order - share parameters across the sequence

5 Preparation of Datasets

goals: - dataset to train and validate different types of regression models - target variable: air temperature - input variables: - weather station measurements (air temperature, humidity, wind speed, wind direction, precipitation) - satellite data (surface temperature, surface roughness, soil temperature, land coverage indexes, sky view factor, ...)

Need to separate between reference grade data (weather station calibrated), and low-cost sensors without placement information

5.1 Overview Data Sources

Reference data: DWD station data (see https://dwd-geoportal.de/products/OBS_DEU_PT10M_T2M/)

-> 10 min 2m height air temperature https://opendata.dwd.de/climate_environment/CDC/observations_ge

need to write script to download all files and for each file do some conversion to csv

- overview of sources for good datasets for temperature and climate related research

goal: - collect multiple datasets (many features, fine-granular spatiotemporal) - enhance datasets with additional information (soil conditions, zoning plans, vegetation health)

6 Evaluation

TODO Steps: - deterministic approaches - "naive" approach with nearest neighbor -> show high error rate - probabilistic approaches - reference approach with geostatistical methods (ordinary kriging, empirical bayesian kriging, EBK with regression) -> still high error rate, especially with lower density of weather stations/bad support for irregularly spaced data - ordinary krigin: - temperature semivariogram first - add additional features (e.g. soil temperature, land coverage, sky view factor, ...) as semivariograms and use cokrigin to combine them - empirical bayesian kriging: - not implemented out of the box (pykrige)

- semivariogram: <https://pro.arcgis.com/en/pro-app/latest/help/analysis/geostatistical-analyst/understanding-a-semivariogram-the-range-sill-and-nugget.htm>

- deep learning approach with neural networks -> iteratively improve model by adding additional features, compare with reference approach

6.1 Geostatistical Interpolation Baseline

In order to evaluate the performance of the ML model, we need to first get a better understanding of the interpolation quality of existing interpolation techniques. Next to simpler deterministic interpolation methods, such as inverse weight distance (IWD) or k-nearest neighbours (KNN) that are easy and performant, but struggle to capture more complex interdependencies, there are also more complex methods available. The most common geostatistical method for interpolation is Krigin, which is based on a gaussian process and uses a covariance function to model the spatial correlation between data points. The covariance function is a measure of the similarity between two data points, which is used to calculate the weight of the data point in the interpolation process. There are different types of Krigin methods available, each suited for different use cases, including:

1. Simple Krigin: the simplest form of Krigin, that assumes that the mean of the measured values is known and constant
 2. Ordinary Krigin: same as Simple Krigin, but the mean is an unknown constant
 3. Universal Krigin: instead of assuming a constant mean, the mean is modeled as a deterministic function
 4. Indicator Krigin: same as Ordinary Krigin, but for categorical data
-

5. Propability Krigin: same as Indicator Krigin, but assumes two types of random errors that can are each auto-correlated and cross-correlated to each other
6. Disjunctive Krigin: same as Ordinary Krigin, but tries to improve the prediction quality by using an unknown constant and approximating an arbitrary function. It requires the bivariate normality assumption and is difficult to verify and solutions might be mathematically and computationally complicated
7. Cokrigin: offers methods for the previous Krigin methods, but uses information on several variable types. This could improve the prediction quality, but might increase the variance of the prediction, as more much more estimation is required

In the context of geostatistical analysis, there are different types of Krigin methods available that combine the aforementioned methods with other techniques, such as regression analysis. The following list is the geostatical methods offered by ArcGIS Pro as part of the Geostatistical Analyst toolbox ¹:

1. Empirical Bayesian Krigin (EBK)
2. Empircal Bayesian Krigin 3D (EBK3D)
3. EBK Regression Prediction (EBKRP): Empirical Bayesian Kriging with regression prediction
4. Global Polynominal Interpolation
5. Kernel Interpolation with Barriers
6. Moving Window Krigin
7. Radial Basis Function

In the scope of this work, we unfortunately cannot compare all of these methods with each other and therefore need to focus on a subset of methods. EBK and EBKRP are one of the most commonly used methods for temperature interpolation (cite). According to [NAEB23], EBKRP continously outperforms EBK in different weather station density scenarios, therefore we will use EBKRP as a baseline for our comparison.

In the following, the machine learning fundamentals for this work are explained and the different ML regression model types are introduced.

6.2 Data Set Procurement

TODO

¹<https://pro.arcgis.com/en/pro-app/latest/tool-reference/geostatistical-analyst/an-overview-of-the-geostatistical-analyst-toolbox.htm>

6.3 Model Comparison

TODO

7 Conclusion

7.1 Summary

TODO: Rewrite once Evaluation done

With the growing need to analyze microclimates of cities in order to protect them against new phenomena like UHIs, this paper proposes the use of citizen-owned sensor networks that offer a higher spatial and temporal resolution of data points in comparison to traditional approaches such as relying on LST data. This approach also comes with challenges such as observing areas without stationary sensors and identifying poor quality data-points from broken or incorrectly installed sensors. With the obtained data, we create a temperature interpolation service that predicts temperature data between data points using a regression model that can act as a building block for further temperature-based analysis by abstracting the underlying single data-points in the data-layer away. In order to improve the quality of temperature predictions for unobserved areas, we investigate how temporary sensor readings, f.e. by attaching sensors to buses, bikes or e-scooters, can be used to capture temporary local meteorological snapshots, and how these snapshots can be incorporated into the interpolation process. We also evaluate which features need to be captured to generate the most accurate predictions, if machine-learning is a suitable approach, and how it compares to more traditional geostatistical approaches.

7.2 Future Outlook

TODO

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