

Big Data and Advanced Analytics

Improving Data Quality For Big Data Using Advanced Analytics



Aytac Ozkan

Supervisor: Prof.Rachid Chelouah

Department of Engineering
Ecole internationale des sciences du traitement de l'information

This dissertation is submitted for the degree of
Master of Big Data

Acknowledgements

I owe *Mr. PICHOT Christian* a debt of gratitude for his kind assistance and his endorsement through the preparation of this scientific paper. In the presence of yours, I would like to thank him.

Abstract

Digital data play a crucial role in the information and communication technology (ICT) society: they are managed by business and governmental applications, by all kind of applications on the Web, and are fundamental in all relationships between governments, business, and citizens.

Data quality can be defined as "the measure of the agreement between the data views presented by an information system and that same data in the real world". Data quality is a multidimensional construct consisting of different data quality dimensions such as accuracy, completeness, consistency, and currency. [31]

Furthermore, quality of data is also a significant usage for operational process of business and organizations. Some disasters are due to the presence of data quality problems, among them the use of inaccurate, incomplete, out-of-data.

As a consequence, the overall quality of the information that flows between information systems may rapidly degrade over time if both process and their inputs are not themselves subject to quality control.

On the other hand, the same networked information system offers new opportunities for data quality management, including possibility of selecting sources with better quality data, and of comparing sources for the purpose of error localization and correction, thus facilitating the control and improvement of data quality in the system.

Due to the described above motivations, researchers and organizations more and more need to understand and solve data quality problems, and thus answering the following questions: What is in essence, data quality? Which techniques, methodologies, and data quality issues are at a consolidated stage?

In this paper, we first review relevant works and discuss machine learning techniques, tools and statistical models. Second, we offer a creative data profiling framework based deep learning and statistical model algorithms for improving data quality.

Keywords: Deep Learning, Statistical Quality Control, Machine Learning, Data Cleaning

Table of contents

List of figures	ix
List of tables	xi
1 Introduction to Data Quality	1
1.1 Introduction to the Concept of Data Quality	1
1.2 Data Quality: Wrangling and the Big Data Life Cycle	2
1.3 Big Data and Parallelism	7
1.4 Why Data Quality is Relevant	9
1.5 Why Data Quality is Matters	9
1.6 Data Quality and Types of Information Systems	12
1.7 Main Research Issues and Application Domains in Data Quality	13
2 Data Quality Dimensions	15
2.1 Accuracy	17
2.2 Completeness	18
2.2.1 Completeness of Web Data	19
2.3 Consistency	20
2.3.1 Integrity Constraints	20
2.4 Other Data Quality Dimensions	21
3 Data Quality (DQ) Evaluation	23
3.1 Metrics and Measurement	23
3.2 DQ Issues and Big Data Characteristics	24
3.3 Big Data Quality Evaluation Scheme	25
3.3.1 Big Data Sampling	26
3.3.2 Data Profiling	26
3.3.3 Data Quality Evaluation	27
3.3.4 BDQ Evaluation Algorithm	29

3.3.5	After Evaluation Analysis	29
4	Experimentations , Results and Analysis	31
4.1	Experimental Methodology	31
4.2	The NettoyageML [2] Schema	31
4.3	Analysis Methodology	33
4.4	Design of Benchmark	35
4.5	Error Types and Cleaning Methods	35
4.5.1	Missing Values	36
4.5.2	Outliers	36
4.5.3	Duplicates	37
4.5.4	Inconsistencies	37
4.5.5	Mislabeled	37
4.6	Datasets	37
4.7	ML Models	40
	References	41

List of figures

1.1	Quality Loss Function (QLF)	2
1.2	The big data life cycle	3
1.3	IBM data scientists break big data into four dimensions: volume, variety, velocity and veracity. This infographic explains and gives examples of each. [55]	11
1.4	Types of information systems	13
1.5	Main issues in data quality	14
2.1	A graphical representation of completability	20
3.1	Big Data Quality Evaluation Scheme	25
3.2	Big Data Quality Sampling Evaluation	27

List of tables

1.1	Big data life cycle processes definitions I.	4
1.2	Big data life cycle processes definitions II.	5
1.3	Big data life cycle processes definitions III.	6
2.1	Data Quality Dimensions I	16
2.2	Data Quality Dimensions II	17
3.1	Data Quality Issues vs DQD	23
3.2	DQD metric functions	25
3.3	Big Data Quality Evaluation Algorithm	28
4.1	NettoyageML Relational Schema	32
4.2	Cleaning Methods	35
4.3	Dataset and Error Types	38

Listings

4.1	Q1: Flag	34
4.2	Q2: Scenario	34
4.3	Q3: ML Model	34
4.4	Q4.1:Clean Method	34
4.5	Q4.2:Clean Method	34
4.6	Q5: Dataset	35

Chapter 1

Introduction to Data Quality

A Web search of terms "data quality" through the search engine Google, returns about three millions of pages and indicator that data quality issues are real and increasingly important (the term data quality will be shortened to the acronym DQ)

1.1 Introduction to the Concept of Data Quality

From a research perspective, data quality has been addressed in different areas, including statistics, management, and computer science. Statisticians were the first to investigate some of the problems related to data quality, by proposing a mathematical theory for considering duplicates in statistical data sets, in the late 1960's. They were followed by researchers in management, who at the beginning of the 1980's focused on how to control data manufacturing systems in order to detect and eliminate data quality problems. Only at the beginning of the 1990's computer scientists begin considering the problem of defining, measuring, and improving the quality of electronic data stored in databases, data warehouses, and legacy systems.

Dr. Genichi Taguchi [33], who was a world-renowned quality engineering expert from Japan, emphasized and established the relationship between poor quality and overall loss. Dr. Taguchi (1987) used a quality loss function (QLF) to measure the loss associated with quality characteristics or parameters. The QLF describes the losses that a system suffers from an adjustable characteristic. According to the QLF, the loss increases as the characteristic y (such as thickness or strength) gets further from the target value (m). In other words, there is a loss associated if the quality characteristic diverges from the target. Taguchi regards this loss as a loss to society, and somebody must pay for this loss. The results of such losses include system breakdowns, company failures, company bankruptcies, and so forth.

Figure 1.1 shows how the loss arising from varying (on either side) from the target by Δ_0 increases and is given by $L(y)$ when y is equal to m ,

THE IMPORTANCE OF DATA QUALITY

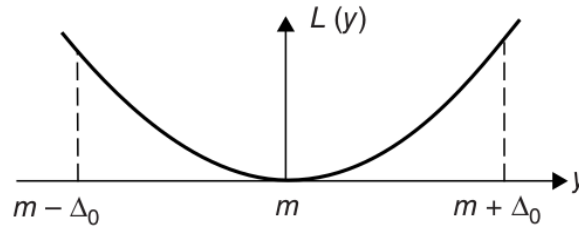


Fig. 1.1 Quality Loss Function (QLF)

the loss is zero, or at the minimum. The equation for the loss function can be expressed as follows:

$$L(y) = k(y - m)^2$$

where k is a factor that is expressed in dollars, based on direct costs, indirect costs, warranty costs, reputational costs, loss due to lost customers, and costs associated with rework and rejection. There are prescribed ways to determine the value of k . The loss function is usually not symmetrical-sometimes it is steep on one side or on both sides. Deming [17] says that the loss function need not be exact and that it is difficult to obtain the exact function. As most cost calculations are based on estimations or predictions, an approximate function is sufficient-that is, close approximation is good enough.

The concept of the loss function aptly applies in the DQ context, especially when we are measuring data quality associated with various data elements such as customer IDs, social security numbers, and account balances. Usually, the data elements are prioritized based on certain criteria, and the quality levels for data elements are measured in terms of percentages (of accuracy, completeness, etc.). The prioritized data elements are referred to as critical data elements (CDEs).

1.2 Data Quality: Wrangling and the Big Data Life Cycle

When talking about data quality in this document, it is done referring to the degree in which data fits to serve for its aimed purpose [60], for example, how well a medical record allows a nurse to identify the medicine that should be given to a patient, where “well” comprises,

among general qualities, how accurate, complete, up to date, valid and consistent [48] is the information so that the task can be successfully achieved. There are several processes required to assess and improve data quality, which include data extraction, data profiling, data cleansing and data integration [29], as the major ones; altogether in “the process by which the data required by an application is identified, extracted, cleaned and integrated, to yield a data set that is suitable for exploration and analysis” [53] is known as Data Wrangling. Figure 1.2 shows how each process is placed within the big data life cycle [Divyakant Agrawal] [29], where data profiling is the step in which this research contributes to.

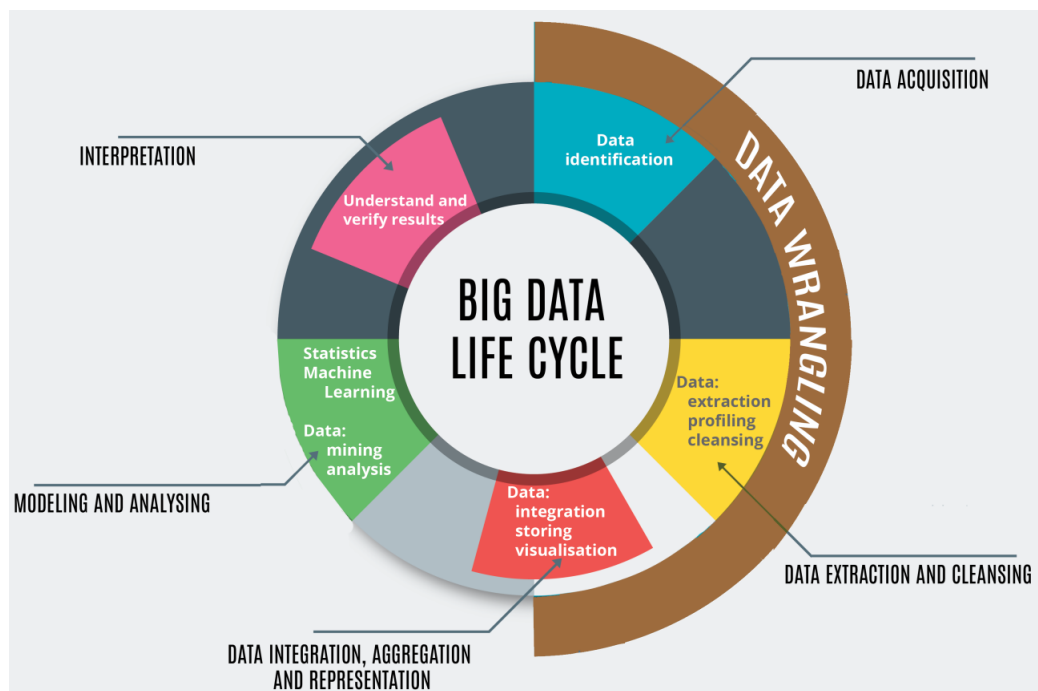


Fig. 1.2 The big data life cycle

Table 1.1 Big data life cycle processes definitions I.

Major Process	Process included	Description
DATA ACQUISITION	Data identification	Data has to be first generated from the real world, then converted to electrical signals so it can then be recorded in a machine. This process is called data acquisition [Divyakant Agrawal]. Identifying data means to provide useful metadata about its provenance, intended use, recording place and motivation, etc. [1] [47].
DATA EXTRACTION AND CLEANSING	Data extraction	This is the process in which data from source systems is selected and transformed into a suitable type of data according to its purpose, e.g. coordinates from a set of stored satellite images [Divyakant Agrawal].
	Data profiling	This refers to generating convenient metadata to support measurements against quality settings previously established, and to contribute towards “well known data”, clearing up the structure, content and/or relationships among the data. E.g. data types, data domains, timeliness, completeness, statistics, etc. [64] [58].
	Data cleansing	Also known as cleaning or scrubbing. Requires solving errors found in invalid, inconsistent, incomplete or duplicated data so the quality of the data can be improved. To find the errors this process relies on profiling information [64] [56].
DATA INTEGRATION, AGGREGATION AND REPRESENTATION	Data integration	Integrating data involves combining data from multiple sources into one, meaningful and valuable set of data [39] [5] [64].

Table 1.2 Big data life cycle processes definitions II.

Major Process	Process included	Description
MODELING ANALYZ- ING	Data storing	To preserve integrated data understandable, maintaining its quality, and adequacy to its purpose, it is also required to develop a suitable storage architecture design, taking into account the type of database suitability (e.g. relational, non-relational), the capacities of the database management system, etc., among all the alternatives in which data could be stored. [Divyakant Agrawal]
	Data visualization	Typically one step before analysis techniques. This process is about applying a graphical representation to the data, aimed at providing ease at future usage, transformation and understanding [72] [77] [9].
	Statistics & machine learning	This concerns about stating facts in this context, from a given dataset, by interpreting data and providing a numerical picture of it, as well as using computer systems that emulate the human learning process, saving new information and outcomes, closely related to artificial intelligence (AI). Parallel statistics algorithms have been proposed to approach big data [61] [10].
	Data mining	This process involves techniques to find latent valuable information, revealing patterns, cause-effect relations, implicit facts, etc., to hold up data analysis [46] [9] .

Table 1.3 Big data life cycle processes definitions III.

Major Process	Process included	Description
INTERPRETATION	Data analysis	A task done by the perceptual and cognitive system of an analyst, although nowadays machine learning and AI techniques can also be used. This is the ultimate phase in the process of obtaining the value from the data, by finding the significance on the insights provided by, for example, correlations or graphical representations. [77]
	Understand and verify results	This is the phase in which the information obtained is used and transformed into a decision that could lead to a tangible value (e.g. economic gaining, marketing advantages, scientific progress), differing each time according to the context on which it has been obtained and its purpose. This phase also comprises retracing the results obtained, verifying them and testing them in several use cases [Divyakant Agrawal].

In order to support the value characteristic of the data it is important to satisfy high quality conditions of the large data sets [7], where quality could be measured by its dimensions, having completeness, uniqueness, timeliness, validity, accuracy and consistency considered as the six core ones [48], among other identified dimensions, such as reputation, security, transactability, accessibility and interpretability [40] [45]. The processes, technologies and techniques aimed at obtaining the value from big data, are known as big data analytics [50], applied in several ambits, such as health care, social sciences, environmental and natural resources area, business and economic domains, and technology fields. Recently, big data quality has been approached from a big data analytics point of view [37] [6] [67]. Some studies might conclude that data quality is not a bigger challenge than the lack of knowledge from analysts to implement

the correct methods to manage big data value [67], however, data management is an inherent phase of the big data analytics, and it involves the capacity to gather, integrate and

analyze data as well, where data quality should not be considered as a separate phase. The Data Warehousing Institute estimated low quality data cost U.S. businesses more than 600 billion USD per annum [22]. The U.S. Postal Service estimated that wrong data cost 1.5 billion USD in 2013 from mailpieces that could not be delivered to the given addresses, facing data quality problems from around 158 billion mailpieces in that single year. Data quality management strategies were recommended to increase address information accuracy, timeliness and completeness [49]. In big data, “low” error rates translate into millions of faults annually, where the risk is to lose 10-25% of the total revenues from it [22]. Big data quality requires multidisciplinary participation to progress [6] and propel the development of simple and low-cost data quality techniques, reduce the cost of poor quality data, the data error rate, and the need of data cleansing processes which involve investing not only budget, but time and effort to manage. IS research is demanded to collaborate with data wrangling insights and advances, working together with statistical experts to leverage the techniques involved, where domain specific authorities are needed to set the data analytics management, which should support the right value retrieval out of relevant problems from each area [6].

1.3 Big Data and Parallelism

The term big data itself comprises a deeper meaning, being not only a term to be defined but the name of a phenomenon and an emerging discipline [19]. The earliest mentions of big data were made, to the best of my knowledge, in 1979 by Lawrence Stone, when describing the work of cliometricians dealing with “vast quantities of data using electronic computers to process it and applying mathematical procedures” [68], and by Charles Tilly, who in 1980 describing the work done by the former, used the term “big-data people” referring to the cliometricians Stone mentioned before [71]. Then, in 1997 Michael Cox and David Ellsworth, described the term as large data sets that surpasses the available size in main memory, local disk and even remote disk [13]. Following that year, Sholom M. Weiss and Nitin Indurkha in their book “Predictive data mining: a practical guide”, contextualize not only the term but the phenomenon, mentioning that “millions or even hundreds of millions of individual records can lead to much stronger conclusions, making use of powerful methods to examine data more comprehensively” and also acknowledges that analyzing big data, in practice, has many difficulties [78]. Two years later, Francis X. Diebold defined big data as “the explosion in the quantity of available and potentially relevant data, largely the result of recent and unprecedented advancements in data recording and storage technology”. By this time, it was clear that big data was not only about size, but about the insights that a large set of data could eventually bring.

The Oxford English Dictionary, which added the term to its data base in 2013 [18], defines big data as “data of a very large size, typically to the extent that its manipulation and management present significant logistical challenges”.

Nevertheless, those “logistical challenges” for one organization could be necessary to be done when facing a smaller size of data compared to another [42], in this sense, it seemed that relying only in the size depends on the available technology within each organization and its capability to handle a given amount of data, so, to scope the definition, the size of big data could be thought as the size in which using traditional techniques to process it, is not longer an option.

The above led to define big data not only regarding size, but taking into account another identified characteristics, known as the “V’s of big data” [43] : Volume, Velocity, Variety, Veracity and Value; where Volume refers to the data size, Velocity evokes the high speed of change and fast generation of data, Variety relates to the different type of data (structured, unstructured and semistructured), Veracity is the degree of trustworthiness of the data (quality and accuracy) and Value indicates the worth or benefit of gathering, storing, processing and analyzing the data.

Because of the nature of big data, traditional approaches to managing data are not suitable, for example, since the main aim was to handle relational data, and as previously mentioned, big data is not always relational, so, traditional techniques are not expected to work correctly [25].

When processing data, one of the main challenges faced with big data is the large volume of it; this require scaling, and there have been two types of scaling for big data processing: scaling-up and scaling-out, where the former is about implementing powerful machines, with great memory and storage capacity, as well as quick but expensive processors, and the latter refers to the usage of several commodity machines connected as clusters, having a parallel environment, suitable to handle large volumes of data, and an advantageous price-performance relation, compared to the scaling-up approach [88] [25]. For big data frameworks, it is known that with the proper optimizations, scaling-up performs better than scaling-out [57], however, it is still unknown exactly when is better to opt for one approach or the other, this is, the results presented were not dependable on the framework solely, but on the processed data characteristics. Nevertheless, it might be strongly preferred to utilize several smaller machines than high performance computer systems (HPC), because of the higher cost scaling-up represents, and considering the support that new paradigms provide by avoiding the necessity to communicate data, but having the processing ap-publications running where the data is, which proposes a significant performance advantage [70], trading off performance in certain degree for a better cost-benefit ratio.

Distributed and parallel computation are two major ways of processing big data, where a distributed system communicates and coordinates their processes without a global clock, through messages, and in a component's independence working as single system [69], and parallel computing is a term generally used to identify those processes carried out simultaneously by numerous processors, intended to reduce the runtime [4]. Besides solely parallel, distributed or a mixture of both, new techniques are being developed and selected towards aiding the whole big data life cycle. Recent studies target “granular computing, cloud computing, biological computing systems and quantum computing” [10] as the emergent areas, theories and techniques for big data.

1.4 Why Data Quality is Relevant

The consequences of poor quality of data are often experienced in everyday life, but often, without making the necessary connections to their causes.

For example, the late or mistaken delivery of a letter is often blamed on a postal service, although a closer look often reveals data-related causes, typically an error in the address, originating in the address database.

Data quality has serious consequences of far-reaching significance, for the efficiency and effectiveness of organizations and business.

1.5 Why Data Quality is Matters

Poor data quality is enemy number one to the widespread, profitable use of machine learning. While the caustic observation, “garbage-in, garbage-out” has plagued analytics and decision-making for generations, it carries a special warning for machine learning. The quality demands of machine learning are steep, and bad data can rear its ugly head twice - first in the historical data used to train the predictive model and second in the new data used by that model to make future decisions. [59]

Data quality is no less troublesome in implementation. Consider an organization seeking productivity gains with its machine learning program. While the data science team that developed the predictive model may have done a solid job cleaning the training data, it can still be compromised by bad data going forward. Again, it takes people — lots of them — to find and correct the errors. This in turns subverts the hoped-for productivity gains. Further, as machine learning technologies penetrate organizations, the output of one predictive model will feed the next, and the next, and so on, even crossing company boundaries. The risk

is that a minor error at one step will cascade, causing more errors and growing ever larger across an entire process.

Bad data costs the U.S. \$3 trillion per year, IBM's estimate of the yearly cost of poor quality data, in the US alone, in 2016. While most people who deal in data every day know that bad data is costly, this figure stuns. [55]

Importantly, the benefits of improving data quality go far beyond reduced costs. It is hard to imagine any sort of future in data when so much is so bad. Thus, improving data quality is a gift that keeps giving — it enables you to take out costs permanently and to more easily pursue other data strategies. For all but a few, there is no better opportunity in data.



Fig. 1.3 IBM data scientists break big data into four dimensions: volume, variety, velocity and veracity. This infographic explains and gives examples of each. [55]

1.6 Data Quality and Types of Information Systems

Data are collected, stored, elaborated, retrieved, and exchanged in information systems used in organizations to provide services to business processes. Different criteria can be adopted for classifying the different types of information systems, and their corresponding architectures; they are usually related to the overall organizational model adopted by the organization or the set of the organizations that make use of the information system.

The three classifications are represented together in the classification space of Figure 1.2. Among all possible combinations, five main types of information systems are highlighted in the figure: Monolithic, Distributed, Data Warehouses, Cooperative, and Peer-to-Peer.

- In a *monolithic information system* presentation, application logic, and data management are merged into a single computational node. Many monolithic information systems are still in use. While being extremely rigid, they provide advantages to organizations, such as reduced costs due to homogeneity of solutions and centralization of management. In monolithic systems data flows have a common format, and data quality control is facilitated by the homogeneity and centralization of procedures and management rules.
- A *data warehouse* (DW) is a centralized set of data collected from different sources, designed to support management decision making. The most critical problem in DW design concerns the cleaning and integration of the different data sources that are loaded into the DW, in that much of the implementation budget is spent on data cleaning activities.
- A *distributed information system* relaxes the rigid centralization of monolithic systems, in that it allows the distribution of resources and applications across network of geographically distributed systems. The network can be organized in terms of several tiers, each made of one or more computational nodes. Presentation, application logic, and data management are distributed across tiers. Usually, the different tiers and nodes have a limited degree of autonomy, data design is usually performed centrally, but to a certain extent some degree of heterogeneity can occur, due to the impossibility of establishing unified procedures. Problems of data management are more complex than in monolithic systems, due to the reduced level of centralization.

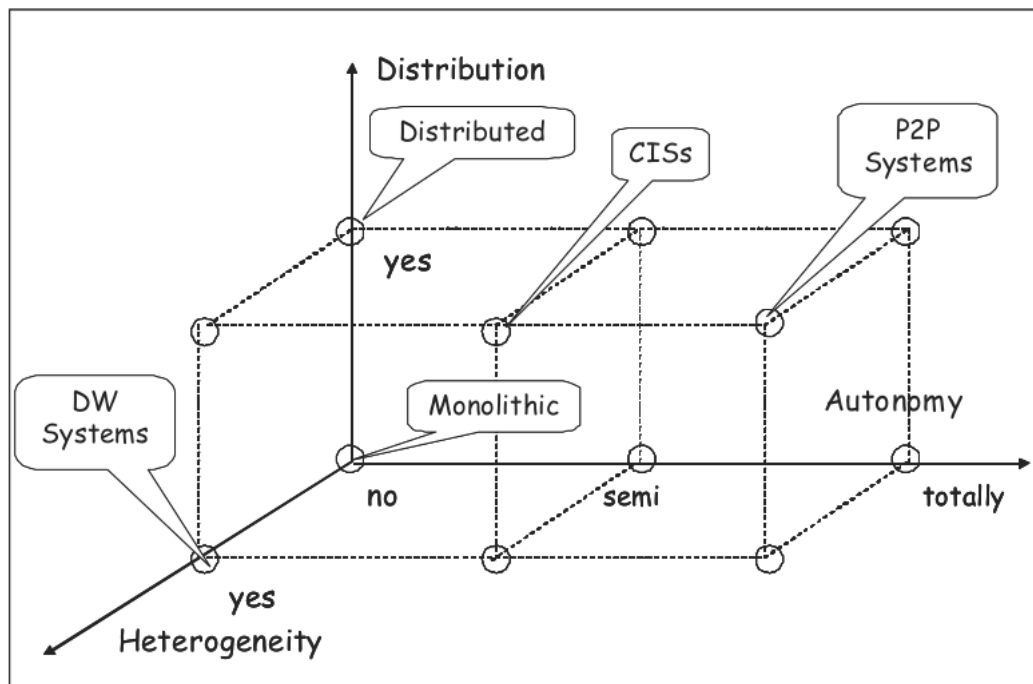


Fig. 1.4 Types of information systems

- A *cooperative information system* (CIS) can be defined as a large-scale information system that interconnects various systems of different and autonomous organizations, while sharing common objectives.
- In a *peer to peer information system* (usually abbreviated P2P), the traditional distinction between clients and servers typical of distributed systems is disappearing. A P2P system can be characterized by a number of properties: peers are highly autonomous and highly heterogeneous, they have no obligation for the quality of their services and data, no central coordination and no central database exist, no peer has a global view of the system, global behavior emerges from local interactions.

1.7 Main Research Issues and Application Domains in Data Quality

Due to the relevance of data quality, its nature, and the variety of data types and information systems, achieving data quality is a complex, multidisciplinary area of investigation. It involves several research topics and real-life application areas

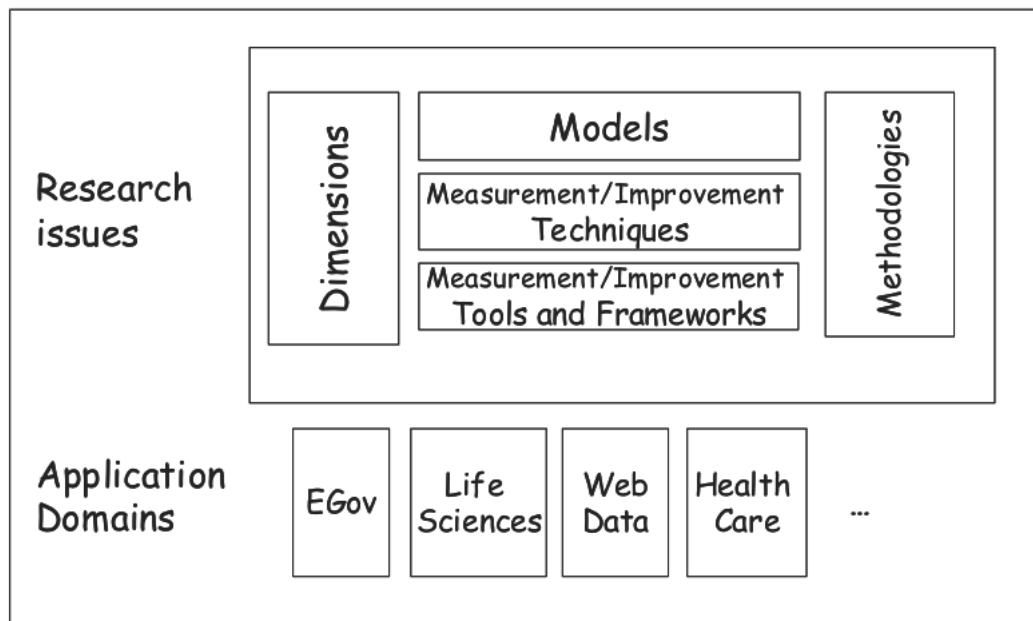


Fig. 1.5 Main issues in data quality

Chapter 2

Data Quality Dimensions

More specifically, quality dimensions can refer either to the extension of data, i.e., to data values, or to their intension, i.e., to their schema. Both data dimensions are usually defined in qualitative way, referring to general properties of data and schemas, and related definitions do not provide any facility for assigning values to dimensions themselves.

Specifically, definitions do not provide quantitative measures, and one or more metrics are to be associated with dimensions as separate, distinct properties. For each metric, one or more measurement metadata are to be provided regarding (i) where the measurement is taken, (ii) what data are included, (iii) the measurement device, and (iv) the scale on which results are reported.

According to the literature, at times we will distinguish between dimensions and metrics, while other times we will directly metrics.

Table 2.1 Data Quality Dimensions I

Dimension Name	Description
Data Governance	Do organization-wide data standards exist and are they enforced? Do clearly defined roles and responsibilities exist for data quality related activities? Does data governance strive to acquire and maintain high-quality data through proactive management?
Data Specifications	Are data standards documented in the form of a data dictionary, data models, meta data, and integrity constraints?
Data Integrity	How is data integrity maintained? How are data integrity violations detected and resolved ?
Data Consistency	If data redundancy exists, how is data consistency achieved? What methods are used to bring consistency to data that has become inconsistent? If data is geographically replicated, how is the consistency and latency managed?
Data Currency	Is the data current? Do procedures exists to keep the data current and purge stale data?
Data Duplication	Are there effective procedures in place to detect and remove duplicate data?
Data Completeness	Is the data about entities complete? How is missing data managed?
Data Provenance	Is a historical record of data and its origination maintained? If the data is acquired through multiple sources and has undergone cleaning and transformations, does the organization maintain a history of all changes to the data?
Data Heterogeneity	If multi-modality data about an entity is available, is that data captured and used?
Streaming Data	How is streaming data sampled, filtered, stored, and managed for both real-time and batch processing?
Outliers	How are outliers detected and addressed? Are there versions of datasets that are outlier-free? Does each version correspond to a different method for outlier detection and treatment?
Dimensionality	Reduction Do the datasets feature dimensionality reduced versions? How many versions are available?
Feature Selection	Do datasets have versions that exclude features that are either redundant, highly correlated, or irrelevant? How many versions are available?

Table 2.2 Data Quality Dimensions II

Dimension Name	Description
Feature Extraction	Do the datasets provide a set of derived features that are informative and non- redundant, in addition to the original set of variables/features? How many such derived feature sets are available?
Business Rules	Does a process exist to identify, refine, consolidate, and maintain business rules that pertain to data quality? Do rules exist to govern data cleaning and transformations, and integrating related data of an entity from multiple sources? What business rules govern substitutions for missing data, deleting duplicate data, and archiving historical data? Are there rules for internal data audit and regulatory compliance?
Data Accuracy	Data can be syntactically accurate and yet semantically inaccurate. For example, a customer's mailing address may meet all the syntactic patterns specified by the postal service, yet it can be inaccurate. How does the organization establish the accuracy of data?
Gender Bias	Is the data free from factors that lead to gender bias in machine learning algorithms?
Confidentiality and Privacy	Are procedures and controls implemented for data encryption, data de- identification and re-identification, and differential privacy?
Availability and Access Controls	How is high data availability achieved? What security controls are implemented to protect data from unauthorized access? How are user entitlements to data access and modifications defined and implemented?

2.1 Accuracy

Accuracy is defined as the closeness between a value v and a value v' , considered as the correct representation of the real-life phenomenon that v aims to represent. As an example if the name of a person is Aytac, the value $v' = \text{Ayta?}$ is correct, while the value $v = \text{Ayt}$ is incorrect. Two kinds of accuracy can be identified, namely a syntactic accuracy and a semantic accuracy.

Let us consider a relation schema \mathbf{R} consisting of \mathbf{K} attributes and a relational table \mathbf{r} consisting of N tuples.

Let $q_{ij}(i = 1..N, j = 1..K)$ be a boolean variable defined to correspond to the cell values y_{ij} , is syntactically accurate, while otherwise it is equal to 1.

In order to identify whether or not accuracy errors affect a matching of relational table \mathbf{r} with a reference table \mathbf{r}' containing correct values, we introduce a further boolean variable s_i equal to 0 if the tuple t_i matches a tuple in \mathbf{r}' , and otherwise equal to 1. We can introduce three metrics to distinguish the relative importance of value accuracy in context of the tuple. The first two metrics have the purpose of giving a different importance to errors on attributes that have a higher identification power, in line with the above discussion.

The first metric called *weak accuracy error*, and is defined:

$$\sum_{i=1}^N \frac{\beta(q_i > 0) \wedge (s_i = 0)}{N}$$

where $\beta(\cdot)$ is a boolean variable equal to 1 if the condition in parentheses is *true*, 0 otherwise, and $q_i = \sum_{j=1}^K q_{ij}$. Such metric considers the case in which for a tuple t_i accuracy errors occur ($q_i > 0$) but do not affect identification ($s_i = 0$).

The second metric is called *strong accuracy error*, and is defined assigning

$$\sum_{i=1}^N \frac{\beta(q_i > 0) \wedge (s_i = 1)}{N}$$

where $\beta(\cdot)$ and q_i have the same meaning as above. Such a metric considers the case which accuracy errors occur ($q_i > 0$) for a tuple t_i and actually do affect identification ($s_i = 1$).

The third metric gives the percentage of accurate tuples matched with the reference table. It is expressed by the degree of syntactic accuracy of the relational instance \mathbf{r}

$$\sum_{i=1}^N \frac{\beta(q_i = 0) \wedge (s_i = 0)}{N}$$

by actually considering the fraction of accurate ($q_i = 0$) matched ($s_i = 0$) tuples.

2.2 Completeness

Completeness can be generically defined as the extent to which data are of sufficient breadth, depth, and scope for the task at hand [76] three types of completeness are identified. Schema completeness is defined as the degree to which concepts and their properties are not missing from the schema. Column completeness is defined as a measure of the missing values for a specific property or column in a table. Population completeness evaluates missing values with respect to a reference population. If focusing on a specific data model, a more precise

characterization of completeness can be given. In the following we refer to the relational model.

2.2.1 Completeness of Web Data

Data that are published in Web information systems can be characterized by evolution in time. While in the traditional paper-based media, information is published once and for all, Web information systems are characterized by information that is continuously published.

We consider a function $C(t)$, defined as the value of completeness at the instant t , with $t \in [t_{pub}, t_{max}]$, where t_{pub} is the initial instant of publication of data and t_{max} corresponds to the maximum time within which the series of the different scheduled updates will be completed. Starting from the function $C(t)$, we can define the completability of the published data as

$$\int_{t_{curr}}^{t_{max}} C(t),$$

where t_{curr} is the time at which completability is evaluated and $t_{curr} < t_{max}$.

Completability, as shown in Figure 2.1, can be graphically depicted as an area C_b of a function that represents how completeness evolves between an instant t_{curr} of observation and t_{max} . Observe that the value corresponding to t_{curr} is indicated as c_{curr} ; c_{max} is the value for completeness estimated for t_{max} . The value c_{max} is a real reachable limit that can be specified for the completeness of the series of elements; if this real limit does not exist, c_{max} is equal to 1. In Figure 2.5, a reference area A is also shown, defined as

$$(t_{max} - t_{curr}) * \frac{c_{max} - c_{pub}}{2},$$

that, by comparison with C_b , allows us to define ranges [High, Medium, Low] for completability.



Fig. 2.1 A graphical representation of completeness

With respect to the example above, considering the list of courses published on a university Web site, the completeness dimension gives information about the current degree of completeness; the completeness information gives the information about how fast this degree will grow in time, i.e., how fast the list of courses will be completed. The interested reader can find further details in [54].

2.3 Consistency

The consistency dimension captures the violation of semantic rules defined over (a set of) data items, where items can be tuples of relational tables or records in a file. With reference to relational theory, integrity constraints are an instantiation of such semantic rules. In statistics, data edits are another example of semantic rules that allow for the checking of consistency.

2.3.1 Integrity Constraints

Integrity constraints are properties that must be satisfied by all instances of a database schema. Although integrity constraints are typically defined on schemas, they can at the same time be checked on a specific instance of the schema that presently represents the extension of the database. Therefore, we may define integrity constraints for schemas, describing a schema quality dimension, and for instances, representing a data dimension.

Most of the considered integrity constraints are dependencies. The following main types of dependencies can be considered:

- *Key Dependency.* This is the simplest type of dependency. Given a relation instance r , defined over a set of attributes, we say that for a subset K of the attributes a key dependency holds in r , if no two rows of r have the same K -values. For instance, an attribute like SocialSecurityNumber can serve as a key in any relation instance of a relation schema Person.
- *Inclusion Dependency.* Inclusion dependency is a very common type of constraint, and is also known as referential constraint. An inclusion dependency over a relational instance r states that some columns of r are contained in other columns of r or in the instances of another relational instance s . A foreign key constraint is an example of inclusion dependency, stating that the referring columns in one relation must be contained in the primary key columns of the referenced relation.
- *Functional Dependency.* Given a relational instance r , let X and Y be two nonempty sets of attributes in r . r satisfies the functional dependency $X \rightarrow Y$ if the following holds for every pair of tuples t_1 and t_2 in r :

$$\boxed{\text{If } t_1.X = t_2.X, \text{ then } t_1.Y = t_2.Y,}$$

where the notation $t_1.X$ means the projection of the tuple t_1 onto the attributes in X .

2.4 Other Data Quality Dimensions

There are general proposals for sets of dimensions that aim to fully specify the data quality concept in a general setting. Some other proposals are related to specific domains that need ad hoc dimensions in order to capture the peculiarities of the domain. For instance, specific data quality dimensions are proposed in the following domains:

1. The archival domain (see [79] and [38]) which makes use of dimensions such as condition (of a document) that refers to the physical suitability of the document for scanning.
2. The statistical domain; every National bureau of census and international organizations such as the European Union or the International Monetary Fund define several dimensions for statistical and scientific data, such as integrity, on the notion that statistical systems should be based on adherence to the principle of objectivity in the collection, compilation, and dissemination of statistics.

3. The geographical and geospatial domain (see [52] [28]), where the following dimensions are proposed: (i) positional accuracy, defined as a quality parameter indicating the accuracy of geographical positions, and (ii) attribute/thematic accuracy, defined as the positional and/or value accuracy of properties such as sociodemographic attributes in thematic maps.

Chapter 3

Data Quality (DQ) Evaluation

3.1 Metrics and Measurement

Any data can have its quality measured. Using a data driven strategy, the measurements acts on the data itself to quantify the DQD (Data Quality Dimension). As mentioned before, our work is based on structured data represented in [62] a set of attributes, columns, and rows with their values. Any data quality metric should specify whether the values of data respect or not the quality attributes. The data quality measurement metrics tend to evaluate a binary results correct or incorrect or a value between 0 and 100, and use universal formulas to compute these attributes. This will apply to many quality dimensions such as accuracy, completeness, and consistency.

	Data Quality Issues	Data Quality Dimensions Related		
		Accuracy	Completeness	Consistency
Instance Level	<i>Missing Data</i>	X	X	
	<i>Incorrect data, Data entry errors,</i>	X		
	<i>Irrelevant data</i>			X
	<i>Outdated data</i>	X		
	<i>Misfiled and Contradictory values</i>	X	X	X
Schema Level	<i>Uniqueness constrains, Functional dependency violation</i>	X		
	<i>Wrong data type, poor schema design</i>			X
	<i>Lack of integrity constraints</i>	X	X	X

Table 3.1 Data Quality Issues vs DQD

The DQDs (Data Quality Dimensions) must be relevant to the DQ problems as identified In Table 3.1 Therefore DQ Metrics are designed for each DQD to measure if the attributes respect the previously defined DQD. These measures are done for each attribute given its type, data ranges values, and if it is collected from data profiling.

For example a metric that calculates the accuracy of a data attribute is defined as follows:

- The data type of an attribute and its values.
- For numerical attributes a range or sets of acceptable values (Textual also) are defined. Any other values are incorrect.
- The accuracy of an attribute is calculated based on the number of correct values divided by number of observations or rows.
- For another data types/formats like images, videos, audio files, another type of metrics must be defined to evaluate accuracy or any other quality dimensions. The authors of [14] describe usefulness as an aspect of data quality for images. For this kind of data, feature extraction functions are defined on the data and extracted for each data item. These features have constraints that characterize the goodness or badness of data values. Some of quality metrics functions are designed based on the extracted features such as, usefulness, accuracy, completeness and any other data quality dimensions judged by domain experts to be candidate for such data type.

3.2 DQ Issues and Big Data Characteristics

Data characteristics commonly named V's are initially, Volume, Velocity, Variety, and Veracity. Since the Big Data inception; we reached now 7 V's and probably we will keep going [41]. The veracity tends more to express and describe trust and certainty of data that can be expressed mostly as quality of the data. The DQD accuracy is often related to precision, reliability and veracity [74].

A mapping tentative between these characteristics, data and data quality is compiled in [32] [14] [8]. The authors attempted to link the V's to the quality dimensions.

DQ Dimensions	Metric functions
Accuracy	$Acc = (N_{cv} / N)$
Completeness	$Comp = (N_{mv} / N)$
Consistency	$Cons = (N_{vrc} / N)$
N_{cv}	Number of correct values
N_{mv}	Number of missing values
N_{vrc}	Number of values that respects the constraints
N	Total number of values (rows) of the sample Dataset

Table 3.2 DQD metric functions

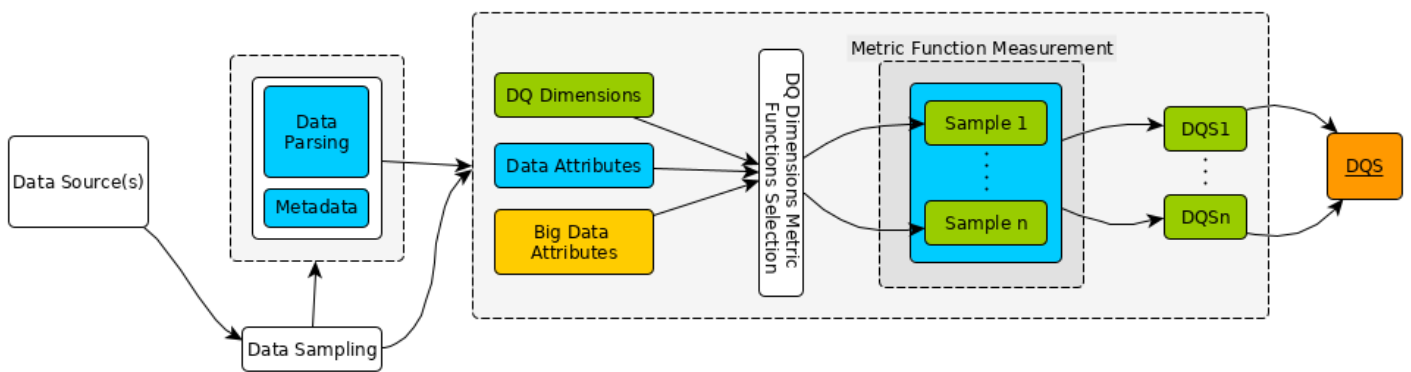


Fig. 3.1 Big Data Quality Evaluation Scheme

3.3 Big Data Quality Evaluation Scheme

The purpose of Big Data Quality Evaluation (BDQ) Scheme is to address the data quality before starting data analytics. This is done by estimating the quality of data attributes or features by applying a DQD metric to measure the quality characterized by its accuracy, completeness or/and consistency. The expected result is data quality assessment suggestions indicating the quality constraints that will increase or decrease the data quality.

The BDQ Evaluation scheme is illustrated in Figure 3.1 where the data goes through many module to estimate its quality. The key modules of our scheme consist of: (a) data sampling; and data profiling, (b) DQD vs attributes selection, (c) data quality Metric selection,

(d) samples data quality evaluation. In the following sections, we describe each module, its input(s), output(s), and the main functions.

3.3.1 Big Data Sampling

A sample is representative of a whole population. Based on a sample, we make several decision about a population. A sample is also called a subgroup. The number of observations or units in a sample is called sample size. The number of times a sample is collected is usually referred to as the sampling frequency. In designing a control chart, we must specify both of these parameters. [33]

There are several sampling strategies that can be applied on Big Data as expressed in [73] [12]. They evaluated the effect of sampling methods on Big Data and believed that sampling large datasets reduces run time and computational footprint of link prediction algorithms though maintaining sufficient prediction performance. In statistic, Bootstrap sampling technique evaluates the sampling distribution of an estimator by sampling with replacement from the original sample. In the context of Big Data, Bootstrap sampling has been addressed in many works [23] [65]. In our data evaluation scheme will used the Bag of Little Bootstrap (BLB) [3], which combines the results of bootstrapping multiple small subsets of a Big data dataset. The BLB algorithm use an original Big dataset used generate small samples without replacements. For each generated sample another set of samples are created by resampling with replacement.

3.3.2 Data Profiling

Data profiling is an exploratory approach to data quality analysis. Statistical approaches are used to reveal data usage patterns as well as patterns in the data [51] [44]. Several tools exist for data quality assessment using data profiling and exploratory data analysis. Such tools include Tableau and Talend Open Studio.

Data profiling module performs screening of data quality based on statistics and information summary. Since profiling is meant to discover data characteristics from data sources. It is considered as data assessment process that provides a first summary of the data quality. Such information include: data format description, different attributes, their types and values. data constraints (if any), data range, max and min. More precisely information about the data are presented in two types; technical and functional. This information can be extracted from the data itself without any additional representation using its metadata or any descriptive header file, or by parsing the data using any analysis tools. This task may become very costly in Big Data. To avoid costs generated due the data size we will use the same sampling

process BLB to reduce the data into a representative population sample, in addition to the combination of profiling results.

3.3.3 Data Quality Evaluation

The data profiling provides information about dataset,

- Data attributes (eg. type format)
- Data summary (eg. max, min)
- Big data attributes; size number of sources speed of data generation (eg. data streams)
- What DQD evaluate.

The previous information's are used to select the appropriate quality metrics functions F to evaluate a data quality dimensions d_k for an attribute a_i with a weight w_j

In the Fig 3.2 we describe how data quality evaluated using bootstrap sampling for Big data. The process follows these steps:

1. Sampling from the data set S n bootstrap sample size of ss size without replacement DS_j .
2. Each sample generated from step 1 is sampled into n' samples of size SS with replacements DS_{ij}
3. For the Each sample DS_{ij} generated in step 2, evaluate the data quality score Q_{ij}

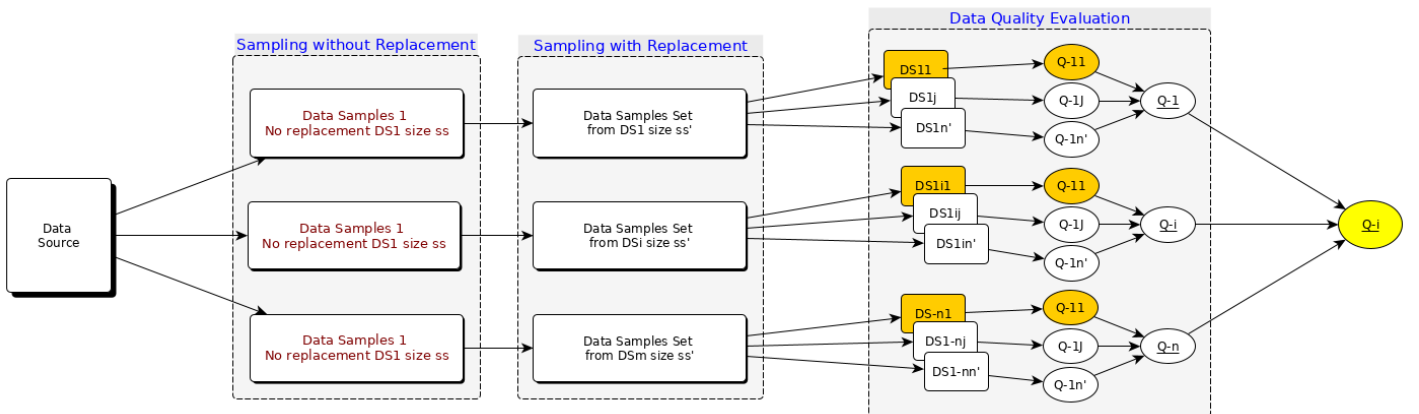


Fig. 3.2 Big Data Quality Sampling Evaluation

Table 3.3 Big Data Quality Evaluation Algorithm

Algorithm: Big Data Quality Evaluation

```

1  let  $ds$  a Original Data Set with size SS and Observation (N-SS);
2  let  $ss$  (b(SS)) the samples with  $ss < SS$  ;
3  let  $n$  samples  $s_i$  of size  $ss$  and  $M$  Observation (M-ss);
4  let  $D$  a set of DQD  $D = \{d_0, \dots, d_k, \dots, d_q\}$ ;
5  let  $F$  a metric function F (completeness, accuracy,...) ;
6  let  $cc \leftarrow 0$  counter of correct valid attribute value (when F is true  $cc = cc + 1$ );
7  let  $S = \{DS_0, \dots, DS_i, \dots, DS_n\}$  without replacement ;

8  for  $i \leftarrow 0$  to  $n$  do
9      Generate sample  $s_i$  of size SS from  $ds$ ;
10     for  $j \leftarrow 0$  to  $n'$  do
11         Generate a sample  $i_j$  of size SS from sample  $s_i$ ;
12         for  $k \leftarrow 0$  to  $j$  do
13             MetricFunctionTuple( $d_k, F$ )
14             for  $a \leftarrow 0$  to  $j$  do
15                 for  $a_{ij}(x)$   $ss$  values do
16                     if  $F(a_{ij}(x), value) == 1$  then
17                         measure metric ;
18                          $c \leftarrow cc + 1$  ;
19                         Calculate the scores vector  $DQD(F, d_k, a_{ij}, DS_i) = \frac{cc}{N}$ 
20                          $cc \leftarrow 0$  counter of correct valid attribute value ( $d_k, F$ )
21                     end
22                 end
23                  $DQD d_k$  computed for all attributes for a sample  $ds_{ij}$ 
24             end
25              $DQS_{ijk}$  is the  $D_K$  scores for an attribute  $a_{ij}$  for sample  $DS_{ij}$   $Q_{ijk}$ 
26             sum of all  $d_k$  scores for attributes  $a_{ij}$  for  $DS_{ij}$ 
27         end
28     end
29      $Q_{ik} + = 1/n'(Q_{ijk})$ 
30 end
31  $Q_k$  is the mean of all  $Q_{ik}$  for a specif  $d_k$   $Q_k + = 1/n(Q_{ik})$ 

```

3.3.4 BDQ Evaluation Algorithm

Let F represents a set of data quality metrics, $F=\{f_0...f_1,...f_m\}$ where f_1 a quality metric function that will measure and evaluate a DQD d_k for each value of an attribute a_i in the sample s_i and returns 1 if correct, 0 if not. Each f_1 function will compute if the value of the attribute reflects the d_k constraints. For example, the metric accuracy of an attribute is defined as a range of values between 0 and 100, otherwise it is correct. Similarly, it can be defined to satisfy a certain number of constraints related to the type of data such as a zip code, email, social security number, or an address. If we are evaluating the same DQD d_k for a set of attributes, if the weights are all equal, a simple mean is computed. The metric f_i will be evaluated to measure if all the attributes individually have their f_i correct. This is done for each instance (cell or row) of the sample s_i .

In Table 3.3, we describe the detail of BDQ Evaluation Algorithm. The Q_k represents the mean quality score for a DQD d_k for measurable attributes. For data set let note. A as a set of attributes or features. The Q_k values respectively for each attribute are represented by a set of quality scores:

$$V = \{Q_{ka_1}, \dots, Q_{ka_m}\}$$

where A is set of m attributes. With this evaluation, we have more insights, statistics and benefits about the Big data quality to ensure a well-refined analytics that targets the best precision.

3.3.5 After Evaluation Analysis

The data evaluation process done on Big data set provides data quality information and scores of quality dimensions of each attributes or features. These scores are used to identify the data that must be targeted and omitted. A set of proposals actions is generated based on many parameters, like DQD, or data quality issue. If a data attribute got a lower score than the required level (%) of accuracy or completeness the following actions are proposed:

- Discard it from the dataset.
- Tune, reformat, and normalize its values.
- Replace values, as in missing data.

Whatever the Quality evaluation results, it always contains actions to be taken on the dataset to remove any irregularities using techniques like cleaning, filtering and pre-processing based on the quality assessment.

Chapter 4

Experimentations , Results and Analysis

In this chapter, we will explain how data quality dimensions are implemented with Machine Learning (ML) techniques towards dirty datasets.

4.1 Experimental Methodology

The impact of the dirt data and data cleaning on ML in a dataset depends on a number of factors – some factors depend on the data cleaning process,

i.e., the error types to be cleaned and the cleaning methods; some factors depend on the ML process, i.e., the model types used; and some factors depend on where the cleaning is performed during the ML process. Hence, in order to comprehensively investigate the impacts, we need to consider data cleaning and ML jointly in our experiments.

4.2 The NettoyageML [2] Schema

The NettoyageML relational schema consists of three relations as shown in Table 4.1 . Firstly will introduced the attributes of NettoyageML relational models, and then will explained the differences between these three relations.

- **Attributes for Dataset.** The first attribute is dataset, which is the input to the data cleaning and ML pipeline. Each dataset can have multiply types of errors and has an associated ML task.

R1 Vanilla

Dataset	Error Type	Detection	Repair	ML Model	Scenario	Flag
---------	------------	-----------	--------	----------	----------	------

R2 (With Model Section)

Dataset	Error Type	Detection	Repair	Scenario	Flag
---------	------------	-----------	--------	----------	------

R3 (With Model Selection and Cleaning Method Selection)

Dataset	Error Type	Scenario	Flag
---------	------------	----------	------

Table 4.1 NettoyageML Relational Schema

Even for one error type, they might appear in a dataset in various distributions and hence affect ML models in complicated ways/ To study the impact of the real-world error types and distribution on ML models, we mostly use real-world-dataset with real errors, and we apply various cleaning methods to detect and repair the errors in them.

- **Attributes for Data Cleaning.** The error type attribute describes which type of dirtiness we are testing. We consider five most common types of dirtiness that are considered in the ML and DB communities: missing values, outliers, duplicates, inconsistencies, and mislabels. For each error type, there exist multiple cleaning methods, and each cleaning method includes an error detection component and an error repair component.
- **Attributes for ML.** The ML model describes the algorithm of training and prediction. Different ML models may have different robustness or sensitivity to dirty data.
- **Flag Attribute.** *The flag attribute summarizes* the impact of data cleaning on ML of an experiment into three categories “**P (positive)**”, “**N (negative)**” or “**S (insignificant)**”, indicating whether the cleaning has a positive, negative, or insignificant impact on the ML performance respectively.

Given these attributes, we designed three relations as shown Table 4.1 *R1* shows the vanilla of the a NettoyageML relation schema with the key $\{ dataset, error\ type, detect, repair, ML\ model, scenario, flag \}$ Every tuple of *R1* represents a hypothesis or an experiment: how

does cleaning some type of error using a detection method and a repair method affect a ML model for a given dataset? We also consider other two versions of relations in *NettoyageML*.

Compared with *R1*, *R2* eliminates the ML model attribute. In this case, we try different models during training and select the model that has the best validation accuracy (or F1 score) as the model to be considered in an experiment in *R2*.

Every tuple of *R2* represents a hypothesis or an experiment: how does cleaning some type of error using a detection method and a repair method affect the best ML model for a given dataset?

R3 further eliminates the cleaning method (detection and repair) attributes. In this case, in addition to model selection, we also try different cleaning methods and select the cleaning method that results in the best validation accuracy as the cleaning method to be considered in an experiment in *R3*. Every tuple of *R3* represents a hypothesis or an experiment: how does the best cleaning method affect the predictive performance of the best model for a given dataset?

All three relations can also be extended with other attributes that are associated with an experiment, which may help obtain insights and interpret the results, such as the accuracy scores before and after cleaning and p-values of hypothesis testing associated with each experiment.

4.3 Analysis Methodology

are associated with an experiment, which may help obtain insights and interpret the results, such as the accuracy scores before and after cleaning and p-values of hypothesis testing associated with each experiment in Table 4.1 .

We first fix the error type and group by flags. The percentage of each type of flag indicates the general impact of cleaning this type of error on ML. For example, if flag “P” dominates in the error type outliers, it indicates cleaning outliers generally improves the performance of ML. Then we group by the other attributes (e.g., ML models, datasets, etc.) in addition to flags to see how each attribute affects the impact.

For example, if flag “S” dominates under the ML algorithm decision tree, it indicates decision tree is insensitive to this error. We also investigate the changes of percentage in each type of flag when moving from *R1*, to *R2* and *R3*.

This indicates how model selection and cleaning algorithm selection affect the impacts.

For example, if the percentage of flag “N” significantly decreases from *R1* to *R2*, it indicates the model selection reduces the negative impact of data cleaning on ML.

We investigate the impact of dirty data on ML models by simply running SQL queries on three relations $R1$, $R2$ and $R3$.

We formally present the SQL query templates as follows, where $E \in$ inconsistencies, duplicates, mislabels, outliers, missing values.

Q1: Flag

```
1 SELECT flag, COUNT(*) FROM R
2 WHERE error_type = E
3 GROUP BY flag
```

Listing 4.1 Q1: Flag

Q2: Scenario

```
1 SELECT scenario, flag, COUNT(*)
2 FROM R
3 WHERE error_type = E
4 GROUP BY scenario, flag
```

Listing 4.2 Q2: Scenario

Q3: ML Model. (Not applicable to R2, R3)

```
1 SELECT model, flag, COUNT(*)
2 FROM R
3 WHERE error_type = E
4 GROUP BY model, flag
```

Listing 4.3 Q3: ML Model

Q4: Clean Method (Not applicable to R3 or $E \in$ inconsistencies, duplicates, mislabels, where only one cleaning method is applied)

```
1 SELECT detect_method, flag, COUNT(*)
2 FROM R
3 WHERE error_type = E
4 GROUP BY detect_method, flag
```

Listing 4.4 Q4.1:Clean Method

```
1 SELECT repair_method, flag, COUNT(*)
2 FROM R
3 WHERE error_type = E
4 GROUP BY repair_method, flag
```

Listing 4.5 Q4.2:Clean Method


```

1  SELECT dataset, flag, COUNT(*)
2  FROM R
3  WHERE error_type = E
4  GROUP BY dataset, flag

```

Listing 4.6 Q5: Dataset

4.4 Design of Benchmark

Based on NettoyageML Relational Schema, we design NettoyageML Benchmark by specifying the domain of each key attribute. In the following sections we present all datasets, error types, cleaning methods, ML models, and cleaning scenarios we consider in the benchmark.

4.5 Error Types and Cleaning Methods

We consider five error types that are prevalent in the real-world datasets, including missing values, outliers, duplicates, inconsistencies and mislabels.

Table 4.2 Cleaning Methods

Error Type	Detect Method	Repair Method
Missing Values	Empty Entry	Deletion
		Imputation: Mean Mode Median Mode Mode Mode Mean Dummy Mode Dummy Median Dummy
Outliers	SD	Deletion
	IQR	Imputation: Mean Median Mode
	IF	
Duplicates	Key Collision	Deletion
Inconsistencies	OpenRefine	Merge
Mislabels	Ground Truth	Flip Labels

While there are many cleaning methods in the literature we consider the most straightforward one in this study. The definition and the cleaning methods of each error type are described below and summarized in Table 4.2

4.5.1 Missing Values

Missing values occur when no value is stored for some attribute in an observation. We detect missing values by finding empty or *NaN* entries in datasets. We use two methods to repair missing values:

- **Deletion:** Delete records with missing values.
- **Imputation:** For numerical missing values, we consider three types of imputation methods: mean, median and mode. For categorical missing values, we use two types of imputation methods: the mode (most frequent class) or a dummy variable named “missing”. Therefore, we have six imputation methods. In Table 4.2 we denote each imputation method by the numerical imputation and categorical imputation (e.g. “Mean Dummy” represents imputing numerical missing values by mean and imputing categorical missing values by dummy variables).

4.5.2 Outliers

An outlier is an observation that is distant from other observations. We only consider numerical outliers in our experiments. We use three methods to detect numerical outliers.

- **Standard Deviation Method (SD:)** A value is considered to be an outlier if it is n numbers of standard deviations away from the mean of the attribute it belongs to. We use $n = 3$.
- **Interquartile Range Method (IQR):** Let Q_1 and Q_3 be the 25th and the 75th percentiles of an attribute. Then, interquartile range $IQR = Q_3 - Q_1$. A value is considered to be an outlier if it is outside range of $[Q_1 - k * IQR, Q_3 + k * IQR]$ We use $k = 1.5$.
- **Isolation Forest Method (IF):** The isolation forest isolates observations by randomly selecting a feature and randomly selecting a split value of the selected feature. This partition can be represented by a tree structure and outliers will have noticeably shorter paths in the random trees. We use **the scikit-learn IsolationForest** and set the contamination parameter to be **0.01**

We use two methods to repair numerical outliers in the datasets.

- **Deletion:** Records with outliers entries are removed from the datasets.
- **Imputation:** Outliers entries are imputed. We consider three types of imputation: **mean**, **median** and **mode**.

4.5.3 Duplicates

Duplicates refer to the records that correspond to the identical real-world entity. We detect duplicates by defining the key attribute that is unique for each entity in the dataset. If two records have an identical value on the key attribute, they will be considered as duplicates. We repair the duplicates by keeping the first and deleting all the others.

4.5.4 Inconsistencies

Inconsistencies occur when two values correspond to the identical real-world entity but have different representations. We detect inconsistencies in datasets using OpenRefine [75] and repair them by merging different representations into one in OpenRefine.

4.5.5 Mislabeleds

Mislabeleds occur when an observation is incorrectly labeled. Since mislabeleds in our datasets come from error injection, we already know which label is incorrect. We repair mislabeleds by flipping the label. Our protocol in injecting class noise follows the recommendation in [63]

4.6 Datasets

Collected 13 real-world datasets from different sources to conduct our experiments. Each dataset contains one or more types of error summarized in Table 4.3 For mislabeleds, we cannot find existing real-world datasets with both mislabeleds and ground truth. Since it is difficult to clean mislabeleds without ground truth (we do not know whether a label is mislabeled unless we have ground truth or domain knowledge), we injected mislabeleds in three real-world datasets.

Table 4.3 Dataset and Error Types

Datasets	Error Types				
	Inconsistencies	Duplicates	Missing Values	Outliers	*Mislabels Data
Airbnb		X	X	X	
Citation		X			
Company	X				
Credit			X	X	
EEG				X	X
KDD			X	X	X
Marketing			X		
Movie	X	X			
Restaurant	X	X			
Sensor				X	
Titanic			X		
University	X				
USCensus			X		X

- **Airbnb :** This dataset contains 42,492 records on hotels in the top 10 tourist destinations and major US metropolitan areas scraped from Airbnb.com. Each record has 40 attributes including the number of bedrooms, price, location, etc. Demographic and economic attributes were scraped from city-data.com. The classification task is to determine whether the rating of each hotel is 5 or not. This dataset contains missing values, numerical outliers and duplicates.
- **Citation: [Das et al.]** This dataset consists of titles of 5,005 publications from Google Scholar and DBLP. Given a publication title, the classification task is to determine whether the paper is related to Computer Science or not. This dataset contains duplicates.
- **Company: [Hatton]** The original dataset contains over 2.5 million records about companies including company names and locations. Because of its large size, we randomly sampled 5records) from the original dataset. Each record has seven attributes including company name, country, city, etc. The classification task is to predict whether the company sentiment is negative or not. This dataset contains inconsistent company names.

- **Credit:** [34] This dataset consists of 150,000 credit data with 10 attributes including monthly income, age, then number of dependents, etc. The classification task for this dataset is to predict whether a client will experience financial distress in the next two years. This dataset has a class imbalance problem. There are only 6.7% in minority class. This dataset primarily contains missing values and numerical outliers.
- **EEG:** [21] This is a dataset of 14,980 EEG recordings. Each record has 14 EEG attributes. The classification task is to predict whether the eye-state is closed or open. This dataset contains numerical outliers. We inject mislabels into this dataset by randomly flip labels.
- **KDD:** [35] This dataset contains 131,329 records about projects and donations from DonorsChoose.org. Each record has 100 attributes. The classification task is to predict whether a project is “exciting”. This dataset has a class imbalance problem. There are 11% records in the minority class. This dataset contains missing values and numerical outliers. We inject mislabels into this dataset by randomly flip labels.
- **Marketing:** This dataset consists of 8,993 data about household income from a survey. Each record has 14 demographic attributes including sex, age, education, etc. The classification task is to predict if the annual household income is less than \$25,000. This dataset contains missing values.
- **Movie:** [27] [80] This dataset consists of 9,329 movie reviews, which we obtained by merging data from IMDB and TMDB datasets. Each record has seven attributes including title, language, score, etc. The classification task is to predict the genre of the movie (romance or comedy). It contains duplicates and inconsistent representations of languages.
- **Restaurant:** [26] This dataset contains 12,007 records about restaurants, which we obtained by merging data from the Yelp and Yellowpages datasets. Each record has 10 attributes including city, category, rating, etc. The classification task is to predict whether the categorical price range of a restaurant is “\$” or not. This dataset consists of duplicates and inconsistent restaurant names and categories.
- **Titanic:** [36] This dataset contains 891 records and 11 attributes from the Titanic including name, sex, age, etc. The classification task is to determine whether the passenger survived or not. This dataset has a significant number of missing values.
- **Sensor:** [16] The original sensor dataset contains 928,991 sensor recordings with eight attributes including temperature, humidity, light, etc. Because of the large size,

we only used recordings from sensor 1 and sensor 2 and sampled the dataset to include 1 observation per hour, and day for each sensor. The sampled dataset contains 62,076 records. The classification task is to predict whether the readings came from a particular sensor (sensor 1 or sensor 2). This dataset contains outliers.

- **University:** [66] This dataset contains 286 records about universities. Each record has 17 attributes including state, university name, SAT scores, etc. The classification task is to predict whether the expenses are greater than 7,000 for each university. This dataset contains inconsistent representations for states and locations.
- **USCensus:** [11] This dataset contains 32,561 US Census records for adults. Each record has 14 attributes including age, education, sex, etc. The classification goal is to predict whether the adult earns more than \$50,000. This dataset contains missing values.

4.7 ML Models

We select seven classical and competitive classification algorithms in our experiments, including **Logistic Regression, KNN, Decision Tree, Random Forest, Adaboost, XGBoost and Naive Bayes**. We used **scikit-learn** [24] to train models. Each model is described below.

References

- [1] (2016). Data observation network for earth. identify and use relevant metadata standards. <https://www.dataone.org/best-practices/identify-and-use-relevant-metadata-standards>. Accessed: 2019-07-19.
- [2] (2019). Nettoyage de données. https://fr.wikipedia.org/wiki/Nettoyage_de_donn%C3%A9es.
- [3] A. Kleiner, A. Talwalkar, P. S. and Jordan, M. (2012). The big data bootstrap.
- [4] Almasi, G. S. and Gottlieb, A. (1988). *Highly Parallel Computing*. Benjamin-Cummings Pub. Co.
- [5] Alon Halevy, A. R. and Ordille, J. (2006). Data integration: the teenage years. page 9–16, Endowment. In Proceedings of the 32nd international conference on Very large data bases.
- [6] Benjamin T. Hazen, Christopher A. Boone, J. D. E. and Jones-Farmer, L. A. (2014). Data quality for data science, predictive analytics, and big data in supply chain management: An introduction to the problem and suggestions for research and applications. 154:72–80.
- [7] Cai, L. and Zhu, Y. (2015a). The challenges of data quality and data quality assessment in the big data era. page 14:2.
- [8] Cai, L. and Zhu, Y. (May 2015b). The challenges of data quality and data quality assessment in the big data era. 14:2.
- [9] Chen, C. P. and Zhang, C.-Y. (2014a). Data-intensive applications, challenges, techniques and technologies: A survey on big data. page 314–347.
- [10] Chen, C. P. and Zhang, C.-Y. (2014b). Data-intensive applications, challenges, techniques and technologies: A survey on big data. 275:314–347.
- [11] Chris Meek, Bo Thiesson, D. H. (2019). UCI machine learning repository us census data (1990) data set.
- [12] Cormode, G. and Duffield, N. (2014). Sampling for big data: A tutorial. page 1975–1975, New York, NY, USA. 20th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining.
- [13] Cox, M. and Ellsworth, D. (1997). Application-controlled demand paging for out-of-core visualization.

- [14] D. Firmani, M. Mecella, M. S. and Batini, C. (2015). *On the Meaningfulness of ‘Big Data Quality’*. Springer Berlin Heidelberg.
- [Das et al.] Das, S., Doan, A., G. C., P. S., Gokhale, C., Konda, P., Govind, Y., and Paulsen, D. The magellan data repository. <https://sites.google.com/site/anhaidgroup/projects/data>.
- [16] Data, I. L. (2019). Sensor dataset. <http://db.csail.mit.edu/labdata/labdata.html>. Accessed: 2019-07-30.
- [17] Deming, W. E. (1960). *Sample Design in Business Research*. John Wiley and Sons, Inc., New York.
- [18] Dictionaries, O. (2013). An oxford english dictionary update — oxfordwords blog. <http://blog.oxforddictionaries.com/2013/06/oed-june-2013-update/>.
- [19] Diebold, F. X. (2012). A personal perspective on the origin(s) and development of big data.
- [Divyakant Agrawal] Divyakant Agrawal, Philip Bernstein, E. B. S. D. U. D. M. F. J. G. L. H. J. H. H. J. A. L. S. M. Y. P. J. Challenges and opportunities with big data. A white paper prepared for the Computing Community Consortium committee of the Computing Research Association.
- [21] Dua, D. and Graff, C. (2017). UCI machine learning repository.
- [22] Eckerson, W. W. (2002). Data quality and the bottom line. achieving business success through a commitment to high quality data.
- [23] F. Liang, J. K. and Song, Q. (2016). *A Bootstrap Metropolis-Hastings Algorithm for Bayesian Analysis of Big Data*. Technometrics.
- [24] F. Pedregosa, G. Varoquaux, A. G. V. M. B. T. O. G. M. B. P. P. R. W. V. D. J. V. A. P. D. C. M. B. M. P. and Duchesnay, E. (2011). Scikit-learn: Machine learning in python. 12:2825–2830.
- [25] FUJITSU (2015). *White paper Solution Approaches for Big Data*. FUJITSU Technology Solutions GmbH.
- [26] Group, A. (2019a). Restaurant dataset. <https://sites.google.com/site/anhaidgroup/useful-stuff/data>. Accessed: 2019-07-30.
- [27] Group, A. (2019b). The tmdb 5000 movie dataset. <https://www.kaggle.com/tmdb/tmdb-movie-metadata>. Accessed: 2019-07-30.
- [28] Guptil, C. and Morrison, J. (1995). *Elements of Spatial Data Quality*. Elsevier Science Ltd, Oxford, UK.
- [29] H. Jagadish, Johannes Gehrke, A. L. Y. P. J. M. P. R. R. and Shahabi, C. (2014). Big data and its technical challenges. page 86–94.
- [Hatton] Hatton, J. A. Company dataset. <https://www.kaggle.com/jacksapper/company-sentiment-by-location>. Accessed: 2019-07-30.

- [31] Heinrich, B., Hristova, D., Klier, M., Schiller, A., and Szubartowicz, M. (2018). Requirements for data quality metrics. *J. Data and Information Quality*, 9(2):12:1–12:32.
- [32] I. Caballero, M. S. and Piattini, M. (2014). A data quality in use model for big data.
- [33] Jugulum, R. (2014). *Computing with High Quality Data*, page 1. John Wiley and Sons, Inc., New Jersey.
- [34] Kaggle (2019a). The credit dataset. <https://www.kaggle.com/c/GiveMeSomeCredit/data>. Accessed: 2019-07-30.
- [35] Kaggle (2019b). The kdd dataset. <https://www.kaggle.com/c/kdd-cup-2014-predicting-excitement-at-donors-choose/data>. Accessed: 2019-07-30.
- [36] Kaggle (2019c). The titanic dataset. <https://www.kaggle.com/upendr/titanic-machine-learning-from-disaster/data>. Accessed: 2019-07-30.
- [37] Karthik Kambatla, Giorgos Kollias, V. K. and Grama, A. (2014). Trends in big data analytics. 74:2561–2573.
- [38] Krawczyk, H. and Wiszniewski, B. (2003). Visual gqm approach to quality-driven development of electronic documents. Edinburgh UK. 2nd International Workshop on Web Document Analysis.
- [39] Lenzerini, M. (2002). Data integration: A theoretical perspective. in proceedings of the twenty-first acm sigmod-sigact-sigart symposium on principles of database systems. 23(4):233–246.
- [40] Leo Pipino, Yang W Lee, R. Y. W. M. W. L. Y. L. and Yang, R. Y. (2002). Data quality assessment. 45(4):211–218.
- [41] M. Ali-ud-din Khan, M. F. U. and Gupta, N. (2014). Seven v’s of big data understanding big data to extract value. page 1–5. American Society for Engineering Education (ASEE Zone 1), 2014 Zone 1 Conference of the, 2014.
- [42] Magoulas, R. and Lorica, B. (2009). Big data: Technologies and techniques for large-scale data. 2.
- [43] Marr, B. (2015). Why only one of the 5 vs of big data really matters — ibm big data and analytics hub. <http://www.ibmbigdatahub.com/blog/why-only-one-5-vs-big-data-really-matters>.
- [44] Maydanchik, A. (2007). *Data quality assessment*. Bradley Beach, Technics Publications, New Jersey, USA.
- [45] McGilvary, D. (2008). *Executing data quality projects: ten steps to quality data and trusted information*. Elsevier Inc.
- [46] Michael J. Shaw, Chandrasekar Subramaniam, G. W. T. and Welge, M. E. (2001). Knowledge management and data mining for marketing. 31:127–137.

- [47] Microsoft (2016). Data identification. [https://msdn.microsoft.com/en-us/library/aa291809\(v=vs.71\).aspx](https://msdn.microsoft.com/en-us/library/aa291809(v=vs.71).aspx). Accessed: 2019-07-19.
- [48] Nicola Askham, Denise Cook, M. D. H. F. M. G. U. L. R. L. C. M. G. P. and Schwarzenbach, J. (2013). *The six primary dimensions for data*. Data Management Association (DAMA), United Kingdom.
- [49] of Inspector General, G. O. (2014). United states postal service. undeliverable as addressed mail audit report. (MS-AR-14-006).
- [50] Ohbyung Kwon, N. L. and Shin, B. (2014). Data quality management, data usage experience and acquisition intention of big data analytics. 34(3):387–394.
- [51] Osborne, J. W. (2013). *Best practices in data cleaning: a complete guide to everything you need to do before and after collecting your data*. Thousand Oaks.
- [52] Ostman, A. (1997). The specifications and evaluation of spatial data quality. In *18th ICA/ACI International Conference*, Stockholm, Sweden.
- [53] Paton, N. (2016). Data wrangling. <http://www.cs.manchester.ac.uk/study/postgraduate-research/programmes/phd/programme-details/projects/description/?projectid=6981>. Accessed: 2019-07-19.
- [54] Pernici and Scannapieco, M. (2003). Data quality in web information systems. *Journal of Data Semantics*.
- [55] Platform, I. A. T. (2018). Extracting business value from the 4 v’s of big data. <https://www.ibmbigdatahub.com/infographic/four-vs-big-data>. Accessed: 2019-07-19.
- [56] Rahm, E. and Do, H. H. (2000). Data cleaning: Problems and current approaches. 23(4):3–13.
- [57] Raja Appuswamy, Christos Gkantsidis, D. N. O. H. and Rowstron, A. (2013). Scale-up vs scale-out for hadoop: Time to rethink? In editor, editor, *Proceedings of the 4th Annual Symposium on Cloud Computing*, page 20:1–20:13. ACM.
- [58] Ralph Kimball, Laura Reeves, M. R. and Thornthwaite, W. (2008). *The Data Warehouse Lifecycle Toolkit*. Wiley.
- [59] Redman, T. C. (2018). If your data is bad, your machine learning tools are useless. <https://hbr.org/2018/04/if-your-data-is-bad-your-machine-learning-tools-are-useless>. Accessed: 2019-07-19.
- [60] Rouse, M. (2005). What is data quality? <http://searchdatamanagement.techtarget.com/definition/data-quality>. Accessed: 2019-07-19.
- [61] Ryszard S Michalski, J. G. C. and Mitchell, T. M. (2013). *Machine learning: An artificial intelligence approach*. Springer Science and Business Media.
- [62] S, J. (2015). Overview of data quality challenges in the context of big data. pages 1–9. International Conference on Computing Communication and Security.

- [63] S. Garcia, J. L. and Herrera, F. (2015). *Data preprocessing in data mining*. Springer.
- [64] Sandra de F. Mendes Sampaio, C. D. and Sampaio, P. R. F. (2015). *DQ2S - A framework for data quality-aware information management*.
- [65] Satyanarayana, A. (2014). Intelligent sampling for big data using bootstrap sampling and chebyshev inequality. pages 1–6. 27th Canadian Conference on Electrical and Computer Engineering (CCECE).
- [66] Souders, S. (2019). UCI machine learning repository.
- [67] Steve Lavalley, Eric Lesser, R. S. M. S. H. and Kruschwitz, N. (2011). Big data , analytics and the path from insights to value big data, analytics and the path from insights to value. 52205.
- [68] Stone, L. (1979). The revival of narrative: Reflections on a new old history.past and present.
- [69] Tanenbaum, A. S. and Steen, M. V. (2007). *Distributed systems*. Prentice-Hall.
- [70] Tekiner, F. and Keane, J. A. (2013). Big data framework. page 1494–1499. IEEE International Conference on Systems, Man, and Cybernetics, IEEE.
- [71] Tilly, C. (1980). The old new social history and the new old social history.
- [72] Usama M Fayyad, A. W. and Grinstein, G. G. (2002). *Information visualization in data mining and knowledge discovery*. Morgan Kaufmann.
- [73] V. Gadepally, T. Herr, L. J. L. M. M. M. and Miller, B. A. (2015). Sampling operations on big data. page 1515–1519. 49th Asilomar Conference on Signals, Systems and Computers.
- [74] V. Goasdoué, S. Nugier, D. D. and Laboisie, B. (2007). An evaluation framework for data quality tools. page 280–294.
- [75] Verborgh, R. and Wilde, M. D. (2013). *Using OpenRefine*. Packt Publishing Ltd.
- [76] Wang and Strong, D. M. (1996). Beyond accuracy: What data quality means to data consumers. *Journal of Management Information Systems*, page 12.
- [77] Ware, C. (2012). *Information visualization: perception for design*. Elsevier.
- [78] Weiss, S. M. and Indurkha, N. (1998). *Predictive Data Mining: A Practical Guide*. Morgan Kaufmann Publishers Inc.
- [79] Wiszniewski, B. and Krawczyk, H. (2003). Digital document life cycle development. In *1st International Symposium on Information and Communication Technologies*, Dublin Ireland.
- [80] World, D. (2019). The imdb 5000 movie dataset. <https://data.world/popculture/imdb-5000-movie-dataset>. Accessed: 2019-07-30.

