AN ONTOLOGY-DRIVEN APPROACH FOR SPATIAL DATA QUALITY EVALUATION

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ABSTRACT:

The process of spatial data quality evaluation is a set of interrelated activities aiming to produce a data quality result, and moreover, to fulfil the quality requirements set forth by the customers. The quality evaluation must be done in a consistent manner in order to determine whether the achieved quality level meets the requirements, and also to be able to compare the quality results between different datasets. Quality assurance and evaluation are integral parts of the dataset production. There exist several quality standards that should be taken into account in the production process. However, it is not always clear how to adopt the standards in practice. The goal of this paper is to offer an ontological framework for the construction of the spatial data quality evaluation process, which will correspond to the domain knowledge and the process workflow presented in the quality standards for geographic information.

In this paper, we define the different process perspectives needed to capture the knowledge related to the spatial data quality evaluation process. Furthermore, we present a partial domain ontology for the spatial data quality and quality evaluation process. Since the ontology makes explicit the conceptualizations behind the terminologies and process models presented in the standards, it can facilitate, among other things, the implementation of the standards in practice, and could thus have an active role in standardization and quality harmonization efforts.

1. INTRODUCTION

With growing usage of geographic information the production of data of good quality is becoming increasingly important. At the same time the competition in the market is increasing, thus driving the data producers to improve their efficiency. In order to cope with these challenges - i.e. to efficiently produce and deliver data of good quality - quality must be built into a production process rather than trying to add it in afterwards. Moreover, users do not necessarily have tools or methods to improve the quality of a dataset once it has been accomplished and delivered.

ISO 9000 (ISO, 2000) standard provides conceptual guidelines to structure and implement widely accepted quality management principles, such as customer orientation and process approach, aiming at the continuous improvement of different processes. Furthermore, ISO 19113 (ISO, 2002) contains the quality principles for geographic information while ISO 19114 (ISO, 2003) covers the quality evaluation procedures, i.e. general descriptions of how to carry out the quality evaluation process. By applying these standards data producers could better response to the user requirements, as well as the challenges placed by the increased competition.

However, applying these standards in practice is rather difficult. The barriers include contradiction of concepts between the standards thus causing misunderstandings and confusion, lack of standard process definitions, heavy loads of paperwork and communication requirements among people; in short, the major disadvantage is time spent on quality management (e.g. Bubshait and Al-Atiq, 1999; Chin et al., 2004). To overcome these barriers, it is necessary to develop new approaches to improve the implementation of the standards.

According to Studer et al., (1998) an ontology is "a formal, explicit specification of a shared conceptualization", where 'conceptualization' refers to the part of reality intended to represent for some purpose, i.e. concepts and the relationships between them that are assumed to exist in some domain. Ontologies are 'formal', which means that they are machine readable, while 'explicit' means the type of concepts used, and that the constraints given on the usage are explicitly defined. Finally, since ontologies are based on the consensus of knowledge, they can be shared throughout the community of the domain.

Recent studies indicate that ontologies can be used to support complex tasks such as enterprise modeling (Grüninger et al., 2000), or when describing biological processes and molecular functions (Ashburner et al., 2000). We argue that the current Semantic Web (SW) technologies (Berners-Lee et al., 2001) could be used to facilitate the implementation of the standards, and also in the attempts to overcome the previously mentioned barriers by providing a set of ontologies to support both the content and the process within the spatial data quality evaluation. According to Berners-Lee et al. (2001) the purpose of the SW is to bring the meaning and the structure of the content of the information machine processable and understandable. The meaning of the content is expressed by RDF triplets (subject, predicate, object) where each element in the triplet is identified by a Universal Resource Identifier (URI).

There are good reasons to use ontologies to enhance the spatial data quality evaluation. To begin with, ontologies can promote the communication between people since they serve as vocabularies of the domain. For example, an ontology can define the core concepts of the process in question (e.g. inputs, outputs, activities and agents) hence supporting process specification and performance, and also the reduction of the ambiguities and misunderstandings related to the terminology. However, it can be demanding and time consuming to come up with such conceptualizations. The advantage of using ontologies is that they are reusable throughout a specific domain, or even across different domains; sharing of ontologies eliminates the need for replicating the knowledge-analysis process (Studer et al., 1998; Chandrasekaran et al., 1999; Chung et al., 2003). Furthermore, URIs can for example refer to a single geographic feature or attribute and its associated quality result. This makes possible to compare the quality of different geographic resources not only on the dataset level but also between the features and attributes.

In the context of spatial data quality evaluation the commitment to and sharing of a common ontology could save resources and guarantee that the evaluation is done in a coherent and consistent manner. This is necessary in order to be able to compare the quality of different geographic resources, and also in determining how well the dataset meets the quality requirements set forth by the customers.

The research on spatial data quality and the uncertainty related to it has been an active area for a long time (Heuvelink and Burrough, 2002). However, the systematic spatial data quality management approaches have received relatively little attention in the scientific literature. The objective of this paper is to define an ontological framework that integrates the process models with the domain knowledge, hence aiming to support the adoption of the process approach in spatial data quality management. In this paper we focus on defining the knowledge the domain ontology should consist of, and on identifying the process workflow constructs that enable to represent the quality evaluation process consistently.

2. CAPTURING THE PROCESS KNOWLEDGE

The ISO 9000 standard series emphasizes the process approach in quality management - that is, activities and related resources are managed as a process. A process is a set of activities that use recourses to transform inputs to outputs and different processes are connected to each other by means of many input-output relationships (ISO, 2000). Processes can be further decomposed into sub-processes or activities (also called as tasks); activities are individual process steps that can be executed (Curtis et. al., 1992).

When considering the nature of processes it is useful to categorize them into three different groups, namely, into managerial process, operational process and supporting process (Childe et al., 1994). Managerial processes cover the high level strategic-planning and decision making activities, which determine how an organization should operate and how the business should be conducted. Operational processes are the way in which the goods and services are produced within an organization. Processes of this type are usually associated with the customers' order and the transformation of different resources into a finished product so that the customers' requirements are fulfilled (Armistead et al., 1997). Typical operational process would thus be the production of a dataset. Finally, supporting processes contain variety of activities which support or enable the operational processes. Those are for example the provision of support technology and human resource management (Armistead et al., 1997), as well as the quality assurance and evaluation during the operational process.

To succeed in quality management all processes have to be identified, understood, and managed together with their integrated set of mutual interactions; this is also called as a system approach to quality management (ISO, 2000; Chin et al., 2004). A workflow process model is an abstract description of an actual or proposed process that defines and represents the necessary details of activities and selected process elements. Process models should integrate many forms of information from different viewpoints in order to capture the complexity. Process modeling objectives are to understand, analyze, and control the processes (e.g. what is going to be done, and by whom), and the interactions between them (Curtis et al., 1992; Luo and Tung, 1999).

By applying Curtis et al., (1992) and Peleg et al., (2002) we propose a set of process model perspectives that are necessary to consistently capture the knowledge of the process of spatial data quality evaluation; these are static-structural, functional and behavioral views.

2.1 The static-structural view

The static-structural view represents the domain knowledge, i.e. the kinds of things, their properties, and the relationships among them that participate in the system. The domain knowledge is static; it has no time dimension, meaning that there are no events and nothing changes (Jackson, 1995).

The domain level class structure consists of things, which can be either informational entities or organizational agents. An organizational agent is an actor that performs the process (e.g. human or machine). A single agent may perform multiple roles in a process (e.g. manager, customer) and a single role can be performed by several agents (Curtis et al., 1992). The domain knowledge of spatial data quality evaluation consists of the concepts and relationships relevant to define digital geographical information and quality components, and the organizational agents being part of the quality evaluation (e.g. a customer, a producer, a measure or a sampling plan).

As discussed in Zhang and Goodchild (2002), geographical information can be decomposed into (x,G) tuples where x refers to a general notation of two-, three-, or four-dimensional position and G stands for one or more properties, spatial or non-spatial attributes or some other things. Thus, in the domain of geographical information an informational entity, *a thing*, is a piece of data related to some geographical locations; it can for example be a measurement of some variable (Zhang and Goodchild, 2002), a geographic feature, a class of features, an attribute, a cell or a spatial object. To be more precise, a spatial object is a digital representation of a real-world phenomenon (i.e., entity), and a feature is a defined entity and its object representation (Zhang and Goodchild, 2002). A spatial object consists of (at least) one spatial attribute that describes the geometry of an object (Brinkhoff et al., 1994).

The measurement value of some variable can represent the quality information (i.e., quality result) from the predefined perspective, and relative to the piece of data being observed. The quality result for geographic information is usually expressed in terms of error or uncertainty; errors refer to the implicit assumption that the variables' true values are known, where as uncertainty is only an approximation or estimate of the true values, and thus the result is complete only when accompanied by a quantitative statement of its uncertainty (Taylor and Kuyatt, 1994; Zhang and Goodchild, 2002).

In order to be able to identify the possible quality variables (i.e., the measurands), it is essential to recognize the components of spatial data quality together with geographic dimensions (Table 1). The fundamental spatial data quality components, also called as quality elements in ISO 19113 (ISO, 2002), are as follows:

Accuracy: the closeness between the measured/observed value of a spatial, temporal or thematic attribute (or cell) to value accepted as, or being true (ISO, 2002).

Completeness: the degree to which all features, their attributes and relationships are either presence or absent in data (ISO, 2002).

Consistency: the degree to which any internal contradiction is absent within a model of reality. It would be impossible to detect the inconsistencies without a data model since it contains the definition of certain constraints (i.e., quality requirements) assigned to the informational entities (Egenhofer, 1997).

Correctness: the degree to which data and reality correspond to each other, i.e. the absence of contradictions with reality (Egenhofer, 1997; Frank 2000).

<table>
<tr><th>Accuracy (a.)</th><th>Space</th><th>Time</th><th>Theme</th></tr>
<tr><td>Absolute positional a.</td><td>SA</td><td>N/A</td><td>N/A</td></tr>
<tr><td>Gridded data positional a.</td><td>C</td><td>N/A</td><td>N/A</td></tr>
<tr><td>Relative positional a.</td><td>SA</td><td>N/A</td><td>N/A</td></tr>
<tr><td>Accuracy of a time measurement</td><td>N/A</td><td>qTE, R</td><td>N/A</td></tr>
<tr><td>Quantitative attribute a.</td><td>N/A</td><td>N/A</td><td>qTH</td></tr>
<tr><td rowspan="2">Completeness</td><td>SA</td><td>qTE, TE</td><td>qTH, TH</td></tr>
<tr><td colspan="3">F, R</td></tr>
<tr><td rowspan="2">Consistency</td><td>SA</td><td>qTE, TE</td><td>qTH, TH</td></tr>
<tr><td colspan="3">R</td></tr>
<tr><td>Correctness</td><td>N/A</td><td>TE</td><td>F, TH</td></tr>
</table>

Table 1. Applicable quality variables (SA = 1D, 2D or 3D Spatial Attribute, qTE = 1D Quantitative Temporal attribute, qTH = 1D Quantitative Thematic Attribute, TH = Qualitative Thematic Attribute, TE = Qualitative Temporal Attribute, F = Feature, FC = Feature Class, R = Relationship, C = Cell, N/A = Not Applicable) according to the spatial data quality components and geographical dimensions (the analysis is based on the standard ISO 19113 (ISO, 2002)).

Each data quality element contains a set of data quality sub-elements; for clarity, the Table 1 shows only sub-elements of accuracy. The classification differs from the one given in ISO (2002). The idea of the reclassification is to group together the quality variables that share similar characteristics (such as the scale and the value type).

The quality measurands subjected to completeness, consistency and correctness are dichotomous variables: that is, the measurand is classified either as true or false. For example in some cases of internal quality measurements (i.e., consistency) it is possible to obtain the correct values for variables, and the quality result can be expressed accordingly in terms of errors. However, since it is not always possible or affordable to measure every instance of discrete data (Zhang and Goodchild, 2002), but rather the elementary units (i.e., the individuals belonging to the sample), it is likely that there will always be some uncertainties related to the quality result. This is usually the case with the continuous variables (i.e. quality variables of accuracy).

2.2 Functional perspective on process

The functional process model represents the process together with the components (i.e., process elements) that are being performed, and the flows of informational entities (i.e., the dataflows). Furthermore, it also describes the actors that perform the process. To ease the comprehension and the management of the processes it is essential to decompose the complex processes into more elementary ones. The lower level models of sub-processes or activities capture more details related to the dataflows, support, and participants of a process or activity in question (Curtis et al., 1992). Typical activities in spatial data quality evaluation are for example sampling, quality measurement, and inspection.

There exist a number of well known process modeling methods that can be used to represent the process functionalities. These models define the modeling constructs that are necessary to describe processes consistently (Table 2).

Method	Functional modeling constructs
IDEF0	Input, Output, Control, Mechanism
OWL-S	Parameter (Input, Output, Precondition, Effect, Participant), Atomic process, Simple process, Complex process
BPML	Parameters (Input, Output), Participants, Simple activity, Complex activity

Table 2: Functional modeling constructs according to the modeling method / language.

Integrated DEFinition method 0 (IDEF0): IDEF0 is a methodology to model the system functionality. Each process or activity in the IDEF0 model is specified by its inputs, outputs, controls and mechanisms. Inputs (e.g. data or objects) are transformed into outputs (e.g. data or objects) by a function that is performed by a mechanism (e.g. an actor) and governed by a control (e.g. a standard) (Chen and Lu, 1997). IDEF0 methodology has been applied for example to model the functionality of the quality management systems (e.g. Chin et al., 2004)

Ontology Web Language for Services (OWL-S): OWL-S is an ontology-based approach to describe web services. It consists of three interrelated sub-ontologies, known as a service profile ontology, a service grounding ontology, and a process model ontology. The process model ontology provides the means to structurally model the process functions, the relationships between them as well as the informational entities and organizational agents participating in the functions. Furthermore, it supports the hierarchical decomposition of functions where lower level functions can be described in increasing details (Martin et al., 2004).

OWL-S defines three different kinds of processes: 1) Atomic processes are non-decomposable processes, that is, they have no subprocesses. They take in the inputs and transform them into the outputs. 2) Composite processes can be decomposed into other composite processes or atomic processes. 3) Simple processes are not invocable; they are abstract processes and provide some perspective on either the atomic or the composite process (Martin et al., 2004, 2005).

Each of these processes is defined by the following properties: preconditions, effects, inputs, outputs, and participants. Preconditions describe the constraints that need to be satisfied (ensure to be true) to be able to execute the functions and the effects (postconditions) are the possible side-effects of the execution of a function (Martin et al., 2004, 2005).

Business Process Modeling Language (BPML): BPML is an abstract model and grammar for describing business processes. It has rich abilities for describing data flows and control flows (Arkin, 2002). The semantics of the modeling constructs corresponds to the OWL-S constructs with the notification that simple activity corresponds to the OWL-S atomic process and complex activity to the OWL-S complex process.

2.3 Behavioural perspective on process

Since functional perspective is also static, to capture the knowledge related to the behaviour of the quality evaluation process we need to adopt the behavioural process characteristics; behavioural aspects organize the processes and activities, and related knowledge in temporal, casual and logical manner. The behavioural process model shows the dynamics of the system, i.e., how activities are ordered over time (control flows) by sequencing them (Curtis et al., 1992). Dynamic process models should also support possible parallel, conditional and iterative behaviours of the processes (Peleg et al., 2002).

Method	Behavioral modeling constructs
IDEF0	IDEF0 does not provide control constructs for modeling the process behavior.
OWL-S	Sequence, Split, Split + Join, If-Then-Else, Choice, Any-Order, Repeat-While, Repeat-Until, Condition, Iterate
BPML	Sequence, Choice, Switch, Foreach, All

Table 3: Behavioural modeling constructs defined according to the modeling method / language.

BPML and OWL-S defines a set of so called behavioural control constructs; processes and activities are related to each in temporal, casual and logical manner by these constructs. For example, a *sequence* is a list of process stages that has to be executed in a given order, and *a split* implicates the parallel processes (Arkin, 2002; Martin et al., 2004).

3. ONTOLOGY CONSTRUCTION

The ontology we are building covers the domain of spatial data quality, and the processes and activities related to the quality evaluation. The ontology consists of concepts (i.e. classes) that describe the informational entities and organizational agents as discussed in the section 3.1 (Figure 1). Most of these concepts are derived from the ISO standards for geographic information (e.g. ISO (2002), ISO (2003), ISO (2005), ISO (2006)), and the ISO standards defining the sampling procedures for inspection (e.g. ISO (1999)).

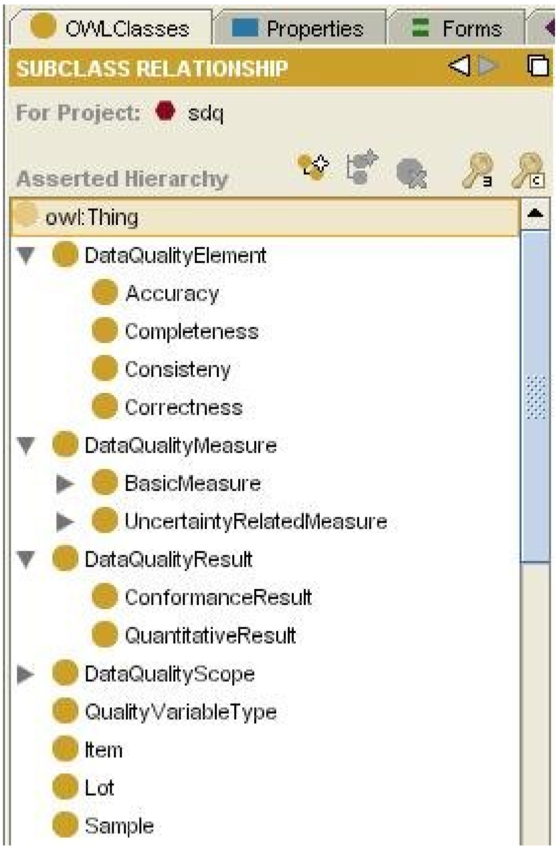

Figure 1. A part of the classes of the domain ontology for the spatial data quality. The ontology is developed by using an open-source ontology editor called Protégé[1].

Besides the hierarchical *subclassOf* relations (Gómes-Péres et al., 2004) classes are connected to each other by some other types of relationships (Table 4). Relationships are specified here by its name, the class it belongs to (domain), the target source (range), and the minimum and maximum cardinality (card.).

Name	Domain	Range	Card.
hasQualityIndicator	Quality variable type	Data quality element	(1,N)
isMeasuredBy	Quality variable type	Data quality measure	(1, N)

Table 4. Two relationships from the domain ontology. For example, the relationship *isMeasuredBy* indicates that each *Quality variable type* must be specified by at least one *Data quality measure.*

[1] http://protege.stanford.edu/

Figure 2 represents a partial class hierarchy and two relationships of the domain ontology. The ontology can help for example data producers in identifying the data quality measures that can be used to measure the quality of different types of quality variables (e.g. a 2D spatial attribute or a qualitative thematic attribute).

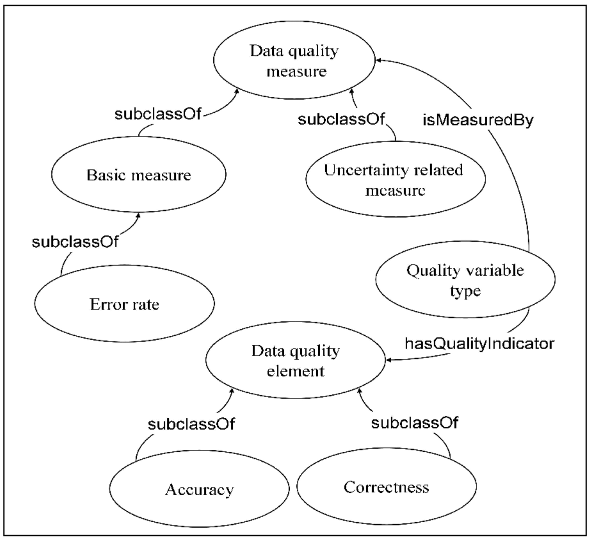

Figure 2. A partial domain ontology with the class hierarchy and the relationships.

The key concepts underlying the quality evaluation process functionality and behavior are derived here form the OWL-S (see Table 2 and Table 3). The functional control constructs enable to connect the informational entities form the domain ontology to the inputs and outputs of the process ontology, as well as the organizational agents to the process participants (Figure 3). The figure 3 shows that *Inspection_A* is an atomic process (i.e. it cannot be decomposed into more primitive activities) having an input named as *Lot_A*, an output named as *ConformanceResult_A*, and a participant named as *SamplingPlan_A*.

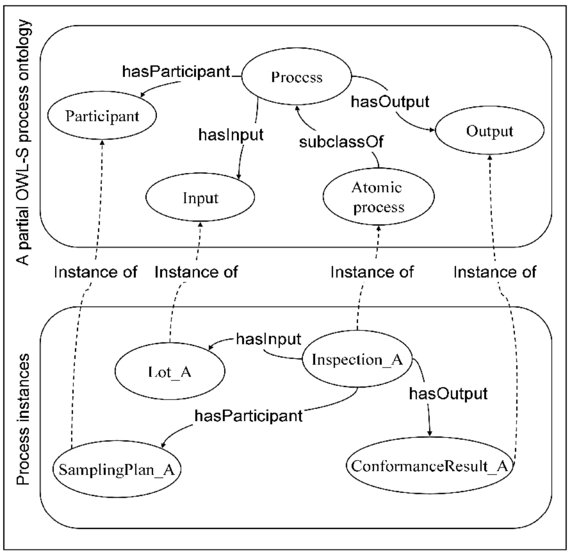

Figure 3. Informational entities and organizational agents form the domain ontology are mapped to the process ontology.

Furthermore, it is possible to model the dynamics (e.g. temporality) of the quality evaluation process by connecting the processes and activities to each other by means of the behavioural control constructs (Figure 4).

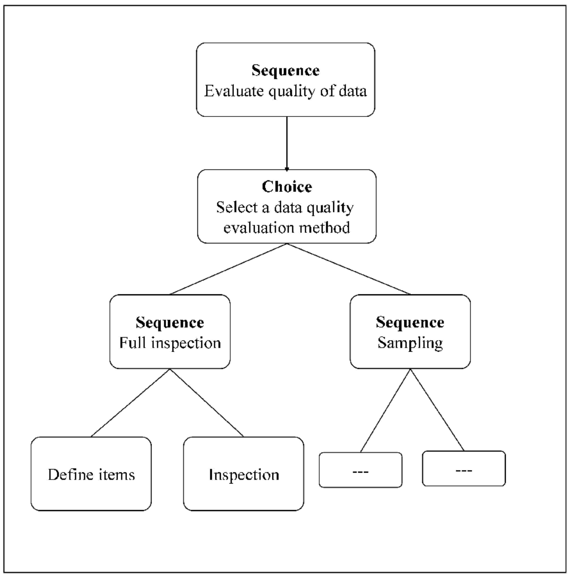

Figure 4. A partial control flow of the spatial data quality evaluation. Quality evaluation is a sequence of process steps and can be accomplished either by full inspection or sampling. Furthermore, full inspection is a sequence of two activities that have to be executed in a given order.

When integrating the structural, functional, and behavioural process aspects it is essential to recognize the executable activities and the needed process precision. We follow precisely the procedures specified in ISO 19114 (ISO, 2003), but do decompose the processes into more elementary ones if seen necessary (Table 5).

Process activity in ISO 19114	Process activities in our model
Identify an applicable data quality element, sub-element and data quality scope	Identify quality variables
	Select the quality variables to be evaluated
	Identify data quality element and sub-element for each variable
	Identify data quality scope for each variable

Table 5. An example of the process decomposition.

4. CONCLUSIONS AND FURTHER RESEARCH

Standards on spatial data quality and quality evaluation can be difficult to implement in practice. Thus, the benefits that they could bring to customers and producers are not always obtained. Furthermore, the quality evaluation must be done in a consistent and standardized manner in order to determine whether the achieved quality level meets the requirements, and also to be able to compare the quality results between different geographic resources. This paper presented an ontological framework to enhance the comprehension and implementation of the quality standards for geographic information. The use of OWL-S allows us to combine workflow models from the functional and behavioral perspectives with an ontology defining the informational entities and organizational agents from the area of spatial data quality and quality evaluation process.

The domain ontology of spatial data quality and quality evaluation process is useful in many ways: 1) it makes the understanding of the evaluation process easier for the different process participants and verifies that the evaluation is done in a consistent and standardized manner; 2) it is clear that the process modeling presents significant challenges throughout organizations. The domain ontology enables to obtain a standard representation of the processes, and it is also shareable and reusable; 3) using URIs can facilitate the comparison of quality between the different geographic resources.

The research will continue with the completion of the domain ontology, and the implementation of a prototype service. Also, more research needs to be targeted to the behavioral aspects of the quality evaluation process and data production process itself, i.e., how to integrate the supporting process with the operative process.

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