On Data Reliability Assessment in Accounting Information Systems

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The need to ensure reliability of data in information systems has long been recognized. However, recent accounting scandals and the subsequent requirements enacted in the Sarbanes-Oxley Act have made data reliability assessment of critical importance to organizations, particularly for accounting data. Using the accounting functions of management information systems as a context, this paper develops an interdisciplinary approach to data reliability assessment. Our work builds on the literature in accounting and auditing, where reliability assessment has been a topic of study for a number of years. While formal probabilistic approaches have been developed in this literature, they are rarely used in practice. The research reported in this paper attempts to strike a balance between the informal, heuristic-based approaches used by auditors and formal, probabilistic reliability assessment methods. We develop a formal, process-oriented ontology of an accounting information system that defines its components and semantic constraints. We use the ontology to specify data reliability assessment requirements and develop mathematical-model-based decision support methods to implement these requirements. We provide preliminary empirical evidence that the use of our approach improves the efficiency and effectiveness of reliability assessments. Finally, given the recent trend toward specifying information systems using executable business process models (e.g., business process execution language), we discuss opportunities for integrating our process-oriented data reliability assessment approach—developed in the accounting context—in other IS application contexts.

Key words: workflow and process management; accounting information systems; mathematical modeling; internal control

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1. Introduction

The reliability of data produced by organizational information systems used to plan, diagnose, and control business operations has long been considered important. Despite extensive study of this problem in the context of accounting information systems, few rigorous yet practical tools have emerged in the literature (Felix and Niles 1988, Waller 1993). The present guidance consists mainly of frameworks that do not provide rigorous, systematic ways to assess data reliability. These frameworks provide checklists of issues that affect data reliability but do not provide formal definitions of the key concepts in the frameworks nor decision rules or algorithms to insure that the reliability assessment is both efficient and effective1 (cf. Committee of Sponsoring Organizations of the Treadway Commission (COSO) 1994, Information Systems Audit and Control Foundation (COBIT) 2000). The lack of formal concept definitions and decision rules makes it difficult to develop practical data reliability assessment systems.

However, the relevance of data reliability assessment—particularly in the context of accounting

1 We provide specific definitions for “efficient” and “effective” in §2.2.2.

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information systems—has increased considerably with the recent passage by the U.S. Congress of the Sarbanes-Oxley (SOX) Act (H.R. 3763—Sarbanes-Oxley, Title IV, §404 2002; Securities and Exchange Commission 2003). The act requires a firm’s CEO and CFO to certify the reliability of the data reported in the financial statements as well as the reliability and documentation of the information system that produced those data. These mandates may well be overdue because reports of significant reliability problems in current accounting information systems have begun to appear in practitioner outlets. For example, CFO magazine states “Experts estimate that anywhere from 10 percent to 30 percent of the data flowing through corporate systems is bad…” (Goff 2003, pp. 97–98). In addition, recent surveys indicate that improving the reliability of a firm’s AIS to meet SOX requirements will require significant effort. For example, Business Week (2003) reports that a recent survey found SOX will “…prompt 85% of America’s largest 100 companies to overhaul many components of their financial-reporting systems.”

In this paper, we develop a formal approach to data reliability assessment motivated by a field study of a major international accounting firm. The field study focused on data reliability assessment of accounting functions of management information systems. “Accounting functions” are all information-capturing and processing activities that lead to the maintenance of general ledger account balances in a management information system (MIS), regardless of whether those functions are embedded in an integrated MIS or in a freestanding accounting information system (AIS). General ledger account balances are the core financial data used by organizations to make managerial decisions and to report the financial status of an organization to external stakeholders (Hollander et al. 2000). The field study identified important decision support requirements and a data reliability assessment task (key control selection, discussed in detail in §2) considered to be important to auditors—the professionals tasked with conducting data reliability assessments of organizational information systems. The approach we have developed consists of (a) an ontological metamodel that permits the representation of key concepts needed to assess data reliability, and (b) a set of algorithms that can process instances of the ontological model to support decision making by auditors. We provide preliminary evidence that the use of this approach improves the effectiveness of auditors engaged in data reliability assessment.

The rest of the paper is organized as follows. Section 2 defines the key-control-selection problem and describes how it fits into the process of evaluating AIS data reliability using an illustrative example of a portion of an AIS. Section 2 also reviews relevant prior work on reliability assessment, including work in the accounting and auditing literature, the software literature, the data quality literature, and the literature on CASE tools and emerging work on declarative, yet executable, business process models. Section 3 presents our process-oriented ontological metamodel of basic concepts and relationships that describe an AIS as a directed, attributed, acyclic graph. Using this ontology, §4 formulates key control selection as a set-covering problem and presents two procedures required to compute the parameters of the model from instances of the ontological model. Section 5 presents preliminary results comparing our AIS data reliability assessment approach with that of experienced auditors. Finally, §6 discusses how the general approach we develop for AISs is more broadly applicable to other IS applications.

2. The Key-Control-Selection Problem

2.1. Description of the Field Study

We conducted a field study in a large international accounting firm to understand their data reliability assessment practices. The field study consisted of extensive interviews with seven audit managers in three different offices of the audit firm. The firm’s director of audit research selected the managers to interview based on their extensive knowledge and experience with AIS reliability assessment. All interviews with the audit managers were recorded and transcribed for further analysis. The purpose of the interviews, and the analysis of their content, was to identify the process auditors used to evaluate data reliability in an AIS. The analysis identified an important task—key control selection—within that process

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2 For simplicity, we refer to these accounting functions as an AIS for the balance of this paper.
that the auditors identified as a step that required computer-based decision support. We reviewed the results of our analysis of the transcripts with the firm’s director of audit research to confirm our findings. In addition, we conducted a review of the professional literature to confirm the importance of the key-control-selection task, the recommended procedures for key control selection, and the definition of the concepts required to select key controls. A description of the key-control-selection task and how it relates to AIS data reliability assessment is presented in the next section.

2.2. Introduction to AIS Reliability Assessment and Key Control Selection

2.2.1. AIS Reliability Assessment. An AIS is a transaction-oriented information system, and errors arise in the context of these transactions. Auditors who assess AIS reliability rely on four important concepts: (a) assertions, (b) error classes, (c) information transformation processes (ITPs), and (d) control procedures (AICPA 1999). Each of these are discussed in turn.

Assertions and error classes are closely related. An assertion is a statement about the absence of a particular class of error in the general ledger account data. Auditors begin by determining the assertions they would like the data in the general ledger accounts to support. Five classes of errors, namely completeness, existence, valuation, rights and obligations, and presentation and disclosure (AICPA 1990, 1999), are considered. Completeness errors occur when a valid transaction that should be in the system is missing (i.e., it is either not recorded or has been deleted incorrectly). Existence errors occur when an invalid transaction is added to the system. Valuation errors occur when the data in the system does not accurately reflect the economic results of the transaction that created the data. These three error classes are mutually exclusive, and exhaustive in terms of errors that affect the accuracy of the data in the AIS. Auditors also consider rights and obligations, and presentation and disclosure errors, but these errors are relevant to the production of external financial statements from the AIS’ database and not the accuracy of the AIS database, per se. Therefore, we do not consider them in our research. Professional standards do not specify a tolerable error from these sources, but leave this determination to the auditor (AICPA 1990). The set of error classes determined by an auditor to be relevant to a reliability assessment study are referred to as target error classes.

The three error classes we consider capture two key elements of data reliability that have been regularly used in IS data quality research: completeness and accuracy (Ballou and Pazer 1985; Redman 2001, ch. 14; Wang et al. 1995). Based on our fieldwork and review of the literature, we find that “accuracy” is a combination of “existence” and “valuation.” That is, the concept of accuracy includes both the exclusion of invalid transactions in the AIS as well as the accurate valuation of valid transactions. Because different activities may lead to completeness, existence, or valuation errors, the auditors’ practice of decomposing accuracy into existence and valuation errors, as well as considering completeness, contributes to a more complete assessment of AIS reliability.

Information transformation points (ITP) are points in the AIS where these different classes of errors can be introduced. ITPs are arranged in connected structures, such that information flows from one ITP to another. This structure begins at the boundary of the organization when the AIS first captures data about a transaction. This data then flows through a series of ITPs until it reaches the general ledger account, which, for our purposes, is the terminal point of the AIS. These intervening ITPs alter the data in a variety of ways and, therefore, are capable of introducing errors.

Controls are procedures designed to prevent or detect one or more of these errors. The internal control structure of an AIS specifies the set of control procedures included in the AIS; their capacity for error prevention/detection; and the information flows from which each control can prevent/detect errors. The reliability of an AIS is evaluated with respect to the absence of error classes in the general ledger accounts.

Given an AIS and its internal control structure, the auditor assesses the risk that one or more of the target error classes will be present in one or more general

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3 This section, as well as §§3, 4, and 5, contains a variety of technical terms. We provide a glossary of these terms in an appendix to this paper.
ledger accounts (GLAs). In other words, the auditor has to determine if the error elimination capabilities of the controls are adequate to prevent errors from reaching the general ledger accounts (GLAs). Key controls are the subset of controls in the AIS that provide the auditor with the desired assurance about the absence of these error classes in the GLA.

This framing of the data reliability assessment problem focuses on the evaluation of an AIS and its existing internal control structure with respect to a target set of assertions/error classes. Our field study confirmed that this was the framing of the data reliability assessment problem employed by the auditors. The set of controls in the system is taken as given and treated as exogenous to the data reliability assessment problem. We discuss in §6 opportunities for further research into the related problem of how to design the set of controls in an AIS to meet specified data reliability objectives.

2.2.2. Key Control Selection. The auditor needs to develop a plan to test a set of controls in the AIS to ensure that the general ledger accounts are free of the types of error in the target assertions. An AIS normally contains redundant or overlapping controls, and so the auditor need not test all the controls to determine if the AIS is reliable (i.e., his/her target assertions are being met). The subset of the set of controls selected for testing are referred to as key controls. Testing controls is costly. For example, auditors use techniques such as reprocessing a sample set of transactions to verify that the population of transactions has been executed accurately. Therefore, the auditor would prefer to select the smallest set of key controls to test that will provide the required assurance that they are functioning as designed. An effective set of key controls ensures that the selected controls have the capacity to eliminate target error classes (TECs) in the GLAs. An efficient set of key controls includes the fewest (or cheapest to test) set of controls, while still being effective. Auditors find the development of effective and efficient key control sets to be difficult. In §5, we present preliminary evidence to demonstrate how even experienced (e.g., an average of 57 months of audit experience) auditors do poorly when asked to construct effective and efficient testing plans. They choose either too many controls or too few controls, leading to problems with data reliability assessments. Thus, the fundamental importance of selecting key controls for data reliability assessment led to our focus on key control selection in this paper.

2.3. Illustrative Example of an AIS
Figure 1 documents the main portion of an organization’s purchasing processes and depicts information transformation processes (ITP), information flows, control procedures, general ledger accounts (GLA), and target error classes (TEC). It is based on a real case developed by the firm that participated in our field study. Developing such documentation is the first step in the data reliability assessment process (Ballou and Pazer 1985). There are a variety of notations available for documenting the components of an AIS. We have used notation loosely based on business process modeling notation (BPMN) (see BPMN.org) that permits the representation of the key concepts underlying our approach in a direct manner. We leave the question of developing robust extensions of the BPMN notation suited to the needs of data reliability assessment to future work. The formal semantics associated with this notation is presented in §3.

The notation describes the AIS in terms of economic events, information transformation processes, controls, accounts, and error classes. We discuss the example starting at the left of Figure 1. At the left are economic events that create the information flow that triggers the different ITPs shown in the figure (i.e., when merchandise is requested by a unit within the firm, when merchandise is received from a vendor, or when an invoice is received from a vendor). The three documents—purchase order, receiving report, and invoice—are merged to produce a payment voucher that is used to support a cash payment to the vendor, resulting in entries to the cash, accounts payable, inventory, and expense general ledger accounts. The rounded rectangles of Figure 1 are ITPs. Examples are processes labeled “Purchase order” and “Check register.” These are points at which errors can be introduced. For example, completeness, existence, and valuation errors can be introduced by the “Purchase order” ITP. The rectangles are
controls and are associated with ITPs, as indicated by the assurance arrows. For example, the "Account for PO numbers" control eliminates completeness errors on flow $f^4$.

Most controls function by comparing information flowing out of an ITP with information flowing into that ITP. Preventative controls function by screening information flowing into an ITP and, thus, prevent the information flowing out of the ITP from containing errors. Irrespective of the type of the control, the objective of the control is to eliminate errors from the information flowing from an ITP.

The set of errors the control is able to eliminate is referred to as its coverage capability. For example, the "Compare batch totals" control in Figure 1 can prevent completeness, existence, and valuation errors. The information flows on which the control can eliminate errors are referred to as the span of a control. For example, "Compare batch totals" compares information from the "Disbursement" ITP with information from the "Check register" and "Voucher register" ITPs to assure that completeness, valuation, and existence errors are absent in all the flows out of "Disbursement," "Check register," and "Voucher register" transformation points.

As noted above, reliability assessment begins with the auditor using his judgment to establish a set of target error classes (TECs) or assertions in the general ledger account (GLA). The circular nodes in Figure 1 represent the GLAs, and the TECs for each GLA are shown in italics. The set of GLAs and their associated TECs describe the goal of the reliability assessment process. In the example, the auditor has set completeness, existence, and valuation as target error classes for the cash account, while only testing completeness and valuation for the accounts payable account. Auditors use their judgment to select target error classes. For example, in Figure 1 the auditor has elected not to consider existence violations for accounts payable and expenses due to the low probability that the system would record expenses or liabilities if they did not exist.
Given the documentation of the AIS and its internal control structure as depicted in Figure 1, the auditor has to construct effective and efficient control-testing plans. This raises four important research questions:

- **Question 1:** What should be the formal representation of the AIS for purposes of data reliability assessment? We develop a formal approach to support AIS data reliability assessment that permits algorithmic processing but is intuitive enough that auditors could apply it in practice. The foundation of the approach is a semantically precise notation required to model an AIS. While many diagramming notations have been developed by firms for internal use by trained auditors, they do not have formal semantics and therefore do not lend themselves to computer-based decision support. We develop an ontological metamodel of an AIS suited to the needs of data reliability assessment.

Given the characteristics of the problem described above, there are supporting research questions that need to be answered to build a formal approach:

- **Question 2:** Given the internal control structure, on which information flows can a given control prevent or detect errors? That is, what is a control’s span? The span of the control depends on the structure of information flows in the AIS and the set of ITPs from which the control has access to information. Computing the span of the control given the documentation of the AIS is difficult for auditors. We present our approach to this problem in §4.3.

- **Question 3:** Given the TECs associated with each GLA, what TECs should be eliminated from each flow that contributes, either directly or indirectly, to the GLA? This is important because controls are designed to provide assurances for flows coming from each ITP, and different ITPs may generate different sets of error classes. If the correct set of errors is eliminated at each flow, this will ensure that TECs will not be present in the GLAs. We detail our approach to this problem in §4.2.

- **Question 4:** Given the TECs for each ITP and the span of the controls, how should an effective and efficient set of key controls be selected? Even experienced auditors do poorly at constructing effective and efficient key control sets as we discovered during our fieldwork and our preliminary evaluation study reported in §5. We discuss our approach to this problem in §4.1.

### 2.4. Prior Work and Related Literature

#### 2.4.1. Auditing Literature

The most directly related literature is the work on auditing in the accounting literature. While the auditing literature has not studied the key-control-selection problem, it contains work on probabilistic and deterministic models for AIS reliability assessment and decision support. Probabilistic modeling research has focused on finding ways to combine the necessary probability estimates to provide an overall, quantitative assessment of AIS reliability (e.g., Ahituv et al. 1985; Ballou and Pazer 1985; Bodnar 1975; Cooley and Cooley 1982; Hamlen 1980; Haskins and Nanni 1987; Knechel 1983, 1985; Lea et al. 1992). Probabilistic research in AIS evaluation has had little, if any, influence on practice because the models tend to make too many simplifying assumptions to achieve tractability (Felix and Niles 1988).

Research on deterministic models for AIS reliability assessment has focused more on decision support by modeling the evaluator’s cognitive process and building expert systems (e.g., Kelly 1985, Meservy et al. 1986). However, because the approach is not based on formal methods, it cannot guarantee the completeness or accuracy of the resulting evaluation. One deterministic approach that evolved into an applied system was the TICOM project (Bailey et al. 1985). Price-waterhouseCoopers built on the modeling approach developed in the TICOM project to implement a decision support system, called COMET, to help auditors evaluate AIS systems reliability (Nado et al. 1996). However, COMET does not help auditors link weaknesses in AIS reliability directly to TECs and, therefore, provides little support to assist AIS designers in reengineering the internal control structure of the AIS to eliminate future errors.

Our work strikes a balance between the informal heuristic methods used by practitioners and extant formal decision support approaches. We extend the state of the art by developing a formal graph-based notation suited to the needs of reliability assessment. The notation has syntactic similarities to the informal notation used by auditors (cf. Grant Thornton 1996), has formal semantics, and can be processed algorithmically (using a mathematical modeling framework) to provide decision support in the creation of both effective and efficient testing plans.
2.4.2. IS Data Quality Literature. Complementing the work in the accounting literature is the work on data quality (Kaplan et al. 1998, Pierce 2004, Pipino et al. 2002, Wang et al. 1995). This literature draws on the analogy between physical manufacturing processes and information manufacturing and argues that data quality should be concerned about accuracy, timeliness, consistency, and accessibility (Wang et al. 1995). In the AIS context, we decomposed “accuracy” into “existence” and “valuation” to match how practitioners view data reliability. The data quality research offers a starting point towards defining error classes for other IS applications that are analogous to the error classes used to assess data reliability in AIS.

Distinctions are made in this literature between quality problems that arise because of flaws in IS design versus quality problems that arise due to operational flaws. Recent work by Pierce (2004) relates this perspective on data as an information product to ideas from auditing by defining a structure called a control matrix. However, in contrast to our work, Pierce (2004) neither models the information flows in the information system and the location of controls, nor provides a method for reasoning with the control matrices to arrive at overall measures of data quality. In addition, many papers in this literature assume that the systems represent worlds with high rates of change (e.g., stock market data) and offer prescriptions (Orr 1998) with an emphasis on timeliness and accessibility. While the emphasis is different in our application context, the core ideas underlying our work rely on an abstraction—consisting of controls and error classes—of an information system that has applicability in contexts other than AIS (Pierce 2004).

2.4.3. Business Process Modeling and CASE Tools. Because reliability assessment works with a model of information flows and information transformation processes, process-modeling methodologies and related systems analysis and design tools are relevant to our work. In general, the literature on these topics focuses on supporting analysis and design. As noted in §2.2, data reliability assessment of AIS presently focuses on the evaluation of the internal control structure of an AIS rather than on its design. However, modeling representations developed in process modeling and CASE literatures are relevant to our work because documenting the AIS and its internal control structure is essentially an exercise in representation. We briefly discuss the unified modeling language (UML) and business process modeling notation (BPMN) and the reasons why we have not used these approaches in our work.

UML (see www.uml.org) is an industry standard for software design. It provides a number of diagrams (e.g., state transition diagram, activity diagram) for visualizing and documenting the artifacts that make up a software system. Tools are available to help designers create these diagrams. While the advantage of using UML as a starting point in our work is the ability to have an impact on reliability assessment and reliability design in domains other than AIS, there are significant differences in both the conceptualization and the semantics underlying our approach and that of UML. Specifically, UML does not support a process-centric view of the world that is central to our conceptualization. Further, UML diagramming notations lack a formal semantics (Mcumber and Cheng 2001). Even the recently released UML 2.0 specifications from the Object Management Group (OMG) offer only a natural language semantics for UML diagramming notation, and developing a formal semantics is still an active area of research.

In contrast to UML, the recent initiatives in the area of business process modeling and management share the process-centric view underlying our work. Examples include the work on creating declarative, yet executable, models of business processes such as business process execution language (BPEL) and the business process modeling language/notation (BPML/BPMN) (see BPML.org 2003). The advantage of using a broadly adopted and popular notation is the opportunity to integrate our reliability assessment approach in tools created to support business process modeling and execution. However, extensions to BPMN notation and semantics are required to adapt it for use in data reliability assessment.

Because BPMN does not provide specific object types to represent fundamental data reliability concepts such as ITPs, controls, and their attributes, we need specialized notational extensions to BPMN that:

- Distinguish Between ITPs and Controls—Both could be represented as BPMN atomic tasks, however, BPMN cannot capture semantic differences between these objects (e.g., the fact that ITPs generate errors and controls eliminate them).
• Distinguish Between Message Flows from ITPs to Controls and from Controls to ITPs—As with ITPs and controls, the different types of information flows in an AIS have different semantics. However, information flows are represented as message flows in BPMN, and message flows do not have the expressive power to distinguish between the different types of information flows in an AIS (e.g., information flows from controls to ITPs provide assurance, while flow between ITPs may contain errors). In addition, the BPMN syntax only allows messages to link to tasks and not to other information flows, as our assurance flows do.

• Specify Error Classes for ITPs and Controls—The only structure in BPMN that allows tagging of ITPs and controls with error classes is text annotation, which is not executable and lacks formal semantics.

While these notational extensions are relatively easy to make, there is a fundamental difference between the semantics underlying BPMN and the semantics required for data reliability assessment. BPMN semantics are based on a variant of the pi calculus (Milner 1992) and are designed to represent and reason about distributed processes. This is in contrast to the semantics required to reason about the structure of information flows and the error prevention capabilities of internal controls. Because of the basic nature of these changes, we defer further discussion of notational issues to future research and discuss this topic briefly in §6.

3. An Ontological Metamodel of an AIS

The key-control-selection problem assumes a certain conceptualization of the AIS (e.g., in terms of accounts, flows, controls, error classes, and their relationships). Both auditors and systems designers use graph-based structural models of AIS (such as in Figure 1) that are an informal realization of this conceptualization to support both design and testing. As discussed in §2.3, question Q1 is concerned with the formalization of the graphical model required to support the computer-based specification of AIS by auditors as part of a data reliability study. Importantly, such formalization should be open to analysis by inferential procedures. For example, these procedures are required to derive the span of a control, a parameter of the model used to determine effective and efficient key control sets. Formalized models of the structure of a system are referred to as ontological metamodels (Gruber 1991, Noy and Hafner 2000, Wand and Weber 1990) in the literature.

An AIS can be conceptualized at two levels of granularity at least: an action level and a process level. Action-level ontologies (e.g., Hamscher 1992) and the TICOM model (Bailey et al. 1985) are fine grained and describe an AIS in terms of actions, like waiting for a document, and objects on which they operate, such as repositories of files where documents are kept. Other ontologies of AIS have focused on the artifacts developed within the system, but not on the processes that produce them (Wand and Weber 1990). Action-level ontologies are well suited to simulate processing and document flow through an AIS. However, they are too fine grained for the purposes of data reliability assessment. In contrast, a process-level ontology is coarse grained and specifies an AIS in terms of ITPs and information flows. ITPs are at a higher level of abstraction than actions and can be thought of as collections of actions that are used to capture or transform information. This level of abstraction is well suited to the needs of data reliability assessment because the objective is to not to simulate actions, but to identify key controls.

We therefore develop a process-level ontological metamodel using data gathered from field interviews with practicing auditors and a detailed review of the existing literature (e.g., Arens and Loebbecke 1997, Grant Thornton 1996). The model uses set theoretic notation and provides a language to state the key components of an AIS and their interrelationships in a precise manner. We provide a brief overview of the ontology using set-theoretic notation developed in the model management literature (Bhargava and Kimbrough 1993).

3.1. Definition of AIS Components

The metamodel of an AIS consists of the following major components and their interrelationships.

Economic Event (EE)—Event that generates the initial need for the AIS to capture information.

General Ledger Accounts (GLA)—Maintain total of financial activity (i.e., the output of the AIS from which the financial statements are produced).
Information Transformation Process (ITP)—Processes that transform information from one form to another. ITPs can introduce errors. These processes also are where control procedures designed to eliminate errors introduced by processes are located.

Control Procedures (CONTROL)—Procedures designed to eliminate specific error classes. A control is associated with one or more ITPs in that it has access to information present in the flows emanating from them. Controls have the capacity to eliminate error classes that are introduced by ITPs.

Information Flows (FLOW)—Abstractions of information that flow through the AIS, i.e., the output of ITPs.

Target Error Classes (TEC)—Error classes the evaluator wants to determine are not present in an account. ECs are associated with accounts and ITPs as well as with controls. In the case of accounts, their association implies the need to check an account for the presence of the given error class. In the case of ITPs, the association is used to identify the classes of errors the ITP can generate. In the case of a control, the association is used to assert the capability of the control to eliminate the EC.

3.2. Formal Specification of Relationships Between AIS Components

An AIS is conceptualized as a directed, acyclic, attributed graph (see Figure 2). The nodes of the graph are GLAs, EEs, ITPs, and controls. The arcs are the FLOWs. TECs are attributes of GLAs. These objects are modeled as sets, and each set is required to be nonempty. In our description of the ontological meta-model, we use special fonts as follows: sets, functions, relations, and VARIABLES. Additionally, we refer to the power set of a set using square brackets (e.g., [EC] is the power set of EC). Each node and arc in the notation is required to be an object in this conceptualization.

Each AIS component also has both an ID and a description attribute. The ID is a unique identifier.

The description allows an auditor to make any special notes about each component. Each node and arc has an identifier and a description (see Figure 3).

Next, we specify the FLOWs in the AIS (see Figure 4). Each FLOW has an origin and a destination where information flows from the origin to the destination. Origin and destination are modeled as functions. Their domain and range for each class of flow is declared in Figure 4. Because the output of an ITP is a flow and because ITPs contain processes that can create errors, we can only draw conclusions about the degree to which FLOWs whose origins are ITPs are free of errors. We refer to these FLOWs as Checkable_Flows. We distinguish between two classes of checkable flows, Middle_Flows and End_Flows. End_Flows are FLOWs whose destination is a GLA, the output of the AIS. Middle_Flows are FLOWs between ITPs. In contrast, Beginning_Flows are those whose origin is an economic event and represent information-capturing activity at the boundary of the organization where the auditor does not have the ability to assess data reliability. That is, the auditor cannot verify the accuracy of the information con-
“Compare batch totals” can eliminate completeness, existence, and valuation errors. A control has access to information from the flows that emanate from at least one ITP in an AIS. We model this as a relation located-at that relates a control to the ITPs from which it can obtain information (see Figure 7). This relation is not explicitly represented in Figure 1. The control “Compare batch totals” is located at the “Check register” and “Voucher register” ITPs. In addition, a control may have access to other ITPs that are upstream of the ITPs at which it is located. For example, the control “Compare batch totals” has access to information from the “Disbursement” ITP as well, as indicated by its span (defined below). Given the set of ITPs from which the control has access to information, an evaluator needs to determine the set of flows—referred to as the span of a control—on which the control can eliminate errors. This requires an analysis of the structure of information flows in the AIS and is a difficult and error-prone step for human auditors (cf. Q2 in §2.3). However, span is an important parameter of the key-control-selection model, and §4.3 presents an algorithm that uses the ontological model discussed in this section to compute the span of each control in the AIS.

The set of objects and the relations presented define the structure and the semantic constraints on the AIS. The expressiveness of these constructs was validated using the set of real-world cases made available by the firm that participated in the field study (see §5). This specification can be implemented using a logic programming language such as Prolog or implemented using a database with the constraints stated using an imperative language such as C (the option we chose in our implementation). Irrespective of the option chosen, the ontological metamodel provides both a language and formal semantics for representing and reasoning about the information flows and structure of an AIS. We are not aware of other
ontological models that have been developed for the purpose of AIS reliability assessment and, therefore, there may be other ways to structure an ontological metamodel to support AIS reliability assessment. Thus, as the first metamodel for this task presented in the literature, we focus on demonstrating that it will achieve the goals we have set for it. We now present the mathematical model and associated algorithms used for reliability assessment and discuss its relationship to the ontological model.

4. Mathematical Model Development

The Key-Control-Selection Problem: Given an instance of the metamodel of an AIS (as defined in the previous section) and a set of target error classes, determine the smallest set of controls that will need to be tested to assess the absence or presence of the target error classes in the accounts of the AIS.

As noted in the previous section, a control is designed to eliminate a specific set of error classes in the set of flows in its span. Referring to the graphical model of the AIS (Figure 1), if the accounts in the AIS are to be free of the target error classes, this requires that each flow that directly or indirectly contributes to the information in the accounts should also be free of these errors. Auditors can establish if this is the case by testing a set of controls whose coverage capability on the flows in their span is a superset of the target error classes on these flows. We formulate this as a set-covering problem (Cormen et al. 1992) under the following assumptions. These assumptions were derived from our field interviews with experienced auditors and from their firm’s technical guidance (Grant Thornton 1996) and were not adopted simply to make our model more tractable. Auditing research also finds that auditors use simple deterministic models to assess AIS reliability (Felix and Niles 1988, Waller 1993), rather than probabilistic models.

**Assumption 1.** Controls are designed to operate deterministically. For each error class in its coverage set, a control is designed to eliminate the error with probability 1.

**Assumption 2.** The capability of a control to eliminate an error is independent of the capability of any other control.

**Assumption 3.** The cost of testing a control is fixed and is the same for every control.

**Assumption 4.** All ITPs generate all possible error classes.

Although the assumptions on which the model is based may seem to be simplistic and restrictive, the most restrictive assumptions offset each other because they have the opposite impact on reliability. Assumption 4 (i.e., that all ITPs generate all error classes) offsets Assumption 1 (i.e., that controls eliminate errors with probability 1). Further, the preliminary evaluation we conducted (described in §5) supports the validity of our approach. The mathematical formulation of the key-control-selection problem is shown below in Figure 8.

The objective function of the model minimizes the number of key controls selected for testing and follows directly from Assumption 3. However, it is quite straightforward to take differences in control testing costs into account by modifying the objective function into a weighted, additive cost function. The constraint set insures that at least one control that can cover each target error class on each flow will be chosen. The constraint set follows from Assumptions 1, 2, and 4.

The inputs required to use the model for key control selection are the set of information flows (F), the error classes on these flows that need to be detected or prevented (E(f)), the set of available controls (C), and their span (D_{c,f}). These inputs are derived (as noted in Figure 8) from an instance of the ontological model developed by the auditor as a first step in the data reliability assessment process. In other words, no additional effort is invested by the auditor to use

![Figure 8 The Set-Covering Model Formulation](image-url)
the model. The output is the set of key controls. Two metrics used to evaluate the quality of a set of key controls are effectiveness and efficiency, respectively. A key control set is effective if each of the required information flow/error class combinations is covered by at least one key control. The smallest effective key control set is efficient. Any feasible solution to the model in Figure 8 is effective and the optimal solution is efficient. This follows directly from an inspection of the structure of the set-covering model (Cormen et al. 1992). If the set of available controls is insufficient to meet the target reliability goals set by the auditor, the constraints will not be satisfied, thereby resulting in the model not having a feasible solution. In this case, an auditor could use judgment to modify the set of available controls and use the model to design a feasible internal control structure. We remark on this issue and the problem of optimally designing a control structure to meet desired data reliability objectives in §6.

Because the set-covering model is NP-hard (Cormen et al. 1992), large instances of the model are intractable. We have developed heuristic methods to both select key control sets—what we refer to as key control recommendation—as well to evaluate auditor-proposed key control sets—what we refer to as key control evaluation. Because of space constraints and because the procedures are variants of well-understood heuristics for the set-covering problem (Feo and Resende 1989, Cormen et al. 1992, Fisher 1990), we do not discuss these procedures in detail. Before we proceed to the next section, we reiterate that the model and the associated procedures can be used in two modes. In the recommendation mode, the model would recommend to auditors the set of key controls to test. The decision support offered in this context is primarily sensitivity analysis where the auditor may make changes to the AIS model and rerun the recommendation algorithm. Alternatively, the model could be used to evaluate the effectiveness of, and to suggest improvements to, auditor-generated key control sets. Computationally, evaluation is fast because it only checks to see if the constraints of the mathematical model are satisfied. If the constraints are not satisfied given a set of controls (as discussed in the previous paragraph), the auditor can be guided in the selection of controls to add to regain feasibility. Recent work by Chinneck (2001) discusses tools for automating infeasibility analysis. Through these features, the system supports the decision-making capabilities of auditors. We next discuss methods used to compute the parameters of the model.

4.1. Computing Mathematical Model Parameters from the Ontological Model

Of the four inputs required to use the model, \( E(f) \) and \( D_{\text{ef}} \) are not directly specified in the ontological model of the AIS. For example, in Figure 1, target error classes are associated with GLAs. However, \( E(f) \) is the set of target error classes that need to be eliminated in every information flow that can have an effect on the account.

4.2. Computing Target Error Class Propagation—\( E(f) \)

Because errors are introduced into the GLAs by ITPs, the information flowing out of every ITP flows directly or indirectly into a GLA and needs to be tested for TECs. For example, the information flow \( f7 \) created by process “Voucher package” in Figure 1 can affect all four GLAs. Therefore, to ensure data reliability, information flowing from it must not contain TECs associated with all these GLAs (i.e., \( E(f7) = \{C, E, V\} \)). Because each ITP may produce information flows that affect the balances of numerous GLAs in a real AIS, the determination of the error classes that need to be tested for in each flow can be tedious and error prone. Exploiting the graphical structure of the AIS, we formulate a procedure (referred to as propagate) that conducts a depth-first search of the graphical representation specified in the instance of the ontological model. Given a table consisting of the set of GLAs and their target error classes and the set of checkable flows, propagate returns a table of error classes that need to be tested for each checkable flow in the AIS. The sample input and output of the propagate function used to compute \( E(f) \) for the flows in Figure 1 are shown below (Figure 9).

4.3. Computing the Span of a Control—\( D_{\text{ef}} \)

The span of a control defines the set of flows for which a control can prevent or detect its error classes. By definition, a control needs to have access to all the information that flows into an ITP for it to be
able to eliminate errors in the flows emanating from the ITP. Consider the case of the “Compare batch totals” control. It has the capability to eliminate completeness, existence, and valuation errors—however, on which flows? It is located at the “Check register” and “Voucher register” ITPs, and the documentation of the AIS asserts that it spans to the “Disbursement” ITP. Here the term spans is interpreted to mean that the control has access to information in flow f7 that flows into the Disbursement ITP, which in turn implies that the control is able to eliminate errors in flows f9 and f10, as shown using the dotted arrows linked to this control in Figure 1. Because the control has access to all the information (flow f9) flowing into the “Check register” ITP, it is able to eliminate errors in flows f11 and f12 that emanate from the “Check register” ITP. However, it does not have access to all the information flowing into the “Voucher register” ITP. It has access to flow f10, but does not have access to flow f8, which is one of the outputs of the “Voucher package” ITP to which this control does not span. Therefore, the “Compare batch totals” control cannot provide assurance about the absence of the error classes on flows f13, f14, and f15 that emanate from the “Voucher register” ITP. Through this sort of reasoning about the structure of flows in the AIS, an auditor can determine that the span of the “Compare batch totals” is the set of flows {f9, f10, f11, and f12}. In this section, we exploit the fact that the AIS is represented as a directed, acyclic graph to formulate an algorithm to compute the span of a control, thereby enabling the parameter $\mathcal{D}_{ct}^{ef}$ to be computed from the instance of the ontological metamodel.

The informal reasoning illustrated in the example demonstrated the need to reason with flows in the AIS. We generalize this intuition by first considering paths in the AIS. A path is a sequence of information flows leading from an economic event (EE) or ITP through one or more ITPs to a GLA or ITP. In the above example, consider the candidate set of information flows for which the “Compare batch totals” control can provide assurance. Because it is located at the ITPs “Check register” and the “Voucher register,” the flows {f11, f12, f13, f14, f15} that flow out of these ITPs are candidates for inclusion in the span of the control. Because the control spans to “Disbursement” (i.e., has access to information flowing into this ITP), flows {f9, f10} are added to the set of candidate flows. Now consider paths from the ITP “Voucher package” to a GLA such as “Inventory.” Why choose “Voucher package?” We do so because it is the highest ITP upstream of ITP “Disbursement” to which the control “Compare batch totals” spans, which has a path to the GLAs that share flows with the paths to the GLAs from “Disbursement.” There are two paths from “Voucher package” to “Inventory.” The first, (f7, f10, f14), is a strict superset of the path (f10, f14) from “Disbursements” to “Inventory.” The second path, (f8, f14), shares a flow f14 with the path (f10, f14) from “Disbursement” to “Inventory.” However, the flow f8 is a flow to which the control does not have access. As errors in the flow f8 may propagate through to flow f14, and because the control “Compare batch totals” cannot eliminate these errors, the flow f14 that is shared between these paths cannot be in the span of the control. For the same reason, flows f13 and f15 cannot be included in the span of this control. This leads to the span of this control consisting of flows f9, f10, f11, f12.

Span computation requires reasoning with the structure of the flows and paths in the AIS. The procedure presented below formalizes the intuition and reasoning illustrated in the example.

Procedure: Span-computation.

Input: Declarations in the ontological metamodel instance encoded as a directed, acyclic, attributed graph, and C, the control whose span is to be computed.

Output: The set of flows in the span of the control C.

1. Let G := AIS-graph.
2. Let SG := toposort(G). Topsort is the topological sort (Aho et al. 1983) of a directed, acyclic graph. It orders the nodes in linear sort order. In our setting, the topological sort orders the nodes (the economic events, information transformation points, and GLAs) in a linear order. Using this ordering, the procedure can determine node precedence relationships.
3. Let SpanITP be the ITP that control C participates in a spans-to relation. In Figure 1, “Disbursement” is the only ITP that “Compare batch totals” participates in a spans-to relationship. If the control does not participate in a spans-to relation, let SpanITP be the ITP at which the control is located. In our example, SpanITP is “Disbursements.”

4. Let candITPset := precede(SpanITP, SG). Precede is a function that computes the set of ITP’s that precede SpanITP from the topologically sorted AIS graph SG. In our example, candITPset is [Purchase Order, Receiving Report, Purchase Invoice, Voucher Package].

5. Let SpanANDflows be candidate flows that should be included in the span of a control. SpanANDflows is the union of the set of flows whose origin nodes are either the ITP’s that the control C is located at or the ITP with which it participates in a span-to relationship. In our example, the SpanANDflows is \{f_9, f_{10}, f_{11}, f_{12}, f_{13}, f_{14}, f_{15}\}.

6. Let Deleteset be the set of flows in the SpanANDflows set that should be removed to determine the span. For each element E of the candITP set and each GLA, let path(E, GLA) be the set of paths—sequence of flows—from E to the GLA. In our example, the path from “Voucher package” to “Inventory” consists of two paths (f_7, f_{10}, f_{14}) and (f_8, f_{14}). Eliminate all paths that are strict supersets of paths from SpanITP to the GLAs. In our example, SpanITP is “Disbursements.” The path from Disbursements to Inventory is (f_{10}, f_{14}). Thus, all paths that contain (f_{10}, f_{14}) are eliminated. Of the paths that remain, compute the set of flows that are both elements of the paths from candITP set to the GLA and the SpanITP to the GLA. This is a simple set intersection operation. In our example, the flows are (f_{13}, f_{14}, f_{15}).

7. Return SpanANDflows – Deleteset; In our example, this returns the set \{f_9, f_{10}, f_{11}, f_{12}\} as the flows in the span of the control.

4.4. Application of the Model
To apply our model, the auditor would need to provide four classes of information:

(1) A list of all the components of the AIS to include such as economic events, ITPs, controls, GLAs, and how they are related (i.e., the flows between these items). This is the AIS graph shown in Figure 1 and would be encoded using the notation introduced in the ontological metamodel.

(2) The error classes that each ITP could generate.

(3) The error classes each control could eliminate, the ITP where the control was located, and a list of the ITPs to which the control spans.

(4) A set of TECs for each GLA.

As noted, this information is represented in the instance of the ontological metamodel. Two important parameters, \(E(f)\), and each controls span, \(D_{cc}f\), are computed using the procedures described in §§4.2 and 4.3. Given these parameters, an instance of the set-covering model is created and solved using the heuristic methods briefly discussed in §4.1. Using the model, auditors can select an effective and efficient set of key controls or can evaluate the effectiveness and efficiency of a key control set that is judgmentally derived.

5. Model Validation
5.1. Validation Strategy
The goal of our validation strategy was to demonstrate that our approach produces solutions to the key-control-selection problem that approximate the solutions that would be produced by expert auditors using the firm’s methods (i.e., the “right answer”). A complete test of our premise would lead to a large set of more specific hypotheses that should be tested to validate the model and its underlying approach. As a first step in justifying expending substantial auditor time to test the features of the model and its underlying approach, we developed an exploratory validation study that was designed to provide prima facie evidence that the decision support tool can produce a set of key controls comparable to sets produced by expert auditors. This exploratory study used an existing data set from an experiment where experienced auditors employed by the same firm that participated in our field study selected a set of key controls in three cases developed by expert auditors (Davis 1996). We found that our approach selected a set of key controls in those three cases that were comparable to the sets selected by the expert auditors (experts in the firm who developed the materials used in the study) and was better than the sets selected by the experienced auditors (auditors with an average of 57 months of experience; please see §5.3) in the Davis study.
Because an AIS can contain several controls that, in different combinations, could produce the same potential reliability, possibly at the same cost, merely comparing the specific controls in two key control sets may not reflect the true degree of similarity between those sets. Therefore, our validation study compared the similarity in effectiveness and efficiency between the model’s key control sets and the auditors’ sets in Davis’s study to two types of professional benchmark sets.

All three cases used in Davis’s study were based on training materials developed by expert auditors. Therefore, our first professional benchmark was the solution to each case provided by the case developers (the expert auditors). In addition, because Davis’s participants selected control-testing plans individually, while in practice these plans would be determined by an audit team, we also established a consensus set of key controls (i.e., those controls selected by at least half the auditors in each case) that should more closely represent key control sets that might be produced by audit teams.

5.2. Test Case Representativeness

Davis gave his subjects case materials that closely approximate the information an auditor would need to apply our model. This included

1. a diagram showing the economic events, ITPs, controls, and flows in the portion of the AIS represented by the case;
2. each control’s span and coverage; and
3. a set of target error classes.

Davis then asked his subjects to select key controls sets for each case.

The cases were relatively diverse, were based on firms in different industries, and contained a variety of types of controls and ITPs. Table 1 summarizes the number of ITPs, controls, GLAs, and flows in the cases as well as the types of controls and industries. To demonstrate the variety of controls included in the cases, Table 1 classifies the controls along three dimensions: the type of action performed by the control, whether the control was computerized or manual, and whether the control was preventive or detective.

These cases are a “holdout sample” in that they were not used to develop our model. In addition, the

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Summary of Test Case Control Characteristics</th>
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<tbody>
<tr>
<td></td>
<td>A</td>
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<tr>
<td>Type of firm</td>
<td>Retail</td>
</tr>
<tr>
<td>Size of portion of AIS described in each case</td>
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<tr>
<td>Number of controls</td>
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<td>Number of GLAs</td>
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<tr>
<td>Number of flows</td>
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<tr>
<td>Types of controls included in the cases</td>
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<tr>
<td>Classified by type of action performed</td>
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<td>Access controls</td>
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<td>Analytical procedure</td>
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<td>Approval and signatures</td>
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<td>Edit controls</td>
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<td>Detective</td>
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<tr>
<td>Total</td>
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5 Although Davis (1996) studied both experienced and inexperienced auditors, only the data from Davis’s experienced auditor group were used in the validation analysis.
57 months of experience, performed 47 audits, supervised 22 audits, documented the internal control structure in 24 audits, and made preliminary control risk assessments on 32 audits. These auditors also had 18 hours of firm training with the internal control documentation and evaluation procedures used by the firm and in Davis’s study. There were 5, 9, and 15 subjects in Cases A, B, and C, respectively.

5.4. Analysis Method
The documentation of the AIS in each of these cases was used to obtain the inputs required to create the instance of the mathematical model presented in Figure 8. The key control sets recommended by the model were compared for similarity to the sets developed by the subjects (i.e., the experienced auditors) and the professional benchmarks. The comparison was based on two attributes of the sets: effectiveness, as measured by the percentage of required information flow/error class combinations covered by the key control set, and efficiency, as measured by the percentage of controls tested. “Required” flow/error combinations were calculated based on the target-error-class-propagation method described §4.2. Because the case descriptions given to the auditors included each control’s extended span, the span propagation algorithm was not needed to calculate $D_{c,f}$. Percentages were used to allow the results from the three test cases to be combined.

5.5. Validation Results
Figure 10 presents a graph of the efficiency versus the effectiveness metrics for the consensus and professional benchmarks described above, our model, and the individual auditor subjects who solved each case. Any key control sets that are effective by our definition would lie on the right-hand axis of the diagram (i.e., 100% of required error class/information flow combinations covered). The goal of key control selection, however, is to achieve 100% effectiveness by testing the minimum number of controls (in this case, represented as a percentage of total controls in the case and plotted on the Y-axis). Therefore, the lower the point representing the key control set is on the Y-axis, the more efficient the set is; and the farther to the right it is on the X-axis, the more effective the set is.

In two of the three cases, both the model and the professional benchmark produced effective key control sets (i.e., sets that cover 100% of the flow/TEC combination needed to achieve the target level of assurance the subjects were asked to achieve). However, the model was able to achieve 100% by testing fewer controls. The professional benchmark did not develop an effective key control set in one of the three cases. Only two of the auditors in Davis’s study developed an effective key control set, and there were significant differences in the auditors’ key control sets.
These results imply that the model comes closer to the "correct answer" than the experienced auditors in Davis's study. The fact that the model seems to achieve more efficient and effective results than even the benchmark could be because of subtle differences in the goals of the expert auditors who built the cases, or because the model is more internally consistent in applying the same decision rules as the expert auditors. Research in decision support systems for auditors indicates that a major advantage of these systems is their internal consistency compared to auditors (Messier 1995).

We believe these data provide sufficient support for our approach to justify further testing. The model's key control sets are similar to the professional benchmark, indicating that its results are approximating what the developers of the cases believed were the optimal solutions to each case. However, the individual auditors showed significant variability in selecting key control sets and rarely achieved results similar to the benchmark. Therefore, providing evaluators with the model's information on a case should help them develop key control sets that more closely approximate those of expert auditors.

The significant variation among auditors should be of some concern given that they all came from the same firm, had similar amounts of experience, and were asked to apply the same approach in which they had just received 18 hours of training. The variation does not appear to be a function of the different cases. The model's, professional benchmarks', and consensus auditors' results were very similar across cases, indicating that the expert auditors who developed the cases believe different AIS have broad similarities in how their controls are designed. Use of the proposed model-based tool might therefore be used in training to assist evaluators in identifying that underlying similarity and developing more consistent key control sets.

6. Discussion and Future Work

This work contributes to the literature on data reliability assessment. While the work was motivated by and set in the context of AISs, the key concepts that underlie our approach have the potential to be more broadly applicable. Essentially, the approach defines a structured methodology for data reliability assessment based on the following core concepts:

- A definition of data reliability in terms of presence/absence of error classes.
- A commonly understood and shared definition of error classes.
- Formalized conceptualization of the information system in terms of information transformation processes that can introduce errors and controls that can prevent/detect error classes.
- Decision support methods that exploit the formalized conceptualization to assist in data reliability assessment, permitting an auditor to combine appropriately human judgment and algorithmic processing.

There are at least two specific opportunities for transferring these ideas to domains and contexts other than the problem studied in the paper. The first opportunity relates to the distinction we made in §2 between evaluation of a given internal control structure versus design of an internal control structure to meet desired reliability objectives. Recall that the dominant practice in reliability assessment assumes that the AIS and its internal control structure are fixed. The emphasis is on evaluating the reliability of the given system. However, given a set of controls and their coverage capability, is there an optimal internal control structure for a given set of information transformation points and flows? In other words, what is the optimal location of each of the controls that make up the internal control structure? At which ITP should they be located? This can be viewed as an optimization problem over the set of admissible internal control structures for an AIS. Because the methods developed in this paper evaluate any AIS and its associated internal control structure, they can be used as part of a solution to the design problem. The design problem is not limited to AIS and can arise in the context of other IS applications. In fact, one could make the argument that IS designers would benefit from considering the data reliability perspective during system design. The principal condition for transferring the ideas developed in the AIS context to other domains is the conformance with the conceptual (ontological) model developed in the paper. Specifically, error classes, transformation processes, controls and their interrelationships are fundamental to the approach. As Pierce (2004) demonstrates in applying a very similar conceptualization to the data quality
evaluation of an e-mail archive, the conceptualization we have developed is not limited to AIS. Once the data reliability assessment problem in the new domain is mapped into the graph-theoretic, ontological metamodel developed in this paper, the decision support methods used in this paper become directly applicable. Of course, extensions or customizations to the ontological model to meet application-specific needs will require extensions to the decision support methods developed in this paper.

The second opportunity is complementary to the first and related to the use of a BPMN-based notation for specifying AIS. The advantage of using BPMN notation is twofold. The first is the availability of visual tools (see www.intalio.com) for modeling with BPMN. The second advantage is tied to its growing popularity for IS specification, permitting the work developed in this paper to have a broader impact. However, as noted in §2, the semantics underlying BPMN are based on pi-logic (Milner 1992) and designed to reason about distributed processes. Data reliability assessment requires reasoning about the structure of the information flows, as discussed in §4. How can one gain the benefits of using a popular notation like BPMN while still taking account of the semantic differences? In §2, we identified extensions and customizations of BPMN that would be needed to model information reliability for an AIS. Implementation of an interpreter for the extended BPMN notation with access to the methods that implement the semantics described in §§3 and 4 permits the interoperability sought for integration. As with the first opportunity, the impact of this integration of our ideas with BPMN is not limited to AIS. Any information system that can be specified using the extended BPMN notation can benefit from both the evaluation methods developed in this paper as well as any methods developed to support design.

Beyond these opportunities, there are a number of interesting ideas for future research. Some of these stem from the limitations of this work. While the assumptions underlying the model were developed in discussions with experienced auditors and represent the way they approached key control selection, they are simplistic and do not represent the way processes and controls really function. For example, controls do differ in the costs needed to test them. Some controls, like authorization controls, can be tested by merely verifying a signature, while others, like matching documents, require reconstruction of the matching process to test them properly. In addition, controls differ in their strength. Further, a control that matches all aspects of two documents would be much stronger than a control that merely compares general ledger balances to budget numbers. All of these observations demand model refinements. However, we left these refinements to future research because our goal was to bring an increased level of formalism to existing practice, and these attributes of controls were not considered by the experienced auditors we interviewed in our fieldwork.

With regard to transferability of the decision support methods, the model that was developed was based on how auditors approach AIS evaluation. While recent work (Pierce 2004) adopts a very similar conceptualization of the problem, a thorough study of how IS designers in other application contexts perceive data reliability is required. For example, the auditors' main concern is that the GLAs are free of errors, not that the output from all the ITPs in the AIS are free from errors. Our definition of a control's span assumes that errors can occur in flows within the AIS as long as they are eliminated before the reach the GLAs. A firm's management may rely on the output of ITPs as well as the information in a GLA for making decisions and, therefore, would require that the output of all ITPs be free of errors. What are the requirements for data reliability in other IS contexts such as medical information systems or credit-processing systems? Are they similar or different to the AIS context? We believe application contexts merit careful study (as we have using AIS) and the literature on data quality (Pipino et al. 2002) offers a starting point for this type of work.

In conclusion, we believe the decision support systems approach to data reliability assessment that combines human judgment and the appropriate use of model-based algorithmic procedures has important advantages. First, because it does not attempt to mathematically model the entire reliability assessment process, it is able to address the problem at a level of granularity that renders previous mathematical model-based approaches computationally intractable.
(Felix and Niles 1988). Second, its use of model-based tools that recommend key control sets with known error detection properties provides assessors with assurance about the reliability of their assessments. Finally, the ability to use the tool either to recommend key control sets or to evaluate assessor-proposed sets permits the human assessor to rely on the model to the extent desired. However, will the availability of this technology result in better data reliability assessment outcomes? Our preliminary evaluation study indicates that our approach holds promise. A detailed evaluation of how auditors adopt this technology, how they incorporate it into their work processes, and the data reliability assessments that result is an interesting topic for future study.

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References

Appendix. Glossary

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tbody>
<tr>
<td>AIS</td>
<td>Accounting Information System.</td>
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<tr>
<td>Beginning flows</td>
<td>An information flow that begins with an economic event and is not checkable.</td>
</tr>
<tr>
<td>Checkable flows</td>
<td>Information flows that originate in an ITP.</td>
</tr>
<tr>
<td>Completeness</td>
<td>All the required information about economic events has been captured by the AIS and all economic events have been captured. None of this information has been lost in processing.</td>
</tr>
<tr>
<td>Control</td>
<td>A process within an AIS that eliminates errors from information flowing out of an ITP.</td>
</tr>
<tr>
<td>Control’s coverage</td>
<td>All the information flows from which a control can eliminate errors.</td>
</tr>
<tr>
<td>Control’s span</td>
<td>The set of information flows from which a control can eliminate errors.</td>
</tr>
<tr>
<td>End flows</td>
<td>A checkable flow that ends in a GLA.</td>
</tr>
<tr>
<td>Error class (EC)</td>
<td>As used in this paper; these are completeness, existence, and valuation.</td>
</tr>
<tr>
<td>Existence</td>
<td>The information about economic events that has been captured by the AIS reflects events that actually occurred and affected the firm. No information about nonexistent events has been added during processing.</td>
</tr>
<tr>
<td>General ledger account (GLA)</td>
<td>Maintain total of financial activity (i.e., the output of the AIS from which the financial statements are produced).</td>
</tr>
<tr>
<td>Information transformation process (ITP)</td>
<td>A process within an AIS that captures or processes information in some way.</td>
</tr>
<tr>
<td>Key control selection</td>
<td>The process by which an AIS evaluator selects a key control set.</td>
</tr>
<tr>
<td>Key control set</td>
<td>A set of controls that, if functioning as designed, will provide the evaluator with their target level of AIS reliability.</td>
</tr>
<tr>
<td>Middle flow</td>
<td>A checkable flow that does not end in a GLA.</td>
</tr>
<tr>
<td>Paths</td>
<td>A sequence of information flows leading from either an economic event or an ITP to either another ITP or GLA.</td>
</tr>
<tr>
<td>Paths—bad</td>
<td>A path for which a control does not have access to all the information needed to insure that information leaving the path is free of the error classes the control covers.</td>
</tr>
<tr>
<td>Paths—good</td>
<td>A path for which a control has access to all the information needed to insure that information leaving the path is free of the error classes the control covers.</td>
</tr>
<tr>
<td>Target error class (TEC)</td>
<td>Error classes (EC) the evaluator wants to determine are not present in an account.</td>
</tr>
<tr>
<td>Target reliability</td>
<td>An AIS-evaluator-determined level of reliability for each error class and account in an AIS.</td>
</tr>
<tr>
<td>Valuation</td>
<td>Given that information about an economic event that affects the firm has been captured by the AIS, the value associated with that event has been properly recorded and has not been changed during processing.</td>
</tr>
</tbody>
</table>


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