

# **Fault Detection and Diagnosis for Compliance Monitoring in International Supply Chains**

*Full Paper*

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## **Abstract**

Currently international supply chains are facing risks concerning faults in compliance, such as altering shipping documentations, fictitious inventory, and inter-company manipulations. In this paper a method to detect and diagnose fault scenarios regarding customs compliance in supply chains is proposed. This method forms part of a general approach called model-based auditing, which is based on a normative meta-model of the movement of money and goods or services. The modeling framework is proposed on compliance monitoring of supply chains with focus on information systems and compliance reporting tools. The innovation lies in the application and mapping of modeling techniques from dynamical systems engineering to business process analysis for audit and supervision purposes. Specifically, the application domain is where money, goods as well as information are transferred between international supply chain partners. A case study of a leading company in electronics manufacturing applying the model is analyzed.

## **Keywords**

Auditing, fault detection and diagnosis, compliance, international supply chains.

## **Introduction**

The complex nature of international trade lanes places an increasing demand for knowledge about compliance. Businesses are links in supply chains. From a compliance perspective, the focus of regulatory authorities is not only on the goods itself, but also on the kind of businesses “behind” the imports and exports, as well as the availability of data about them (WCO 2015). To be certified as Authorized Economic Operator and receive benefits in the form of reduced inspections, the quality of control measures has to be demonstrated to the authorities (Burgemeestre et al. 2011). By using IT solutions, customs administrations try to detect potential risks without unnecessary disruptions in the border crossing goods flows. By cooperation and collaboration both customs and businesses want to achieve an effective and efficient control on goods brought across the border.

Businesses are required to collect information and send reports, such as financial statements and tax declarations, to regulators to demonstrate that they are compliant (Power 1997; Power 2007). Reports are generated by business processes and information systems (ERP etc.), which are under control of the party being regulated. To ensure reliability, certain provisions must be built in the processes and systems. These provisions are called internal controls (COSO 1992), considering organizational measures like segregation of duties, procedural controls like approval by supervisors, and technical measures like automated checks on business rules, access control and the establishment of an audit trail (Romney and Steinbart 2006, Ch 10). Risk assessment plays an important role, as controls must be proportional to the risk. Many frameworks and guidelines exist to help companies set up a reliable system of internal controls e.g. COBIT 5, COSO ERM, the 2013 COSO Framework. Because internal controls are effectuated on behalf of management, the regulator or external auditor must regularly assess the adequacy of the design of the control measures, as well as their implementation and operating effectiveness. Blokdiijk (2004) stresses that internal controls must ensure reliability of audit evidence, even before any substantive testing can be performed. Nowadays, most control measures are in some way dependent on information systems, so these assessments are often performed by specialists: IT auditors.

Despite these control efforts, there is still a risk of faults. Consider such classic faults as altering shipping documentations, fictitious inventory, and inter-company manipulations (Landman 1952), resulting in inefficiencies, malfunctions, and losses, or even accidents. In the supply chain domain, faults and errors are often perpetuated by immature information systems and lack of coordination (Steinfeld et al. 2011). In addition, redundancy and post processing are common problems in measures of control. For example, import declarations and bills of lading are often made several days after the vessels with the goods have left the port of origin. Meanwhile, auditing and risk monitoring techniques are mostly driven by individual business interest. They need to be connected to the applicable regulations and to the whole supply chain to be monitored. Currently, there is no modeling framework for fault detection and diagnosis in supply chains that can be used for continuous monitoring.

The need for monitoring, detection and diagnosis techniques is common to other domains, for which such frameworks have already been developed (Ogata 2001). Transport systems and industrial processes have strict safety and reliability requirements. Faults may cause great damage, so monitoring the operating conditions is of great importance. There exist many methods to perform fault detection and diagnosis (Hwang et al. 2010; Landman 1952). These techniques are of particular interest for dynamical systems.

Continuous control monitoring and continuous auditing are promising approaches to provide assurance over a continuous stream of data (Alles et al. 2008; Chan and Vasarhelyi 2011; Kuhn and Sutton 2010; Vasarhelyi et al. 2004). Simultaneously, there is a computational approach to auditing called model-based auditing, based on a mathematically precise model of the value-cycle: the flow of money and goods or services in a transaction (Christiaanse and Hulstijn 2013; Elsas 1996; Griffioen et al. 2000; Weigand and Elsas 2012). The value cycle model generates a set of reconciliation relations, expressed as equations, which can be used to verify actual audit samples, using independent data sources. Initial studies show that this approach is also feasible in the supply chain domain (Veenstra et al. 2014).

In this paper we propose to connect a computational analysis of supply chain risks, in particular concerning customs compliance, with models from dynamic systems engineering to detect potential fault scenarios and diagnose the underlying causes. That suggests the following research question:

*How can we extend model-based auditing by techniques from systems engineering to provide the backbone for fault detection and diagnosis regarding customs compliance in the supply chain domain?*

To address this question, insights from accounting and auditing will be combined with dynamic systems engineering and corresponding fault diagnosis frameworks. The remainder of this paper is structured as follows. First, existing research on model-based auditing is described. The analogy of faults in auditing

and dynamic systems engineering makes modeling using similar techniques feasible. After presenting a theoretical framework in supply chain compliance, a mathematical model for fault detection and diagnosis is applied to a case study. The case study is about a customs warehouse of a well-known international electronics manufacturer.

## Model-based Auditing

Model-based auditing aims to formalize the forms of reasoning used in monitoring and auditing tasks (Christiaanse and Hulstijn 2013). The approach is by analogy with approaches like model-based diagnosis (Reiter 1987), which are also based on a precise model of the application domain, rather than on heuristics. A typology of value-cycle models can be taken from accounting practice (Starreveld et al. 1994), see Blokdiijk et al. (1995)) for a translation. These templates need to be adapted to modern business practice. In case of regulatory compliance the value cycle model must reflect the legal issues and distinctions that play a role in demonstrating compliance. In our case study, this means that we need to represent the specific considerations related to a customs warehouse license.

A value cycle model can be formalized as a Petri net  $\langle P, E \rangle$  with states (or places)  $P$  and events  $E$ . States collect value and events transfer value from one state to another. States are recorded in their proper unit of measurement. For instance, shoes are counted in pairs, oil in barrels, and money in Euros or Dollars. It is possible to formulate two types of equations (Blokdiijk et al. 1995; Starreveld et al. 1994).

The first type of equation is concerned with *transformation*. Suppose we have a transfer  $e$  linking two states  $S$  and  $T$ . Let the effect of  $e$  on  $S, T$  be new states  $S', T'$ . Then  $S-S'$ , the value taken from  $S$ , must be proportional to  $T'-T$ , the value added to  $T$ . This relative proportion can be expressed by a constant  $c$ . For example, let  $e$  be a sales event,  $S$  be an inventory of products and  $T$  be accounts receivable. In this case the proportion  $c$  is the average sales price. We have the *transformation* equation:

$$S - S' = c \times (T' - T)$$

The second type of equation is about *preservation*. For all states the amount at the end of a period should equal the amount at the beginning, with all inputs added and all outputs subtracted. Written loosely:

$$Begin - End + In - Out = 0$$

This is analogous to Kirchoff's law of preservation. *Begin* and *End* are state variables, but *In* and *Out* are totals, summarized over the events occurring in a period [*Begin*; *End*], e.g. [Jan-01-2015, Dec-31-2015]. For example, for inventory, *In* depends on the total number of products purchased in that period, and *Out* depends on the total number of products being sold. In IT auditing practice, the state variables *Begin* and *End* can be measured. The effects of events on states are known from the transformation model. The occurrence of events is typically recorded in log-files or ERP systems. Proportion constants are derived from price lists, a bill of materials to see which parts are needed to make a machine, or hour sheets to see how much labour is spent. So we have two independent sources for cross verification: inventory levels and the predicted increments and decrements over a period based on event logs and known proportions.

## Faults in Auditing from a Dynamical Systems Engineering Perspective

Fault detection and diagnosis in engineering is an effective methodology ensuring reliable and robust operation of a system under different faults scenarios, which plays a significant role in multiple disciplines and industries (Gertler 1998). So far, a large number of investigations have been conducted on fault detection and diagnosis methods. These methods are widely applied in electrical systems, integrated circuits, cyber security and so on (Venkatasubramanian et al. 2003). In order to comprehensively detect and diagnose faults, it is important to first identify and classify them in a systematic way.

According to relevant theories in engineering, faults can be classified into three types: actuator faults, sensor faults, and component faults (Hwang et al. 2010). These faults have specific interpretations within the auditing domain. Firstly, sensor faults correspond to unreliable or missing measurements and records in the monitoring system. Such faults negatively affect the accuracy and completeness of the audit evidence and reduce its quality. Secondly, actuator faults affect the exchange of material and monetary flows with the system and can be seen as human-driven faults in business processes, e.g. altering shipping documentations. Human faults could be caused by mistakes, ignorance or deliberate manipulations. Sensor and actuator faults are commonly modeled as additive faults. Lastly, component faults could be errors in the implementation of business processes, for instance, resulting in unauthorized flows of materials, money, information, or perturbation of the normal characteristics of authorized flows. They are commonly modeled as multiplicative faults, i.e., they are modeled as changes in the parameters of the system matrices (Gertler 1998).

### Theoretical Modeling of Supply Chain Compliance

Through recordings into information systems and auditing evidence generated, the material flow can be linked with information flow and money flow. Conversely, all the data from information flow and money flow can change the structure and variables in physical models. In this paper, the fault detection and diagnosis processes are conducted by comparing the expected behaviors or outcomes in the theoretical model with the corresponding recording data in information systems (e.g. ERP). The current focus is on the material and information flows, while in future research the money flow will also be analyzed.

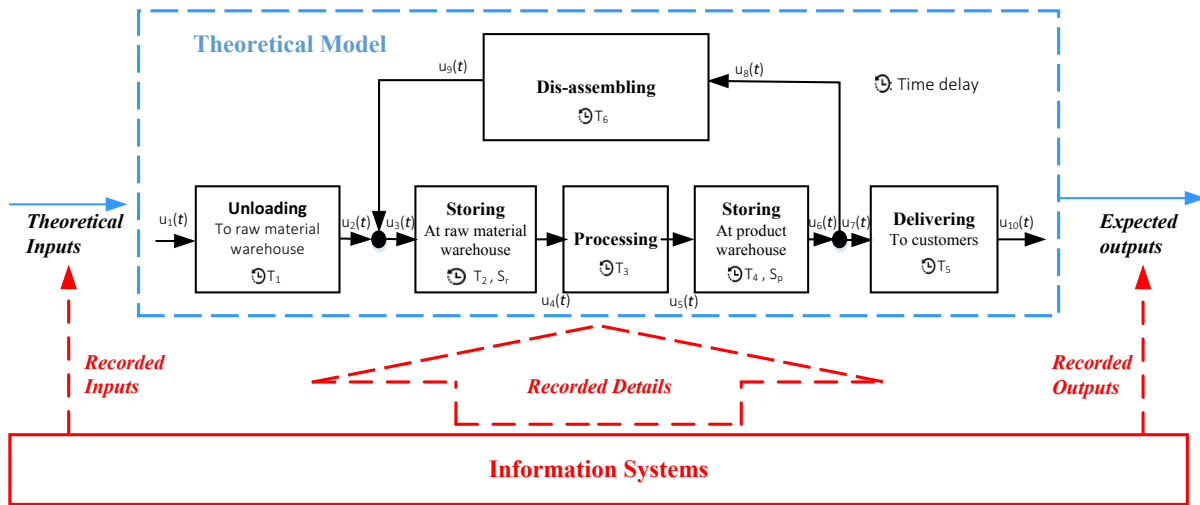


Figure 1. A Framework of Theoretical Modeling for Supply Chain Compliance

The theoretical model is developed based on the fundamental material flow in supply chains (Figure 1). The material flow involves unloading, storing materials, processing, storing products, delivering and if necessary, disassembling. These activities often have time delay and costs. As these activities take place, the corresponding attributes of each object (materials or products) will change. These changes are recorded in the theoretical model and used for further fault detection and diagnosis processes.

This theoretical model is a stochastic model established from individual material/product perspectives. In other words, this model may represent all the possible flow paths of a specific material/product including its different resources and targets. These possible flow paths are measured and analyzed in terms of occurrence probabilities with the assumption that their occurrences follow certain patterns in the long-term equilibrium situation. The occurrence probabilities can be estimated by statistical methods on real data. By synthesizing individual possible flow paths and combining different processes of materials/

products, the expected value of supply chain indicators will be calculated which can be compared with real data in order to test whether faults are happening in the systems and where they may be.

### ***System Dynamics***

The implementation of each activity takes time, leading to specific time delay  $T_i$ . In order to simplify the model, it is assumed that these time delays have constant values in long-term equilibrium situations. In this model, the material flow of this supply chain system is modeled as a set of discrete variables  $u_i(t)$  ranging from  $u_1(t)$  to  $u_{10}(t)$ . When products are moved from the product warehouse, they may have two alternative directions: being delivered to customers  $u_7(t)$  or disassembled into raw materials again  $u_8(t)$ . It is assumed that in long-term equilibrium situations, the ratio of the material flow going to different directions is fixed. Namely, in this case, certain percentage  $P_1$  of the output from product warehouse  $u_6(t)$  will be delivered to customers, the leftover will be disassembled and goes back to the raw material warehouse. These percentages may be obtained from historical data in the information system. With the material flow variables available, the inventory level of raw material and product warehouse  $s_1(t)$  and  $s_2(t)$  can be calculated by the following equations:

$$\begin{cases} s_1(t) = \sum_{t=0}^N [u_3(t) - u_4(t)] \\ s_2(t) = \sum_{t=0}^N [u_5(t) - u_6(t)] \end{cases}$$

We can use the model to detect scenarios of sensor faults, actuator faults and component faults, as discussed in the previous section. The details are illustrated in the case study section.

## **Case Study: Customs Warehouse of an Electronics Manufacturer**

### ***Case Description***

ABC is a leading electronics manufacturer, headquartered in the Netherlands. As part of its supply chain operations ABC is running a customs warehouse under license. Goods from outside the European Union (EU) in such a warehouse are formally placed under customs supervision and payment of import duties is suspended until a final customs destination is known: import or re-export. Thus, the warehouse contains so called “bonded” goods, for which no customs duties have been paid, and “free” goods, for which import duties have been paid, and which may enter into free circulation. To keep its license, ABC must demonstrate to the customs administration that the warehouse maintains a reliable administration of the product movements: all products entering and exiting the warehouse are recorded (completeness), and for all materials and products their customs status (bonded or free) is known (accuracy). Every month ABC prepares an Electronic Periodic Declaration (EPD): an audit file with evidence of the warehouse movements, so customs can supervise at a distance. Before granting a license, IT auditors of customs must make sure that the processes and information systems that feed the EPD can be relied on.

### ***Data Collection***

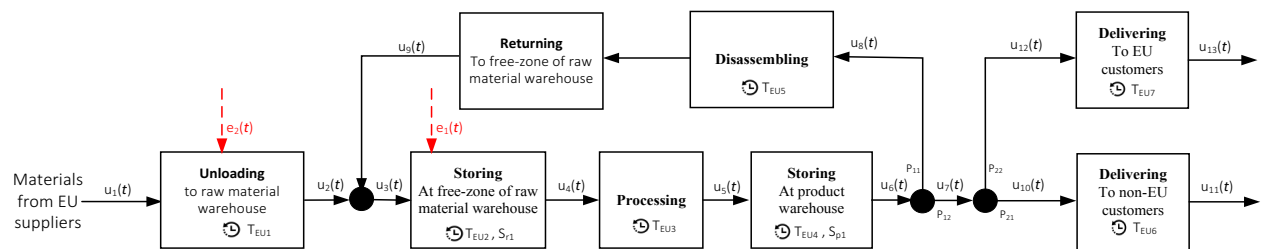
Data for this case was collected by a series of interviews conducted between May-September 2015, with experts at both ABC and the Netherlands Customs Administration. The informer at ABC is manager for logistics and customs compliance. The experts at customs are IT auditors, some of them with extensive experience at ABC. In addition to interviews, we collected documentation on systems, risk management, inbound processes and the legal rules of the warehouse license. We also made visits to the premises of a logistics service provider to observe how the inbound process is carried out.

**Problem description**

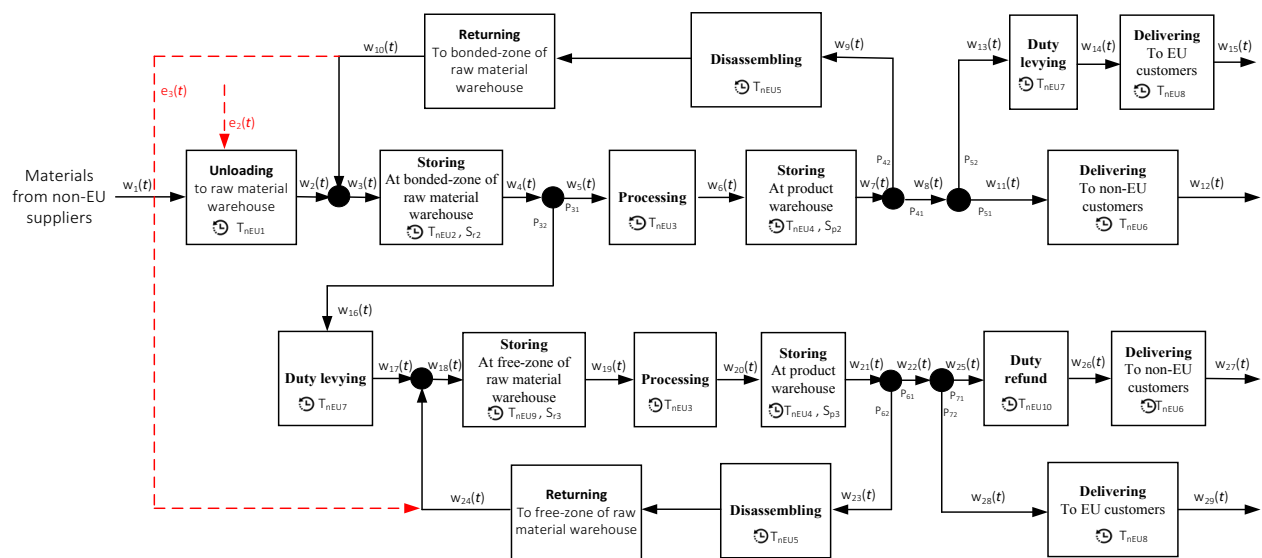
In this case, we focus on possible deficiencies that are hidden in the information architecture and business processes and that may lead to faults in reporting. Faults may originate in the ERP system, in the compliance reporting system that generates the electronic declarations (called T&T), and in the inbound process where goods are delivered by a third-party logistics provider (3PL) and entered into inventory. In theory, also the outbound process could produce faults. Some trade documents (e.g. transit documents) are prepared by a freight forwarder (FF). Every month, the T&T system is used to generate an EPD in the form of an audit file and sent to customs. An audit file is a large data file in pre-defined format.

**Problem Investigation**

The ERP system of ABC records a stream of movements: transactions that represent a status update. The T&T generates the EPD, based on a subset of ERP movements. Customs experts have determined in advance which types of movements in ERP are customs relevant, for example when they involve goods from foreign origin. So irrelevant movements are filtered out. If risks are recognized, additional controls can be set up. The controls must be validated from a legal perspective. To this end, a so called risk matrix was set up. Together with customs experts, ABC identified 55 risks. ABC arranges regular IT audits to verify whether the internal controls to cover these risks are operational in ERP.



(1) Materials from EU suppliers



(2) Materials from non-EU suppliers

**Figure 2. Material Flows from Suppliers to Customers (Red Arrows Represent Faults)**

Initial analysis has revealed that many errors can be attributed to the inbound process, where goods are entered into the warehouse. As a result ABC had to implement several additional controls, many of them manual. These controls are meant to detect and immediately correct deviations between trade documents, such as the purchase order, invoice, customs declaration, and the actual goods received at the warehouse. These additional controls are costly. In the long run, ABC would like to rely on automated controls.

### Modeling and Analysis

One risk that could result in faults is due to duty levying regulations based on origins and destinations of goods entering the warehouse, represented by different processes of Figure 2. For goods from non-EU suppliers that are re-exported to non-EU destinations after processing, no customs duties have to be paid. Therefore, for the materials from non-EU suppliers, there are two possibilities when exiting the bonded-zone. Some of them will be directly processed into products, while the others may be moved to the free-zone after levying necessary duties. In this case, the materials moved from the bonded-zone to the free-zone may get a duty refund if the final destination is non-EU customers.

The raw material warehouse can be separated into two different zones: a free zone for goods categorized as “free circulation” and bonded zone for goods “in transit”. From the material flow diagram, it is indicated that different zones have specific input and output flows as shown in Figure 3.

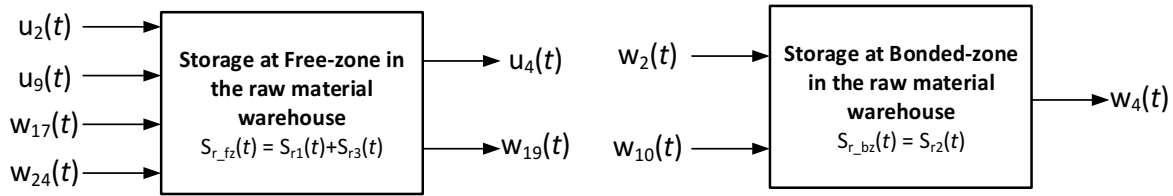


Figure 3. Storage in the Raw Material Warehouse

For the free zone of the material warehouse, the storage comes both from EU suppliers  $S_{r1}$  and from non-EU suppliers after levying import duties  $S_{r3}$ .

$$S_{r1}(t) = \sum_{t=0}^N [u_2(t) + u_9(t) - u_4(t)]; \quad S_{r3}(t) = \sum_{t=0}^N [w_{17}(t) + w_{24}(t) - w_{19}(t)]$$

$$S_{r_{fz}}(t) = S_{r1}(t) + S_{r3}(t) = \sum_{t=0}^N [u_2(t) + u_9(t) + w_{17}(t) + w_{24}(t) - u_4(t) - w_{19}(t)]$$

While for the bonded zone, the storage is only from the materials from non-EU suppliers  $S_{r2}$ .

$$S_{r_{bz}}(t) = S_{r2}(t) = \sum_{t=0}^N [w_2(t) + w_{10}(t) - w_4(t)]$$

In total,  $S_r(t) = S_{r_{fz}}(t) + S_{r_{bz}}(t)$ . As for the product warehouse, all products resulting from assembling raw materials will be stored here before being delivered to customers. The storage comes from three sources: the materials from EU suppliers in the free-zone  $S_{p1}$ , the materials from non-EU suppliers in bonded-zone  $S_{p2}$  and the materials from non-EU suppliers but in free-zone  $S_{p3}$ . Hence the storage in the product warehouse is given by:

$$S_p(t) = S_{p1}(t) + S_{p2}(t) + S_{p3}(t) = \sum_{t=0}^N [u_5(t) - u_6(t) + w_6(t) - w_7(t) + w_{20}(t) - w_{21}(t)]$$

## **Fault Detection and Diagnosis**

Customs relevant movements are transferred from ERP to T&T in the form of an iDoc message, which is a proprietary data representation format, similar to XML. The interface between ERP and T&T has an automated completeness check. T&T also checks syntactic correctness of the iDoc. Incorrect or incomplete movements are sent to an error portal. However, not all trade documents are filled out correctly or completely. Some movements contain errors. These errors are filtered out and stored in an error portal to be resolved later. Meanwhile, as part of regular audits, both customs and the compliance department of ABC have identified some weaknesses. In particular the expected reconciliation between ERP and T&T could not be established systematically.

The model we proposed could theoretically detect possible fault scenarios and act as a guideline for the information system design, particularly for reconciliation checks interfacing ERP and T&T. Denoting the actual values by  $u_i(t), w_i(t)$ , the expected value of flow variables by  $u_{Ei}(t), w_{Ei}(t)$  and the recorded values in ERP by  $u_{Ri}(t), w_{Ri}(t)$ . It is noted that the expected values are calculated from the previous model indicating the normal behaviors in theory. We discuss three types of fault scenarios below:

- Sensor fault - Missing inventory information or under-reporting

In reality, missing data in information systems is a common fault caused by improper operations (wrong movement type) or system malfunctions. This type of fault may significantly influence data quality. Take the missing recording in the inbound process from EU suppliers  $S_{r1}(t)$  as an example. The missing recording  $e_1(t)$  (see Figure 2) may significantly decrease the recorded total storage  $S_{Rr}(t)$  of the raw material warehouse. Namely,  $S_{Rr}(t) = S_r(t) - e_1(t)$ .

In this case, the expected value of total storage  $S_{Er}(t)$  of raw material warehouse will be equal to its actual value  $S_r(t)$ . If recorded variables in ERP are complete and accurate, this fault can be detected and diagnosed if only the recorded value  $S_{Rr}(t)$  is continuously smaller than the expected value  $S_{Er}(t)$  and the deviation is closer to the material storage from EU suppliers  $S_{r1}(t)$ .

- Component fault - Inbound failure due to incomplete documents

A typical example of component faults in this case is the inbound failure caused by incomplete documents such as incomplete New Computerized Transit System (NCTS) declarations by 3PL or FF and missing unloading permissions from customs, which is crucial for legitimacy of inbound processes. This type of inbound failure may cause delay or cancellation of materials delivery into the warehouse.

It is assumed that complete documents will be delivered in T&T after a time delay of  $T_{id}$ . In other words, incomplete documents may only lead to time delays. However, it also results in unclosed transactions in the information systems. Take the raw material inbound process for instance: a temporary difference between the recorded value  $S_{Rr}(t)$  and the expected value  $S_{Er}(t)$  will be recognized during the time delay  $T_{id}$ . And after this short delay, the recorded value  $S_{Rr}(t)$  will again correspond to the expected value  $S_{Er}(t)$ . This type of fault can be distinguished with the help of our model.

- Actuator fault - Improper handling of the return materials from non-EU suppliers

Sometimes, part of the finished products will be dis-assembled into raw materials and returned to the raw material warehouse again. During this process, these materials are supposed to be returned to different zones according to their specific suppliers. Namely, the materials from non-EU suppliers should be returned to the bonded-zone. However, sometimes employees may move these non-EU materials directly to free-zone by mistake or on purpose to avoid declaration procedures in T&T which



require more time and effort of these employees. Materials entering into the bonded-zone require extra certificate and declaration time. Moreover, inter-company manipulations could happen since no duties are levied for bonded materials. Those bonded materials could be intentionally moved to processing with other free materials in the previous phase.

In this case, this fault  $e_3(t)$  may decrease the materials returned to bonded-zone  $w_{10}(t)$  and increase the materials to free-zone  $w_{24}(t)$ . Namely,  $w_{10}(t) = w_{E10}(t) - e_3(t)$ ;  $w_{24}(t) = w_{E24}(t) + e_3(t)$ .

It is assumed that the system is under continuous monitoring. If this fault continued for a period of time, the real storage of bonded-zone and free-zone will become significantly different from the expect value. And the amount of the deviation should be inverse.

$$\text{Namely, } S_{r\_bz}(t) - S_{Er\_bz}(t) = -\sum_{t=0}^N [e_3(t)]; S_{r\_fz}(t) - S_{Er\_fz}(t) = \sum_{t=0}^N [e_3(t)]$$

Under the assumption that ERP correctly records the storage of the warehouses, this fault can be detected by comparing the recorded value and the expected value from the model.

## Conclusion

This research addresses fault detection and diagnosis in international supply chains, in particular concerning reliability of compliance reports. Reliability of reporting is crucially based on the design and operational effectiveness of information systems and business processes. Based on accounting principles and the use of formal models from a dynamical systems engineering perspective, an audit approach of such internal controls is proposed. We present a modeling framework that can be used for identifying and diagnosing faults, based on reconciliation relations between accounts. The model could be generalized to different levels of the supply chain and abstracted to a network of stakeholders.

The use of formal models for compliance monitoring is well accepted in Business Process Management, e.g. (Rozinat and van der Aalst 2008). Control measures to ensure compliance are often built into the processes, called “compliance by design” (Sadiq and Governatori 2009). However, business process modeling often reduces compliance to properties about the order, nature and presence of activities.

The innovation of this approach lies in techniques of dynamics systems engineering. Unlike IT auditing which often focuses on prevention of risks, the stochastic approach of fault detection takes risks present. When risks are measured on a regular basis suggested by fault detection models, it is easier for companies to convince the regulator that they are “in control”. The practical contribution would also be discovering that errors concerning accuracy of customs status of the goods are essentially cases of misplacement.

As for complications of modeling, the detection of sensor faults lies in the assumption of other recorded variables in information systems. Therefore decoupling method from dynamical systems engineering is needed. In addition, the processing of goods from different origins could result in a wrongly calculated value jump. The value jump is the difference between the purchase price of all materials and the sales price of the finished product. Over the value jump also duties are levied. To keep track of different components and products, inside each “inventory” block (e.g. Processing and Storing), sub-inventories per type of component/product should be created. Additionally, the integration of different materials with fluctuating prices will make the model more dynamic. Moreover, the current discrete model can be extended to continuous modeling, taking account the depreciation of materials in warehouse.

For future research, we will also perform simulation of the case scenarios and test on real data. This would involve comparing expected output from the model and audit equations, to data recordings in information systems, and identifying common causes of deviations.

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