Model-based Fault Detection and Diagnosis of Inventory Record Inaccuracy in Customs Warehouse Management in the Netherlands

Y. Tian
4406265

ISBN 000-00-0000-000-0

Model-based Fault Detection and Diagnosis of Inventory Record Inaccuracy in Customs Warehouse Management in the Netherlands

by

Y. Tian
4406265

to obtain the degree of Master
at the Delft University of Technology,
to be defended publicly on Tuesday August 23, 2016 at 12:00 AM.

Student number:	4406265	
Project duration:	March 1, 2016 – August 23, 2016	
Thesis committee:	Prof. Y. Tan,	TU Delft, committee chair
	Dr. A. H. Teixeira,	TU Delft, first supervisor
	Dr. J. A. Annema,	TU Delft, second supervisor
	Ms. Y. Wang,	TU Delft, third supervisor

TU Delft

Acknowledgement

This dissertation represents the final step of my master study period in the Faculty of Technology, Policy, Management of TU Delft in the Netherlands. The two years' study in TU Delft has been an impressive and enjoyable experience to me. As my second master degree, the Engineering and Policy Analysis programme has opened a door to an interesting but challenging world for me. The knowledge and skills acquired from this programme will definitely benefit me in future career and life.

I would first like to thank all my thesis committee members, Prof. Yaohua Tan, Mr. André Herdeiro Teixeira, Mr. Jan Anne Annema and Ms. Yuxin Wang for their kind guidance, encouragement, and full support to my whole research work. Also I would like to express my gratitude to Ms. Laura Bruns for her assistance in arranging all kinds of meetings.

I would also like to thank all the interviewees and experts who were involved in my research project. Without their passionate participation and input, my project could not have been successfully conducted.

Finally, I must express my very profound gratitude to my parents and to my friends for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them. Thank you.

Yifu Tian
August, 2016

Abstract

Nowadays, as the increasingly intense international trade and logistics, the administrative burden of customs has been dramatically raised. In order to reduce repetitive taxing work and promote automatic administration, custom warehouses with electronic declaration systems are introduced and implemented by EU countries. The owner of custom warehouses can postpone the payment of import duties under the supervision of customs in case these goods are re-exported. The implementation of custom warehouses has significantly simplified custom formality and enhance administrative efficiency. However, its successful management highly depends on the accuracy and reliability of inventory information. Inaccurate inventory records may lead to a variety of undesirable effects, such as troubles in taxing and compliance failure with custom terms. As the common way to address this problem in the past, the traditional physical auditing is always time-consuming and costly, especially when the inventory is various and massive. Moreover, since the multiple stakeholders involvement in custom warehouses, the fault detection and diagnosis processes for inventory record inaccuracy in reality are usually problematic and complicated. Without the effective communication and cooperation between different stakeholders, it is difficult to solve inventory record inaccuracy issues and to guarantee the efficiency and reliability of custom warehouse management.

Considering these issues, the main research question in this dissertation is set as "How can faults leading to inventory record inaccuracy be detected and diagnosed considering multiple stakeholder involvement in custom warehouse management?". In order to answer this question, a model-based fault detection and diagnosis methodology is developed and analysed with a comprehensive stakeholder analysis on custom warehouse cases. The research work can be divided into three phases. Firstly, the relevant background information is collected through multiple approaches such as interviews, literature reviews, project conferences and expert consultations. The main results are presented in the literature review. Additionally, the second phase consists of two parallel parts, custom warehouse analysis and general model-based fault detection and diagnosis methodology. It is noted that the stakeholder analysis plays an important role in the custom warehouse management. Meanwhile, the general methodology framework is developed integrating Fault Detection and Isolation (FDI) approaches with Kalman Filter and Diagnosis (DX) approaches with movement sequence check. At last, the third phase focuses on the application of developed methodology in a case study. Based on the general methodology, a case-specific quantitative model has been developed which is then utilized for simulations. The simulation results are helpful in testing system behaviours under different fault and inventory scenarios. Moreover, the effectiveness of the proposed methodology is also preliminarily verified through simulations.

More specifically, the structure of this paper is as follows. Chapter 1 mainly explains the research problem and questions in this work. Chapter 2 reviews the previous research on inventory management, inventory record inaccuracy as well as model-based fault detection and diagnosis. In Chapter 3, a comprehensive analysis is conducted on the inaccurate inventory records issues in custom warehouses. Meanwhile, a general model-based FDD framework is proposed in Chapter 4. To demonstrate the application procedures and test its performance, the developed methodology is applied in a case study on a specific custom warehouse in the Netherlands. In Chapter 5, the customs warehouse in this specific case study is introduced and analysed. Based on the process models developed in Chapter 5, a series of simulations are conducted under scenarios in Chapter 6. Lastly, Chapter 7 summarises all the important results and findings in the research and sheds light on future research directions.

In summary, through literature reviews, interviews and expert consultations, a variety of faults have been found causing inventory record inaccuracy. Theses faults are classified into three groups, transaction, shrinkage and misplacement faults. Each fault group has its own causes and varied effects. By tracing their specific fault patterns, these fault can be detected and diagnosed. Considering the limitation of physical auditing, an innovative model-based fault detection and diagnosis methodology has been developed and tested, which compares recorded inventory information with its expected values predicted from models. The methodology combined FDI approaches from control theory with DX approaches from computer science. Because of its cost-efficiency and fast response, FDI approach with Kalman filter is utilized for fault detection. Considering the complex and dynamic circumstance in custom warehouse management, the more reliable DX approach

such as movement sequence check in this dissertation is applied for fault diagnosis. In addition, from interviews and expert consultations, multiple stakeholders are identified in custom warehouse issues, including different departments of the company, customs, third party logistics, software providers, suppliers and customers. The involved stakeholders play varied roles in detecting and diagnosing faults which contribute to inventory record inaccuracy in custom warehouses. Their effective communication and cooperation can not only assist in fault detection and diagnosis process but also enhance custom warehouse management efficiency.

This research is not only beneficial to the theoretical researches in fault analysis and logistics management but also helpful for the practical management of custom warehouses. From theoretical perspectives, the proposed methodology is an innovative model-based fault detection and diagnosis method combining FDI with DX approaches, which is more reliable than empirical auditing methods and more cost-efficient compared with physical auditing methods. The proposed methodology is extendible and can be applied in multiple circumstances based on case-specific and user-defined models. For practical applications, this work may help in addressing the un-cleared duties and declaration troubles in custom warehouse management. Meanwhile, the stakeholder analysis in this work may enhance the communication and cooperation between different stakeholders leading to reliable and efficient custom warehouses.

Contents

1 Introduction

This chapter consists of five sections. First, the fault detection and diagnosis (FDD) issues in custom warehouse management are introduced. Following the problem statement, research objective is explained and research questions are proposed in section 1.2. While research scope and applied research approaches are introduced in section 1.3 and 1.4 respectively. At last, research framework including thesis structure and relevant task outline is illustrated.

1.1. Problem Statement

Nowadays, with the development of economic globalization, international exchanges and cooperation is happening more frequently. Numerous international companies are building or running factories and warehouses outside their original countries. The increasingly frequent inbound and outbound processes dramatically increase the workload and complexity of custom relevant affairs [11]. Some of these affairs are unnecessary and can be omitted. In order to simplify Customs declaration procedures, reduced administrative costs and increased efficiency, custom warehousing is designed and implemented inside the EU country. The custom warehousing allows the owner of imported goods flexibly choose when to pay the duties. In this way, if the imported goods are re-exported again, the repeated duty levying procedures will be saved. However, the maintenance of custom warehouses needs a series of customs licenses. To obtain this customs licenses, the company are required to periodically report every movements of the goods and prove the reliability of logistics recording systems to the customs administrations. To trace and track inventory flows and storages in an accurate and efficient way is the key to prove the system reliability. Thanks to the development of ICT and sensor technology, increasing number of innovative applications have been developed and applied in current logistics systems for inventory management, such as ERP [83] and RFID [59]. Even though these innovative applications have greatly improved the data quality, the recording inaccuracies still exist and exert significant effects on the effectiveness and efficiency of current logistics management [35].

Recording inaccuracy refers to the discrepancy between the actual physical flows and storages and the recorded data in information systems, which may lead to resource waste, additional cost and poor supply chain performance [46]. In inventory management, if the recorded inventory level is larger than the actual physical level, the production process would be delayed because of raw material shortage and extra lead-time for new replenishment orders. While if the recorded level is smaller, unnecessary and reduplicated replenishments will lead to not only a waste of time and money but also additional inventory costs for storage and maintenance [68].

In reality, multiple events may contribute to recording inaccuracies in logistics, such as shrinkage, misplaced inventories and transaction errors, which are generically denoted as faults. [46] [3]. In order to eliminate or mitigate the negative effects of record inaccuracy, a comprehensive fault detection and diagnosis analysis is important and necessary. In theory, the most effective way to identify and remedy inaccurate inventory records is continuous physical auditing which provides actual inventory information in real time [3]. However, continuous physical auditing is mostly impossible in reality, especially for inventory with large amount and variety [82]. Needless to say physical auditing is always costly and time-consuming. In practice, cycle counts and heuristic auditing are frequently applied. Cycle counts is a physical auditing approach which is generally conducted by at intervals for a small subset of inventory at a specific location. The objects are usually counted by human labours, so the counting time rise as the increase of object amount. And the counting interval may also cause a delay in the fault detection. While heuristic auditing detects and diagnoses faults based on the knowledge derived from experience with similar problems. But it is not always reliable and highly dependent on the auditor's capacity. Considering the shortages of these auditing approaches, an innovative auditing approach base on logistics modelling has been proposed. Based on its ideas, a model-based FDD method for inaccurate inventory records has been developed in this work. However, considering the complicated stakeholder involvement, just mechanically applying the method in custom warehouse cases cannot guarantee its reliability. For example, customs do not have access to the fundamental database of companies. Therefore, it is usually hard for customs to locate the movement faults inside the companies. Therefore, this dissertation proposes a research on how to develop and apply a model-based FDD method for inaccurate inventory records in custom warehouses management considering its multiple stakeholder involvement.

1.2. Research Objective and Question

Given the information described above, the main research objective can be set as developing a extensible model-based FDD methodology to address inventory record inaccuracy issues in Customs Warehouse management. Therefore, the main research question for this research can be proposed as follows:

How can faults leading to inventory record inaccuracy be detected and diagnosed considering multiple stakeholder involvement in custom warehouse management?

In order to answer this research question, five sub-questions are formulated and each involves several research steps.

I. What are the common faults leading to inaccurate inventory records in logistics management and what are their characteristics?

In order to answer this question, at first, common faults contributing to inaccurate inventory records are identified and summarized through literature reviews and expert consultations (2.2). And then a comprehensive analysis of these identified faults are conducted concerning their potential effects and function mechanisms (3.3).

II. How is the inventory record inaccuracy situation in custom warehouses considering multiple stakeholder involvement?

Different from normal logistics system, custom warehouses involve multiple stakeholders like customs, third party logistics and suppliers. To order to comprehensively understand the inventory record inaccuracy situation in custom warehouses. A stakeholder analysis has been conducted (3.2) and the factors affecting inventory record inaccuracy are analysed from different stakeholder perspectives (3.3).

III. How can we develop a model-based fault detection and diagnosis methodology which is applicable in multiple circumstances?

The development of general model-based fault detection and diagnosis framework can be briefly divided into three steps (Chapter 4). The first step is faults identification which is conducted in the first research question. The next two steps are how to model the logistics processes and how to detect and diagnose the faults based on their fault patterns in the model.

IV. How can the model-based fault detection and diagnosis methodology be applied in specific cases considering actual application situations?

The previous research questions focus on general situations and frameworks. The third question pays more attention on the methodology application in reality. In order to answer this question, the model-based FDD methodology is applied in a case study of Custom Warehouse in the Netherlands. The faults identified from the case study are analysed and classified as discussed in the general framework(5.3). Based on the case-specific process models (5.2), The application example of the proposed methodology is demonstrated through quantitative simulations (6.2).

V. What are the possible logistics system behaviours under different fault and inventory scenarios and how can the developed model-based fault detection and diagnosis methodology be preliminarily verified?

This question can be answered through a series of simulations based on the developed models in the case study (Chapter 6). The objective of these simulations should focus on not only the specific fault patterns, but also the evaluation of different inventory policies and the effectiveness of developed methodology. Therefore, the simulations in this work include system performance tests under different inventory policies, fault effects tests and a application example of the developed model-based FDD methodology. By analysing the application example through simulations, the developed model-based FDD methodology can be preliminarily verified.

In summary, these sub-questions focus on different aspects of the main research questions and are interactive with each other during the research process. By answering the sub-questions sequentially, a model-based FDD methodology considering multiple stakeholder involvement is developed and analysed in order to detect and diagnose faults causing inventory record inaccuracy in custom warehouse management (the main research question).

1.3. Scientific and practical contributions

The completion of this dissertation can not only contributes to the theoretical development of model-based auditing in modern logistics management, but also provides an innovative and efficient way to solve the inventory record inaccuracy issues in practical custom warehouse management.

From a scientific perspective, this dissertation has proposed an innovative model-based FDD methodology in inventory management with the help of modern ICT applications. Firstly, the methodology integrates two parallel FDD approaches, FDI approaches from control theory and DX approaches from artificial intelligence. Because of its cost-efficiency and fast response, FDI approach with Kalman filter is utilized for fault detection. Considering the complex and dynamic reality, the DX approach of movement sequence check with reliable FDD performance are applied for fault diagnosis. By integrating the advantages of FDI and DX approaches, the proposed model-based FDD methodology is more reliable than heuristic auditing methods and more efficient compared with physical auditing methods. Moreover, with the assistance of modern ICT applications, the FDD theories and techniques from interdisciplinary backgrounds are creatively integrated and applied for logistics management issues. This innovative integration may contribute to the development of model-based auditing in modern logistics management.

In practice, inaccurate inventory records have caused a series of problems such as huge duty gaps and administrative troubles in custom warehouse management. The proposed model-based FDD methodology provides an effective and efficient tool to solve these problems. As its user-defined and case-specific characteristics, the methodology can be extended and applied in different circumstances for fault detection and diagnosis. Meanwhile, considering the complexity of custom warehouse management, the stakeholder analysis in this dissertation may enhance the communication and cooperation between different stakeholders leading to reliable and efficient custom warehouse systems.

1.4. Research Scope

The main investigated object in this research is the inventory record inaccuracy phenomenon of the logistics system in custom warehouse with ERP systems. As a portion of supply chain management, logistics management is more focused on the internal control of goods flows inside the organisation. Meanwhile, the application of ERP systems provide a continuous track on the inventory movements and storage situations, which is an important prerequisite for the implementation of proposed model-based FDD methodology. Moreover, it is noted that this research is mainly focused on analysing material and information flows in the logistics systems of custom warehouses. While the relevant studies on financial flow will be discussed in future researches.

Even though in this work the proposed model-based FDD methodology is mainly applied for custom warehouse management, it can also be applied in multiple industrial and commercial areas, such as electrical and electronic processing, mechanical manufacturing, fast-moving inventory management and retail trading. On the basis of philosophy of modularization design, this case-specific and user-defined methodology can be easily extended and flexibly applied in varied environments. The main limitation is the availability of inventory information and the complexity of objective systems.

Moreover, in order to better understand the application of this model-based FDD methodology in reality and avoid FDD failures caused by unnecessary stakeholder conflicts, a comprehensive stakeholder analysis is also introduced in this research. The stakeholder analysis results are helpful in gaining support from other stakeholders especially when it involves some powerful stakeholders like customs or other governmental organisations. It is noted that the power of stakeholders depends on not only their roles in the supply chain but also their privilege level in the database.

1.5. Research Approaches

In order to answer the research questions, a series of qualitative and quantitative research approaches have been applied in this research work, including documentary analysis, expert consultation, stakeholder analysis, case study and simulation.

- Documentary analysis and expert consultation

  As major information resources, documentary analysis and expert consultations play a significant role in this research work. They provide not only relevant background information and knowledge, but also useful guidelines for the implementation of research activities.

  More specifically, documentary analysis mainly consists of literature reviews and online researches in this dissertation. Literature reviews provide theoretical background information on model-based auditing in inventory management, influence factors and common faults in inventory record inaccuracy and previous researches on model-based FDD approaches. The information is utilized in later methodology design and case study. Meanwhile, the information about custom warehouse regulations and declaration systems is mainly acquired from online researches from the custom websites in the Netherlands.

  Additionally, expert consultation can be divided into group discussions and individual interviews. As part of a national research project which is hold by the Dutch customs, periodical project meetings are regularly organised. The model-based FDD methodology is presented, discussed and validated in the meeting. Based on the feedback from relevant experts from institutes, companies and customs, the methodology is improved and updated. Moreover, an interview with an experienced employee from Trade and custom department of company has been conducted. Based on the information from the interview, the case study on a real custom warehouse case has been implemented.

  Both documentary analysis and expert consultation are implemented throughout the whole research process, but their scopes and conducting processes are continuously adjusted serving for different purposes.

- Stakeholder analysis

  As a powerful analytical tool for decision making, stakeholder analysis is widely applied in conflict resolution, project management, and business administration. Considering the complexity of custom warehouse management, a comprehensive stakeholder analysis has been conducted on the different roles of stakeholders involved in the inventory record inaccuracy issues. More specific, the stakeholder analysis can be divided into three steps in this work. Firstly, several stakeholders are identified with their different interests and powers in custom warehouse management. Most of the relevant information are acquired from documentary researches and expert consultation. Secondly, based on the predefined evaluation criteria in this dissertation, these stakeholder are divided into four groups in terms of their different interests and powers. Thirdly, their different roles in inventory record inaccuracy issues are analysed based on their varied perspective towards specific faults and their involvement in custom warehouse management.

- Model-based FDD methodology design

  Through brainstorming and multi-disciplinary researches, some of the concepts and techniques from control theory have been transplanted in the methodology design processes. Later, these preliminary ideas are integrated into a draft model-based FDD methodology framework. The drat framework is presented, discussed and tested with relevant experts in interviews and project meetings. With the feedback, the model-based FDD methodology are gradually improved and updated. The improving process is constantly implementing until a relatively concrete and applicable framework is obtained.

- Case study

  The main objective of this case study is to explicate how to apply the developed model-based fault detection and diagnosis methodology in reality. This case study is supposed to be conducted on the custom warehouse of ABC (a famous manufacturing company in the Netherlands). The relevant information are acquired through surveys, conferences and interviews. The results of this case study is also applicable for other logistics systems following custom warehouse regulations in the EU.

- Simulation

  Based on the model developed in the previous case study, a series of simulations can be designed and conducted for the analysis of logistic system in the case. The simulation results may help in explaining existing phenomenon, predicting potential outcomes, identifying specific fault patterns, testing different inventory policies and verifying the developed methodology.

In summary, by implementing these research approaches, an innovative model-based FDD methodology is designed, analysed and tested considering its multiple stakeholder involvement. As major information resources, documentary analysis and expert consultation provide underpinning information in this dissertation. With the information, the innovative model-based FDD methodology is designed and tested in a case study with quantitative simulations. The simulation results are also useful in the identification of specific fault patterns. Meanwhile, the stakeholder analysis sheds light on the multiple stakeholder involvement in inventory record inaccuracy issues which can assist the application of model-based FDD methodology in custom warehouse management.

1.6. Research Framework

The layout of the research tasks and thesis structure are presented in figure 1.1. Chapter 1, introduction, mainly explains the research problem and questions discussed in this work. Chapter 2 presents the previous researches on inventory management, inventory record inaccuracy as well as model-based FDD. While Chapter 3 conducts a comprehensive analysis on the inaccurate inventory records issues in custom warehouses. Meanwhile, a general model-based FDD framework is proposed in Chapter 4 combining both fault detection and isolation (FDI) approaches and diagnosis (DX) approaches. In order to demonstrate its application procedures and test its effectiveness and performance, the developed framework is applied in a case study on a specific Custom Warehouse in the Netherlands. In Chapter 5, the relevant information about the Customs Warehouse in this specific case study is presented, including a brief case description, its specific logistics structure and process models as well as the potential risks leading to inaccurate inventory records. Based on the process models developed in Chapter 5, a series of simulations are conducted under scenarios in chapter 6. Lastly, Chapter 7 concludes all the important results and findings in the research and give suggestions for future research directions.

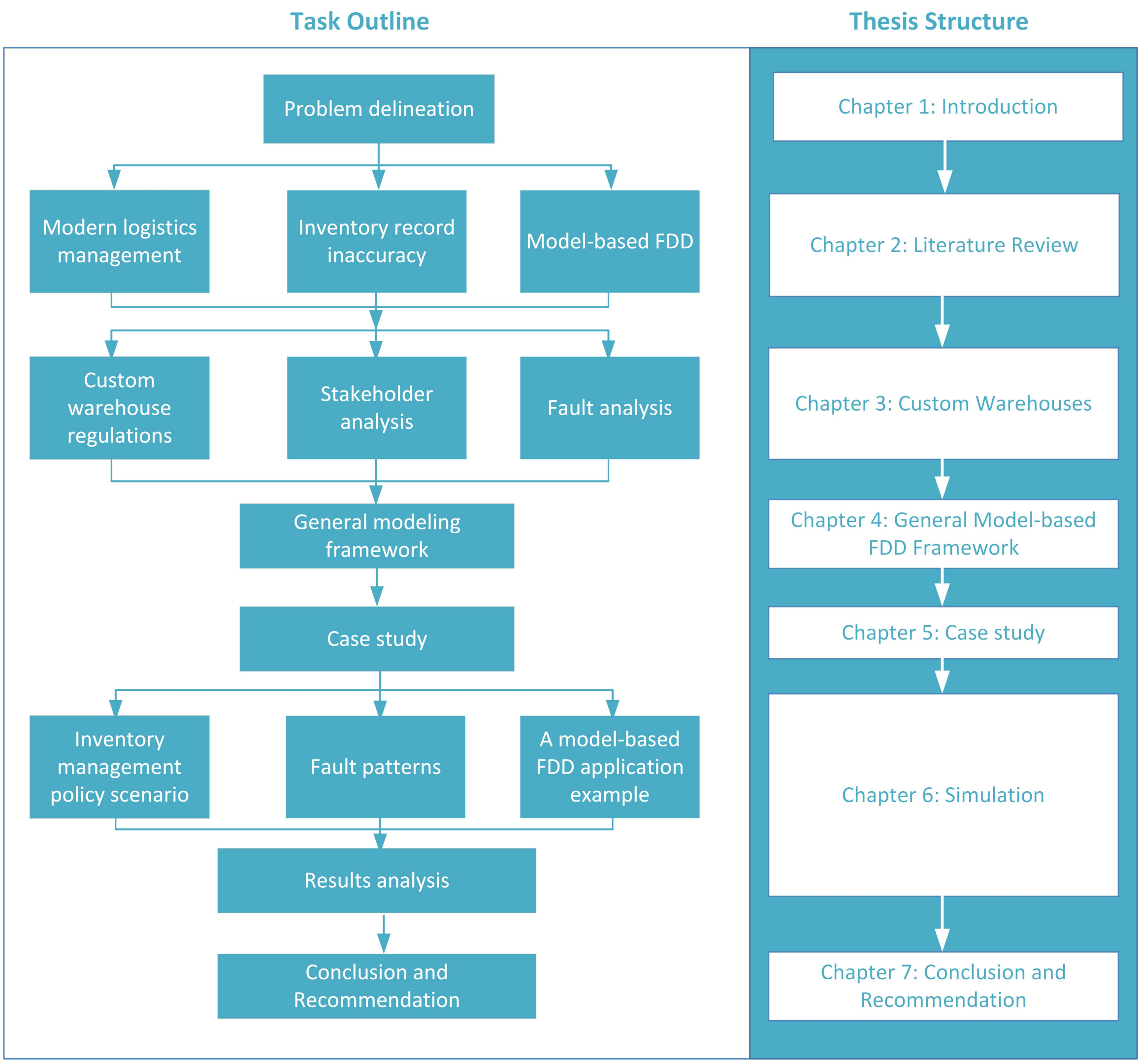


Figure 1.1: Thesis structure

2
Literature Review

This literature review is divided into three sections, model-based auditing in inventory management, inventory record inaccuracy and model-based FDD. Firstly, the theoretical background of model-based auditing in inventory management is introduced. And then the previous researches on inventory record inaccuracy are discussed in the second section, including relevant important hypotheses, common causes and effects. The last section analyses and compares the previous researches on model-based fault detection and diagnosis approaches.

2.1. Model-based Auditing in Inventory Management

2.1.1. Inventory Management and ERP systems

Generally speaking, a warehouse is defined as a “structural unit with all resources and organizational provisions necessary for the execution of processes connected to inventory and warehouse management including the organizational units involved with good receipt and shipping” [43]. The logistics management inside warehouses mainly involves the storage and maintenance of components. Warehouse management, also known as inventory management, is an important realm of logistics management. From a business point of view, the storage in warehouses is always associated with time and size overhead, which ties up not only fixed assets but also liquid asset capital. To sum up, stock keeping in warehouses has negative effects in terms of cost-efficiency. Nevertheless, there are still several management related reasons for creating inventory and maintaining it accordingly.

• The sufficient stock keeping is helpful for guaranteeing continuous production and delivery ability which may improve customers satisfaction (Shorter lead-time)

• The establishment of stock may offset fluctuations in production and demand contributing to relatively stable inventory management (Bullwhip effects)

To secure the production and deliver ability, the general approach is to maintain the inventory level to a higher level, which is also accompanied with a higher capital commitment. Moreover, considering the business concerns, it is important to keep a healthy inventory level for normal operative warehouse functions as well as its cost-efficiency. As the increase of task requirements for modern inventory management, modern IT-supported warehouse management systems are widely applied as an important factor for success.

In this respect, modern IT-supported warehouse management systems are required to be able to support the following core inventory management processes [43]:

• Unloading goods from suppliers and checking the received goods before entering warehouses
• Monitoring goods receipt
• De-consolidating the received goods
• Classifying the received goods and placing them as inventory at the corresponding locations
• Storing and taking care of the inventory in a good state.
• Continuous tracking and tracing goods movements, such as putaway, withdrawal, return and so on.
• Picking the goods to be delivered to customers.
• Packing the selected goods into loading units and loading

The performance of inventory management is significantly affected by the effective and efficient application of modern inventory management systems. Nowadays, one of the most widely applied software for warehouse management is Enterprise Resource Planning (ERP) [26]. ERP is a suite of integrated applications that attempts to combine all departments and functions of a enterprise into a single computer system that can serve all different needs [10]. From the perspective of inventory management, the application of ERP system enables the continuous monitoring of fundamental logistics movements and provides detailed and reliable information for inventory management and business strategy making.

In general, ERP provides two major benefits for inventory management. Firstly, with a unified enterprise view of the fundamental logistics transactions, all these transactions are entered, recorded, processed, monitored, and reported in an automatic and efficient way [79]. In this way, the cooperation and coordination between different department are enhances. Through more efficient communication and involvement among multiple stakeholders, companies may have a more chance in achieving their business objectives [26]. In addition, ERP also may also contribute to an effective and efficient inventory management purpose. The relevant planners and managers can get access to more accurate data with a better predicted market demands [71].

2.1.2. Model-based Auditing

"Auditing is the systematic process of objectively obtaining and evaluating evidence regarding assertions about economic activities and events to ascertain the degree of correspondence between the assertions and established criteria, and communicate the results to interested users" [74]. In the typical audit engagement, three actors are identified: management, stakeholders, and auditors. In our case, customs officers have the role of auditors. Management prepares statements about some object, for instance about accuracy and completeness of financial results, reliability of a computer system, or compliance of a process. Auditors verify these statements, and provide assurance as to their reliability, based on evidence. Stakeholders, such as shareholders or regulators, determine the norms or standards to be verified. Auditors are expected to provide "reasonable assurance that the (financial) reports are free from material misstatements" [45]. Certainty 'beyond reasonable doubt' cannot be provided, as the auditor cannot be present all the time and must rely on accounts from the party being audited. A misstatement or error is called material, when it would affect any auditor's judgement. Weigand and Elsas clarifies the differences between owner-ordered auditing and management-ordered auditing[82]. The paper describes main components of owner-ordered auditing and focuses on the Value Cycle Model. On the basis of explicit control principles, it captures basic requirements for model-based auditing. Then the paper assesses a Resource-Event-Agent (REA) model-based auditing approach by formalizing REA and comparing it with the Value Cycle Model.

Model-based auditing aims to formalize the forms of reasoning used in auditing tasks. The crucial problem is the use of a formal model of the value cycle: the flow of money and goods or services in a transaction [82]. The approach is called model-based auditing by analogy with approaches like model-based diagnosis, 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, although they need to be adapted to modern business practice. The use of formal models for compliance testing is well accepted in Business Process Management. Control measures to ensure compliance are often built-into the processes. This may be called 'compliance by design' [53]. However, business process modelling often reduces compliance to properties about the order, nature and presence of activities. Instead, we look at the effects of activities at a more aggregated level: financial accounts. Note that many inter-organizational business processes are concerned with establishing an economic transaction, see work on value modelling or REA[32] .

2.1.3. Modelling Approaches

As an important part of model-based auditing, modelling approaches for logistics systems have been widely studied. A large number of researches have been conducted on how to model the system either in a qualitative way or a quantitative way [73]. One of the well-known qualitative models is the Supply Chain Operation Reference (SCOR)-model, which is widely applied as a tool in representing, analysing and configuring supply chains [9]. However, only standardizing the terminology and process is no longer enough for current logistics management. Extensive researches have been done on quantitative supply chain modelling as well.

In 1960, a periodic quantitative supply chain model with order-up-to policy and discounted cost framework was proposed by Clark and Scarf [18]. This model focuses on a serial uncapacitated system without setup costs. Following Clark and Scarf 's work, considerable progress has been made in the design and analysis of two-echelon uncapacitated supply chain systems. However, before 1991, not much researches had been conducted on capacitated supply chain system with non-stationary demand in discrete time domain [77]. After 1991, addition researches have been conducted on more complex and advanced models. For example, Kapuscinski and Tayur [30] made a quantitative model on capacitated multi-echelon production-inventory systems to test and optimize supply chain policies.

However, it is noted that the applications of these models are highly limited because of their strict application requirements. Most of them are only suitable for specific cases in ideal circumstances. There is no general frameworks to design case-specific models which can be applied in different cases and circumstances. Moreover, the multiple stakeholder involvement also sets barriers on the model applications. Different stakeholders may accept varied performance indicators and targeting at differed management objectives. Without a fundamental framework of conceptualizing the underlying parameters and behaviours, the usefulness of the models are limited for different stakeholders.

2.2. Inventory Record Inaccuracy

Inventory record inaccuracy is a important issue in logistics management. Accurate inventory records are critical for the decision making process in demand forecasting, production and replenishment planning[70]. Although automatic inventory management with advanced information systems (such as ERP) has been widely applied, the recorded inventory levels do not always match the real physical levels [42]. In an empirical analysis of DeHoratius and Raman [24], 65% of the inventory records (about 370,000 records) from 37 retail stores (Gmma's U.S.-based stores) were observed to be inaccurate. This inventory level discrepancy may significantly affect the performance of whole supply chain system and waste a large amount of money and resources. According to a study conducted for the Grocery Manufacturers of America [44], inaccurate inventory records may cause a loss of $ 2 million for every $ 1 billion sales. It is also predicted that $10 billion profit can be recovered if these inaccuracies were eliminated.

Inventory record inaccuracy is defined as the difference between the recorded and actual inventory records, mostly inventory levels or positions. As an important issue of inventory management, inventory record inaccuracy has been widely researched and measured in a variety of ways. Schrady (1970) comprehensively reviews and analyses the costs and benefits associated with record accuracy and plausible inaccuracy measures [72].

In some researches, a binary evaluation criteria has been employed to determine the occurrence of inventory record inaccuracy. The binary evaluation is implemented by making decision on whether the actual inventory quantity matches the recorded data [65]. Mostly, inventory accuracy is determined within a predefined tolerance. For example, in Rinehart (1960) and Sheppard et. al (1993)'s work, a record is regarded as inaccuracy if the difference exceeding 1% of the actual inventory. Even though binary evaluation criteria is useful and effective to determine the occurrence of inventory inaccuracy, it is hard to measure the magnitude of inaccuracy level. In order to address this problem, the absolute discrepancy between recorded and actual inventory levels is measured in order to determine the inaccuracy level [24]. The absolute deviation is a effective measurement criteria with several nice properties. It not only consider the inaccuracy in inventory operations in a single measure but also reflect its distribution level. The absolute deviation has long been measured in terms of mean absolute deviation in inventory management [14] [56]. Mean absolute deviation is the mean of a set of absolute deviations, capturing both the mean and the spread of the discrepancy in a single measure. In this way, the inaccuracy is evaluated in a more flexible way compared with a normalized binary variable. Moreover, it is also easier to interpret the significance and the direction of estimated deviations.

2.2.1. Factors influencing inventory record inaccuracy

In the empirical analysis of Horatius and Raman [24], several illuminating hypotheses have been proposed based on the theoretical development of inventory management. The hypotheses draw on the factors influencing the inaccuracy level of inventory records.

- Hypothesis 1: Inventory record inaccuracy is positively correlated with transaction frequency.

  Based on the case studies and survey of Bermard [7] and Arnold and Chapman [2], it is concluded that the item with more frequent transaction records is more likely to be inaccurately recorded. The more units an item are transacted per year, the more likely record inaccuracy may occur and vice versa. If the event occurrence probability of accurate records is assumed to be p ($p < 1$), the probability to record an item accurately at its n times transaction is p^n, which is smaller than the previous probability.

- Hypothesis 2: Inventory record inaccuracy is negatively correlated with audit frequency.

  Some researchers [4], [29] argued that the error of inaccurate inventory records would keep on accumulating until the records are updated with the actual inventory condition through a physical audit. Usually, inventory managers will conduct a physical audit at regular intervals, which is also called as cycle count. The inventory records inaccuracy level is highly dependent on the cycle count frequency. Neeley [57] also indicated that apart from eliminating inaccurate records from the source, frequent inventory audits are effective and primary methods to eliminate inventory records inaccuracy in inventory management.

- Hypothesis 3: Inventory record inaccuracy is negatively correlated with the value of items.

  Hypothesis 4: Inventory record inaccuracy is negatively correlated with the dollar volume of each item.

  Both Hypothesis 3 and Hypothesis 4 discuss the relationship between inventory record inaccuracy and its values either in total cost and average prices. It is concluded that the item with higher value will be accompanied with less inventory record inaccuracy because of the additional attention paid by the managers [36]. In inventory management, it is crucial to classify different items according to their relative importance, which is usually measured in two ways, item value [34] and dollar volume [2]. Based on these measurement criteria, the items are classified into three classes (A,B and C). The class with higher value may grab more attentions and be checked more frequently by managers.

- Hypothesis 5: Inventory record inaccuracy is correlated with distribution structure.

  From some empirical studies [36], it is indicated that inventory record inaccuracy of a item is associated with the way how it is distributed. Typically, there are two ways [50]. Firstly, companies may temporarily store the goods in distribution centers and then deliver them to next level customers. Secondly, companies may have their own vendor departments. So they can directly send the goods to next level customers. The different distribution ways may influence the relevant inventory management policy leading to varied inaccurate inventory situations.

- Hypothesis 6: Inventory record inaccuracy is positively correlated with inventory density and variety.

  In reality, companies are always bothered by increasing crowded inventory storage, which makes it difficult and time-consuming to do regular physical audits. Therefore, inventory record inaccuracy level will increase as the increase of inventory density. The corresponding phenomena are shown in a lot of inventory management researches [50] [51] [8].

2.2.2. Common faults leading to inventory record inaccuracy

Since Iglehart and Morey [38] first introduced transaction errors in inventory management, numerous researches have been conducted on the common causes of inventory inaccuracy. Sarac et. al [70] made a comprehensive literature review on the relevant researches. The papers were reviewed and compared in terms of error types, supply chain structure (centralized or decentralized) and modelling structure (additive, multiplicative or fixed error modeling). The common faults leading to inaccurate inventory records were mainly classified into several groups, including transaction errors, shrinkage errors, misplacement errors.

Transaction errors, are the errors caused by misidentification, miscount or wrong operation of the items in inbound or outbound processes leading to the mismatch between recorded values and real stock. As mentioned before, transaction errors were first introduced by Iglehart and Morey (1972)[38] and a lot of studies have been conducted following it [47] [13]. According to Raman's classification, transaction errors mainly consist of shipment errors, delivery errors, scanning errors [64]. Shipping errors refer to the wrongly delivered goods. When customers receive wrong items, they may demand for a refund. As a result, the supplier may lose a lot of money for the repeated transportation cost. Delivery errors generally happen when the delivered quantities do not match the required ones. While scanning errors are explained as the situation when one specific movement of a item is recorded as twice or two items. In a recent study[69], an analytic model is proposed to address the problems caused by scanning errors. The occurrence probability increase dramatically as the rise of transaction frequency [24]. In the cases with large amount and variety of items, transaction errors usually play a significant role for the whole business success. The effects of transaction error is of great uncertainty. For example, if the cargo receivers forget or fail to record a certain batch of item arrivals, it may cause a lower recorded inventory level than the actual one, which may trigger a unnecessary replenishment round and addition cost for inventory storage. While if the amount of items is wrongly input by employees, the effect is most likely following a normal random distribution. Namely, the employees may either overrate or underrate the inventory level of the storage.

Shrinkage, known as stock loss, is found to be a major cause for recording inaccuracies according to many empirical studies [27]. It may be caused by multiple causes, such as employee theft, shoplifting, vendor fraud, spoiled or damaged inventory and administration errors [17] [41]. These errors may lead to a great loss of available products. Both employee theft and shoplifting are illegal theft behaviours causing the missing storage inside companies. While vendor fraud represents the shrinkage errors caused by external factors. In a retail survey, it is found that about 1–2% of total sales loss is caused by theft behaviours[36]. In one of Tellkamp's research [78], unsaleable products which are unavailable for sale in markets are discussed. In a survey among 65 manufacturers [52], 63% of the unsaleable products were found to be damaged products. Others were mainly out-of-code (16%) or discontinued (12%) items. While Chappell et. al indicated that another shrinkage cause is spoilage, generally caused by time or temperature exposure[17]. According to Basinger's research on the impact of inaccurate record [5], there are two major impacts of shrinkage faults. First, the occurrence of shrinkage faults may lead to an uncontrollable reduction in physical inventory levels, which can cause service degradation and lead-time increase. Second, these fault may result in under-ordering and warehouse denials. The effects of shrinkage faults are hard to be distinguished in reality. Generally, these faults can be detected only through conducting physical inventory audit. Mostly when they are found, it is too late to take any actions.

Misplacement errors refer to the inaccessible inventories which are not placed at the right locations and are temporarily unavailable for further operations. Many relevant researches have been conducted to analyse misplacement issues, also known as inaccessible inventory problems [49][16]. Misplacement errors usually happen when workers put items at wrong locations in warehouse or customers take goods from a shelf to another one in shops [41]. These misplaced inventories can be recovered later and be returned for further operations again. In the case study by Raman et. al [64] , it is found that 25% of the company profits were reduced because of misplacement errors. Misplacement faults, similar as shrinkage faults, may decrease the available inventory level. But the misplaced items, also know as inaccessible inventory can also be found and recovered later. Even though the effects of misplacement faults seem to be more moderate, the misplaced items are not always recoverable in reality. If the misplaced items are seasonal goods and are found after the season, companies may only sell them in a discounted price and lose a lot of profits [67]. Another example is when the misplaced items are found too late pasting their expiration date, these items will become unsaleable products [48].

A large number of previous researches and case studies indicated that taking good care of the effects of inaccurate inventory records is crucial for the success in inventory management. Ignoring or overlooking the importance of record inaccuracy will cause significant degradation in supply chain performance and huge increase in risks and costs. In general, the effects of inventory record inaccuracy are mainly studied in terms of two ways in inventory management, inventory level and storage cost [72]. Firstly, in order to guarantee the sustainability of inventory operations, keeping inventory levels in a robust and healthy way is necessary. A low inventory level may lead to a high operation risk and a high inventory level is always accompanied with unnecessary maintenance cost. Inventory record accuracy plays a significant role in the decision processes of production and replenishment plans which determine inventory levels. If the recorded inventory level is higher that the actual stock, companies may fail to order new supplies resulting in a larger inventory shortages and longer lead-time. If the records show a lower inventory level than that is actually present, unnecessary orders will be implemented with a result of high inventory level and large inventory investment. Secondly, inaccurate inventory records may significant influence the inventory cost. The storage of materials including raw materials, intermediate components and finished products are always associated with cost for warehouse rent, employee salary and inventory maintenance. Once inaccurate inventory records happen, additional cost is occurred for operating a system with inaccurate inventory records and maintaining a given level of inventory record accuracy.

In summary, transaction errors, are the faults caused by misidentification, miscount or wrong operation of the items in inbound or outbound processes. The impacts of these faults can be two-sided on the recorded inventory. While shrinkage, known as stock loss, is found to be a major cause for recording inaccuracies in many empirical studies. It may be caused by employee theft, shoplifting, vendor fraud and spoiled or damaged inventory. Once it happens, it may lead to a higher recorded inventory than the actual inventory. Misplaced inventories, refer to the materials or products physically existing in the facility but at incorrect locations. These inventories are not available temporarily but still have the possibility to be recovered as actual inventory. Like shrinkage, misplaced inventories may decrease the actual available inventory.

2.3. Model-based Fault Detection and Diagnosis

As the increasing requirements for system reliability and efficiency, fault analysis has become an important research topic in a multiple fields, especially industrial applications and process supervision [37]. Generally, fault analysis consists of three interactive sections: detection, diagnosis and control [84]. The purpose of fault detection is to test whether any fault has occurred. While fault diagnosis, also known as faults isolation, is to distinguish which kind of fault have happened and where it is. After the faults are detected and diagnosed, a series of corresponding control actions can be taken in order to eliminate or alleviate their negative effects. This dissertation only focuses on fault detection and diagnosis (FDD).

As an efficient and extensible FDD method, model-based FDD has been widely studied recently in order to fulfil the increasingly stringent requirements with respect to system safety and dependability [39]. A large number of model-based FDD methods have been designed and analysed from different perspectives. Among them, two distinct and parallel research directions is becoming increasingly active: fault detection and isolation (FDI) approach based on control and statistical theories and diagnostic (DX) approach applying artificial intelligence (AI) theories [21].

2.3.1. FDI approaches

The FDI approaches have been studied for decades and has reached a mature status. The relevant researches mainly began from the early 1970s in engineering backgrounds [39]. In 1971, Beard first proposed a fault detection methods for linear systems in his PhD thesis [6]. While Rault, et al. applied model-based identification methods for the fault detection issues of jet engines [12]. Similar methods were applied for instrument failure detection based on analytical redundancy of multiple observers [19]. These researches are summarised and reviewed in survey papers by Gertler [31] and Isermann [39].

In the beginning, these FDI approaches were mainly studied and applied in engineering disciplines like chemical engineering, electrical engineering and electronic engineering [31]. Recently, as the wide application of computer-based automatic systems, increasing attentions have been paid on transferring FDI approaches in process management and administration management in order to boost system reliability and efficiency [39]. FDI approaches based on control theory, apply numerical models to generate residuals robust to noise, unknown disturbance and model uncertainty and conduct statistical tests on the residuals in order to detect and diagnose faults.

In the International Federation of Automatic Control (IFAC) congress in 1996, faults are defined as "unpermitted deviations of at least one characteristic property or parameter of the system from the acceptable / usual / standard condition" [80]. According to this definition, the distinguishing of forbidden deviations between observed and expected behaviour is necessary to detect and diagnose faults. In FDI approaches, quantitative models are developed based on control theories to generate robust residuals and test them in order to detect and diagnose faults. However, the development of these quantitative models is always a big challenge in reality because of complicated system compositions and dynamic environment conditions. In practice, it is usually difficult to accurately predict the system behaviours through quantitative models because of model uncertainties, noise and unknown disturbance.

In general, the FDI approaches can be divided into two steps: robust residual generation and residual evaluation [37]. In robust residual generation, residual generation filters are designed in order to generate residuals which are sensitive to faults but robust to model uncertainties, noise and unknown disturbance. While in residual evaluation, decisions are made on whether the system is functioning in normal ways (fault detection) and on which specific type of faults have occurred (fault diagnosis/isolation) by analysing the residuals.

Robust residual generation

The generation of robust residual is an essential section in the framework of FDI. These residuals should be sensitive to faults but insensitive to noise and uncertainties. Some of the most common residual generation methods in FDI are observer-based approaches, parity relation approaches and Kalman filter-based approaches.

- Observer-based approaches [20],[85]

  Observer-based approaches generate diagnostic signals (residuals) by the design of system observers which provide an estimate of the internal states. It is noted that the generated residuals should have a zero mean. The basic observer-based residual generation method is to design a full-state observer which directly nulls the residual responses to unknown disturbances. While unknown input observers null the residual responses to unknown disturbance in an indirect way by controlling the observed state estimation error. The well-known observer design approaches are eigenstructure assignment and fault detection filter.

- Parity relation approaches [61]

Parity relations approach transforms either the input-out transfer function or the state-space models of the plant to yield directional or structural residual vectors directly. The main concept of parity relation-based fault detection utilize the difference between the actual system outputs and the predicted values from mathematic models as primary residuals. These residuals are then subjected to linear transformations, in order to obtain required FDI properties. There are various schemes to design parity relation (or parity equation)-based residual generators. These generators transform the primary residuals in order to enhance the specified responses for certain faults. Moreover, for the purpose of filtering noise and obtaining desired behaviours, the residual generators are also required to possess certain dynamic characters.

- Kalman filter-based approaches [55], [33], [75]

  Since Kalman first introduced a special stochastic filter with linear quadratic optimization [40], the Kalman filter has been widely applied in a variety of fields. It is first applied in FDI field by Mehra and Peschon [55] to generate residuals for fault diagnosis. In general, the Kalman filter-based approaches assumes a stochastic system model with noises following certain probability distributions. The faults are diagnosed through statistical hypothesis tests. A widely applied Kalman filter-based approach is multiple model adaptive estimation (MMAE) approach, which designs a bank of Kalman filters for a fixed number of failure modes. The approach is effective in detecting and diagnosing faults in unknown but constant systems.

Table 2.1: Comparison of the common residual generation approaches

Method	Observer-based approaches	Parity relation approach	Kalman filter-based approaches
Application Occasion	Mainly linear time-invariant systems	Mainly linear time-invariant systems	Discrete-time systems
Complexity	Medium	Medium	High
Advantages	·Straightforward and relatively simple in implementation processes ·Designer- defined structural or directional residuals for fault isolation ·Provide designers more freedom infulfilling multiple design objectives	·Straightforward and relatively simple in implementation processes ·Designer-defined transformation to meet different design objectives	·Provide optimal filtering under the normal (no-fault) operating conditions ·Allow the system to adapt quickly and hence provide accurate state estimation after fault occurs ·Multiple model approach could be expended to nonlinear or time-varying systems
Limitations	·Sensitive to model uncertainty ·Do not consider the effects of multiplicativefaults or model uncertainties ·Mostly limited to linear time-invariant systems	·Sensitive to model uncertainty ·Do not consider the effects of multiplicative faults or model uncertainties ·Mostly limited to linear time-invariant systems	·Complex in implementation processes, especially when the number of failure modes is high ·Discrete-time system and fault parameters

Comparing these three robust residual generation approaches, it is found that different approaches have their own characteristics, advantages and limitations and are suitable for varied objectives and application occasions. As shown in the table, even though the Kalman filter-based approaches are more complicated in implementation processes, they are more reliable and efficient in dynamic systems with uncertainty and disturbances. Considering the complexity of logistics systems in reality, Kalman filter-based approaches will be more suitable for the FDD framework in inventory management.

Residual evaluation
After residuals are generated, the next step is to test whether these residuals show significant changes, which indicates the occurrence of faults. The residual evaluation process can be conducted through statistical tests on the hypothesis that the residual equals zero, i.e. that no fault is presented. Namely, the observation equals the expected value from mathematical models. It is assumed that the observation of the tested parameter is denoted as β. While $\hat{\beta}$ denotes the its expected value.

Therefore, the hypothesis can be presented as,

$$H_0\colon \beta = \hat{\beta} \text{ (No faults are declared)}$$
$$H_1\colon \beta \neq \hat{\beta} \text{ (Uncertain faults are declared)}$$

In order to diagnose multiple faults, multiple hypothesis testing can be applied,

$$H_0\colon \beta = \hat{\beta} \text{ (No faults are declared)}$$

$$H_1\colon \beta = \hat{\beta}_1 \text{ (Fault 1 is declared)}$$
$$H_2\colon \beta = \hat{\beta}_2 \text{ (Fault 2 is declared)}$$

...

$$H_N\colon \beta = \hat{\beta_N} \text{ (Fault N is declared)}$$

In FDI community, two hypothesis test techniques are frequently applied: Sequential Probability Ratio Test (SPRT) and cumulative sum (CUSUM)

- SPRT [54], [76]

  When sequential analysis theory started to be applied for change detection issues, a new hypothesis test technique, Sequential Probability Ratio Test (SPRT), was proposed by Abraham Wald in 1947 [81]. The SPRT is a specific sequential hypothesis test which requires sufficient data on the tested parameters and their likelihood ratio. Currently, the SPRT has been widely used in statistical tests as a termination criterion.

  Given a series of observations on a certain parameter x (x_1,x_2...x_k) during a period of time and their conditional probability density functions $p_{\hat{\beta}}$, the cumulative sum of the log-likelihood ratio is calculated in a recursive way.

  $$S_k = S_{k-1} + \Lambda$$

  Where

  $$\Lambda = log\frac{p_{\hat{\beta}1}(x_k|x_{k-1},...,x_0)}{p_{\hat{\beta}0}(x_k|x_{k-1},...,x_0)}$$

  The stopping rule is then a threshold scheme as follows:

  $$\text{if } a < S_i < b \text{ , continue monitoring}$$
  $$\text{if } S_i \geq b \text{ , Accept } H_1$$
  $$\text{if } S_i \leq a \text{ , Accept } H_0$$

  Note that a and b are constant parameters depending the desired error type.

- CUSUM [58], [63]

  The CUSUM (also known as cumulative sum control chart) is a sequential analysis technique which is widely applied for change detection. The CUSUM was first proposed by Page for statistical quality control in 1954 [60]. Based on Wald's SPRT algorithm. Page picked some parameters of probability distribution as 'quality numbers' to detect changes.

  The CUSUM is equivalent to a repeated SPRT. Once the hypothesis test result is in favour of H_0, the test will be restarted.

  $$\text{if } S_{k-1} + \Lambda > 0 \text{ , } S_k = S_{k-1} + \Lambda$$
  $$\text{if } S_{k-1} + \Lambda \leq 0 \text{ , } S_k = 0$$

  The stopping rule for CUSUM is then dependent on whether the value of S exceeds a certain threshold value (b). If negative changes need to be identified as well, minimization operations will be used.

2.3.2. DX approaches

DX approaches are inspired by artificial intelligence (AI) providing tools for FDD with qualitative models. Compared with FDI approaches, the researches of DX approaches started a bit later but become increasingly active recently. The basic principle behind DX approaches is to detect and diagnose faults by applying human reasoning processes, cognitive methods or heuristic knowledge.

During the development of DX approaches, two different directions appeared in the design of diagnostic reasoning methodology [66].The first direction is often referred to as diagnosis from first principles. Under this direction, the DX approaches diagnose faults by causal reasoning and comparison between expected behaviours with real observations. The expected behaviours are acquired based on the description of objective systems. Together with the observation of real system behaviours, the discrepancy can be used to test whether the system is behaving in a normal way as expected. Once significant discrepancy is distinguished, the next diagnostic problem is to determine which system components are functioning abnormally. Some examples of these approaches are included in the researches of Davis [22] and Kleer [25]. It is noted that no heuristic knowledge has been applied in the diagnosis from first principles. While the second diagnostic reasoning direction is the experiential approach based on heuristic knowledge[15]. Heuristic knowledge is derived from the rules of thumb, statistical intuitions and past experience in similar problems. By synthesizing and codifying these sets of knowledge, experiential approaches design practical strategies to diagnose faults in a loosely optimal but applicable way. In order to facilitate the automatic diagnosis, expert systems are applied in DX approaches[1]. Feigenbaum defined a expert system as "an intelligent computer program that uses knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise for their solution" [28]. With the help of expert systems, faults can be diagnosed automatically using heuristic knowledge rather than precisely formulated causal links.

A well-known example of diagnosis approaches based on first principles is consistency-based diagnosis. In 1987, Reiter proposed a logical theory of diagnosis which has become the theoretical foundation of DX approaches [66]. In the proposed theory, different assumptions about the component constraints are tested in order to obtain consistency between the observed behaviours and the predicted behaviours from modelling. And then de Kleer et al. [23] extended this theory into the well-known consistency-based diagnosis. In this diagnosis approach, two main concepts are discussed: conflict sets and diagnosis objects. Conflict sets are a collection of system assumptions that are inconsistent with current observations. While the diagnosis objects can be obtained from conflict sets as hitting-sets. The fault diagnosis process can be conducted through the analysis on the whole set of minimal diagnosis objects[62]. And then two further steps will be conducted: the first step determines the set of conflict sets ; the second step computes diagnoses from the conflict sets, using hitting sets. In practical, two kinds of reasoning framework are distinguished in consistence-based diagnosis, normal-operation-oriented diagnosis and abnormal-operation-oriented diagnosis. Normal-operation-oriented diagnosis uses knowledge about how normal components work to detect deviations from normality in observed behaviour from which a minimal set of faults is hypothesized. While abnormal-operation-oriented diagnosis uses knowledge about how the components are affected by some specific faults in order to trace those faults.

In summary, within DX community, diagnosis is considered as a reasoning process. Empirical information and experience may be encoded as associative knowledge in rule bases. When many experimental data describing faults are available, case-based reasoning is a powerful approach.

2.3.3. Comparison

As mentioned before, even though the development of FDI approaches are relatively mature compared with DX approaches, both approaches have received extensive attentions in either a theoretical or practical way. Their objectives are the same, to effectively and efficiently detect and diagnose faults in complicated and dynamic systems.

Meanwhile, their detection principles are the same, detecting discrepancies in the observation and the behaviour predicted by modelling. Moreover, even though they applies varied concepts and methods, their general frameworks are similar. A lot of the important elements in FDI approaches can also find the corresponding elements in DX approaches. For example, the system model and system description.

The main differences between two approaches are shown in the table

Table 2.2: Comparison between FDI and DX approaches

Approach	**FDI**	**DX**
Background Theory	Control theory and statistical techniques	Compter science and AI theory
Applied Model	Quantitative model	Qualitative model
Diagnosis Basis	Stochastic process	Causal relationship
Advantages	Direct Measurable Fast response	Reliable Applicable for complex system Can be emerged into automatic diagnosis
Disadvantages	Rely on the accurracy of models Sensitive to noise and discrepancy High error rate in complex system	Time consuming Rely on complete and accurate information

Considering different characters, strengths and limitations of FDI and DX approaches, they are suitable for different situations and objectives. If possible, a combination of this two approaches may be a better choice. In order to do so, two prerequisites are needed. First, the object system should be able to be modelled into quantitative models with measurable parameters and causal relationships linking all the elements. second, sufficient data and information are required in order to trace specific faults.

3
Custom Warehouse

This chapter firstly introduces the relevant regulation and knowledge about custom warehouses, including goods under customs control and custom declaration systems. The information are mainly from official custom websites and interviews with customs experts. And then a stakeholder analysis has been conducted on custom warehouses. The stakeholders involved in inaccurate inventory record issues are identified and classified into different actors. The identified actors are mapped in terms of interests and powers. At last, the faults and influence factors involved in inventory record inaccuracy issues are analysed from different stakeholder perspectives.

3.1. Custom Warehouse description

3.1.1. Goods under customs control

Goods that enter the territory of European Union (EU) from non-EU countries are usually accompanied with import duties and subject to a series of customs regulations. These goods can be marketed within the EU only necessary custom processes. After these processes, these goods are released into free circulation. In order to do so, customs declarations should be filled, certain formalities should be fulfilled and the import duties should be paid.

However, if these goods which are imported from non-EU countries are planned to export outside the EU again, there is no need to levy the duties and release them into free circulation immediately. Moreover, when the goods leave the EU territory, the companies should get the duties back since they do not enter the EU market as commodities. This process may not only impose unnecessary administrative burdens on customs but also increase capital chain risk on companies. For the purpose of addressing this situation, the goods that enter the EU customs territory from outside are allowed to be stored under the supervision of customs without levying import duties immediately. This storage mode is called storage under customs control.

Table 3.1: Type of storage in custom warehouse

Type of storage	Description
Storage in temporary storage premises (RTO)	Short-term storage of goods under customs control. Customs physically supervises the deposit in and removal from RTO.
Storage in custom warehouse (type B,C,D and E)	Long-term storage of goods under customs control. It is possible to partly replace the physical control of customs by the periodical auditing process of the warehouse keeper's accounts.
Storage in free warehouse	Long-term storage of goods under customs control in a number of specific situations. Customs control the deposit and removal of the goods.

As shown in the table 3.1, various options are available for the storage of goods under customs control in the Netherlands. The choice depends on a number of factors, such as storage purposes, commodity categories, license levels and so on.

With these custom warehousing processes, companies can indefinitely postpone the payment of duties on imported goods whilst in storage. This delay may generate major cash flow savings and lower the possibility of paying unnecessary duties for exports. Meanwhile, the customs can largely relieve from the time-costly administrative inspections which is a significant burden for the administration of businesses.

However, for custom warehousing, customs licenses are always required. In order to maintain these licenses, companies need to conduct periodical auditing and internal control to guarantee their fiscal integrity and security of goods flows. The relevant information must be reliable and sufficient for customs to distinguish trusted companies from unknown or unreliable companies.

3.1.2. Customs declaration systems

One of EU customs' most important responsibilities is to control the imported goods by levying duties and to protect EU countries from dangerous goods which may impair EU citizens' safety and security. All the goods entering EU territory are required to be declared to customs. The effective and efficient management of these customs declarations plays an important role in maintaining the sustainable development of supply chain systems. In general, regular customs inspections are conducted on declarations, documentation and goods. These customs inspections check the completeness and correctness of all the relevant information. Based on the results, the authorities make decision on whether these goods are allowed to enter the EU territory and how much duties should be levied. Actually, all the goods movements passing borders should be under customs' supervision.

Recent years, as the increasingly frequent international trades and logistics, the goods flows passing the EU territory have been grown to an enormous scale. Moreover, this growth is most likely to be continued and even accelerated in the coming decades. In the mid 80's, Dutch customs have recognised that just conducting physical inspections was no longer possible to control all the incoming (and outgoing) goods flows. In order to address this issue, an automated customs declaration system, called SAGITTA, was developed and applied in which a risk module is designed to assess the submitted declarations. In SAGITTA, not all the declarations were physically inspected one by one. Instead, the custom inspections are differentiated into four groups in terms of different 'colours'. 'Red' stood for immediate physical inspection, 'Orange' meant an immediate documentation inspection to prove the declaration statements, 'Green' represented documentation inspection after the goods were permitted to leave the customs premises and 'White' meant no further inspection of goods or documentation. Additionally, the random inspections are also regularly conducted to cover remaining risks. Goods entering the EU customs territory are subject to EU customs Regulations. In the Customs Community Code (CCC) (Council (EEC), 1992), it is stated that goods must be conveyed without delay to a Customs office of entry (article 38(1) CCC), presented to Customs (article 40 CCC) and assigned a customs-approved treatment or use authorized for such non-Community goods (article 48 CCC) when entering the EU territory. All goods intended to be placed under a customs procedure shall be covered by a declaration for that customs procedure (article 59 CCC). This declaration has to be made in writing, using a data processing technique or by other means (article 61 CCC).

As the fast development of ICT applications, automated information systems supporting the business management systems is also applied in declaration practices. Based on the Sagitta system developed in 1987, the Electronic Periodic Declaration (EPD) was designed and introduced in 1994, which provide the possibility of submitting the supplementary declaration (art 76(2) CCC) in terms of data files, through a diskette or a CD(Customs administration of the Netherlands, 2014). In general, the EPD is a declaration containing all the records on the customs goods transactions during a period of time, which is submitted periodically. After assessing these periodic declarations, customs claim their findings and requirements to the companies. The companies have to analyse and correct the reports as well as adjust certain procedures for the next periodic declarations based on the feedbacks from customs. Basic principle of the EPD is that the declaration information lines contain all required information of each mutation in the inventory of goods under customs supervision. (Customs administration of the Netherlands, 2014). The EPD is required to contain all the information related with logistic, financial and customs related affairs. EPD has an important advantage as the custom declaration management system. The business information and transaction data can be not only used for customs affairs but also can be directly applied for multiple purposes. The data do not have to be collected and utilized only for customs purposes. In this way, the information from EPD systems can be used in an efficient and effective way.

Nowadays, automated information systems have been widely applied in modern inventory management and supporting the decision making in business processes. Therefore, the electronic way of reporting logistics transaction becomes an integrated part to meet the customs accountability requirements. Moreover, a new electronic system, 'Aangiftesysteem' (AGS), has been developed by customs for declarations. AGS combines all kind of customs declaration processes in one computer system, which may replace all declaration systems presently used by Customs. In fact, this new system was implemented from May 2016,.

3.2. Stakeholder analysis

In modern logistics management, there is a growing awareness on the need of strengthening communication and cooperation among involved stakeholders. The communication and cooperation may help in avoiding unnecessary risks and boosting logistics efficiency. In the custom warehousing cases, multiple stakeholders are involved and the communication and cooperation among the key actors are crucial for the business success. Stakeholder analysis is a useful technique to identify the key actors and analyse their interests and powers.

The main purposes of stakeholder analysis in custom warehouse management are :

- Gaining trust and support from powerful stakeholders, such as customs in this case. As introduced in chapter 3, the maintenance of custom warehouse requires periodical auditing for custom licenses. The effective communication with the customs may not only help companies win a good reputation but also gain customs' trust and support in relevant affairs.
- Continuous communication is beneficial for the collection and renewal of information, such as new fault patterns in this case. Nowadays, the logistics situations are kept on changing. Under this circumstance, new fault patterns may happen cause unexpected consequences. The continuous communication with front line staff may help in timely identifying these faults before it is too late.
- Frequent communications may help in gaining understandings from other stakeholders. When the benefits are understood by multiple stakeholders, the project is more likely to succeed. For example in this case, frequent communications between warehouse workers and the managers for custom affairs may improve normal workers' awareness of inputting correct code in ERP systems which may save a lot of subsequent works.
- Active communication and cooperation may create opportunity for innovations in logistics management. The feedbacks from other stakeholders may not only improve the quality of logistics systems, but also provide new ideas for innovations in logistics management. For example, the ABC's experience in this case can be used to improve the ERP systems developed by software companies.

3.2.1. Stakeholders identification

It seems logistics management is mainly a internal issue inside companies. However, because of different task divisions and the increasing involvement of multiple stakeholders, stakeholder analysis plays a significantly role in modern logistics management. It is noted that stakeholders are usually referred to as actors in stakeholder analysis. In this case of custom warehouse, several actors are identified from surveys and interviews, including different departments inside company ABC, customs, third party logistics (3PL), ERP system provider, suppliers and customers.

- **Departments inside the company**

  According to the different targets and task divisions, the involved departments insides the company are divided into three groups, executive directors, Trade & Customs department and warehouse workers. These actors play different roles in logistics management with varied interests and powers.

  Executive directors refer to the top management layer of the company whose role is to design, develop and direct strategic plans for the company. Generally, compared with short-term profits, they value more about the sustainable development and good reputation of their company. They are also responsible for the supervision of daily operation affairs including logistics management. The executive directors need to be aware of how everything works and integrate the whole resource in a cost-efficient and time-efficient way. In the process of addressing inventory record inaccuracy issues, executive directors usually play a leadership role in the company. In other words, they need to be informed of inventory record inaccuracy situations and set targets and strategies for relevant departments and employees.

  Trade & Customs department(T&C) is responsible for all the affairs related with customs, international trade and export control compliance. Its main job mission is to build a sustainable and healthy supply chain complying with laws and regulation in the various jurisdictions. One of their important jobs is to process the electronic declaration of customs and to correct the inaccurate inventory records. In the case of Custom Warehouses, T&C department is main operator for the fault detection and diagnosis of inaccurate inventory records.

Warehouse workers are responsible for all the logistics movements of materials from suppliers and manufacturing to customers. Every time when material movement occurs, the warehouse workers need to input the corresponding code in ERP systems to track all the material flows. Mostly, warehouse workers do not directly follow the order of T&C department and are under the supervision of an independent department. Even though warehouse workers are required to take training on the utilization of ERP systems, their wrongly record inputs are regard as one common source for inventory record inaccuracy.

- **Customs**

  As introduced before, the main responsibility of Customs is to levy duties and control the incoming and outgoing goods flows across the European territory. As a powerful government agency, Customs design, develop and enforce Customs laws, on behalf of a government. The Custom Warehouse is a kind of warehouses under the supervision of Customs with specially appointed licenses, which allows the postponed payment of duties on the imported goods. The maintenance of necessary license requires the periodical auditing of relevant Customs officers. The inaccurate inventory records of Custom Warehouse may cause trouble in the electronic declaration management processes.

- **3PL**

  3PL is short for third party logistics, which are mainly responsible for the transportation of goods between different actors or locations in the supply chain. In the cases of Custom Warehouse, 3PL is not only in charge of the goods transportation but also take care of the goods before they are put in storage. They are required to provide all the relevant goods documents when passing the border, including invoices which are generally used as an important master data document.

- **ERP system providers**

  ERP system providers are the companies to develop and sell ERP systems. They are also responsible for the maintenance and update of their software products. Generally, they are not directly involved in the inventory record inaccuracy issues. But once the ERP system collapses, they will be informed to solve the problem. Meanwhile, they may also help in addressing the faults by developing new applications in ERP systems.

- **Suppliers and customers**

  Suppliers and customers are the actors from the upstream and downstream of the supply chain respectively. Even though it seems that inaccurate inventory records have no direct relation with them, their assistance may also help in solving the issues. For example the suppliers may provide more precise master data and the feedbacks from customers may help in tracing the outflow of materials.

Specially, these actors also play different roles in the design, implementation and operation of ERP systems. As the designer of ERP systems, system providers are also responsible for maintaining software platform and providing training programs. Generally, they have the power to adjust their products according to customers' requirements such as adding special applications in ERP systems and releasing software patches for identified bugs. This power makes system providers become a potential key actor in solve inventory record inaccuracy issues. Additionally, the choice of ERP systems is made by executive directors in the company corresponding to their management strategies. However, the actual manager of the ERP system is the employees from T & C department, and the system operators are warehouse workers. Typically, the warehouse workers manually input movement codes or scan bar codes into ERP systems when inventory movements happen. The employees from T&C department have the access to monitor and inspect these records in ERP systems. The fundamental database in ERP system will be transferred into EPD and other custom documents automatically which are sent to the customs. Independent from the ERP system inside the company, 3PL also has its own ERP or other digital inventory management systems. The data from 3PL are usually regraded as master data for the company. Understanding the specific role of each actor in ERP systems may help in finding fault sources and making suitable fault control plans.

3.2.2. Stakeholder mapping

Before mapping the stakeholders in terms of interest and power, the evaluation criteria are defined. For each aspect, four levels are set, including high, relatively high, relatively low and low. It is also noted that when deciding the power level of different actors, the authority levels in ERP and auditing systems should also be taken into considerations.

For interest,

- High: The actor regards inventory record inaccuracy as an important issue and believes the effects can directly influence his work or responsibility.
- Relatively high: The actor also regards inventory record inaccuracy as an important issue but does not think the effects may directly influence his work or responsibility.
- Relatively low: The actor does not pay special attention to inventory record inaccuracy, but he does believe the effects may influence his work or responsibility to some extent.
- Low: The actor does not pay special attention to inventory record inaccuracy and does not think the effects may have direct influences on him.

For power,

- High: The actor plays a significant role in the decision making process of logistics management. His behaviours may directly influence the results of inventory record inaccuracy.
- Relatively high: The actor participate in the logistics management and recording processes. But compared with the actors with high power, their influences are relatively indirect.
- Relatively low: The actor does not directly participate in the logistics management. But their behaviours may have indirect influence on inventory record inaccuracy.
- Low: The actor does not show any obvious influence on inventory record inaccuracy.

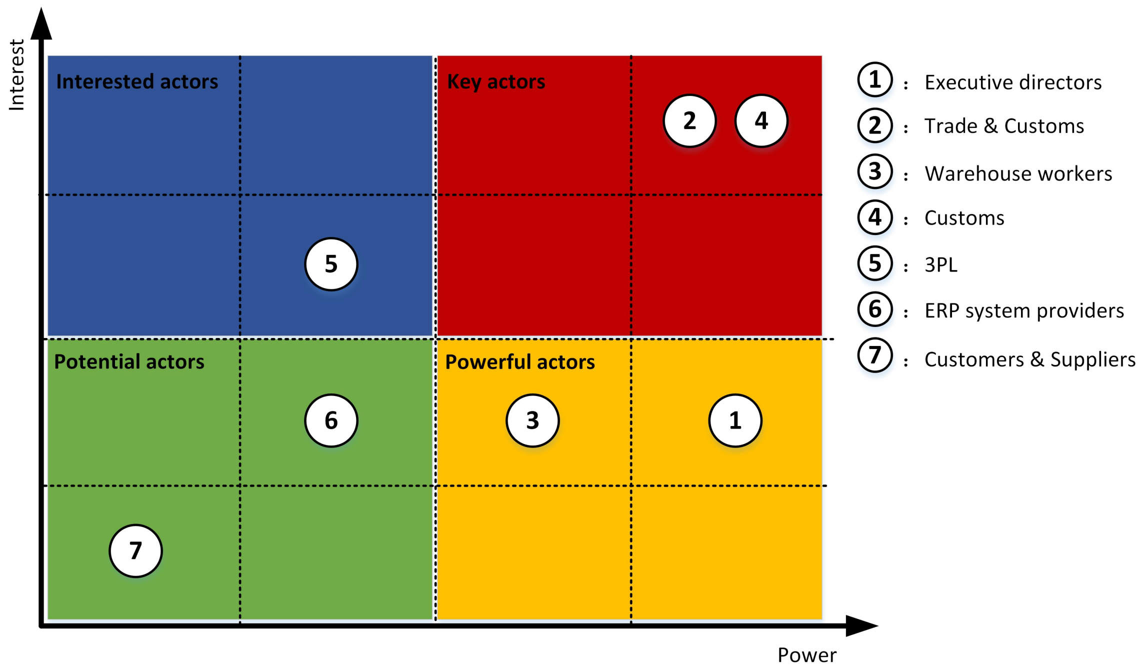


Figure 3.1: Stakeholder matrix diagram

Based on these estimation criteria settings, the actors are mapped into four groups as shown in figure 3.1. It is clearly indicated in the diagram that the key actors in this case are the Trade & Customs department and customs. Even though the Trade & Customs department is under the supervision of executive directors, it is the actual manager of custom warehouse. Meanwhile, according to the regulation, the goods in custom warehouses is under the supervision of customs. As the governmental actor in this case, customs can control custom warehouses by administrative means.

In addition to the key actors, executive directors and warehouse workers in companies are also powerful actors in the custom warehouse cases. The executive directors have a high authority to make decisions inside the company, while warehouse workers are the actual operator of custom warehouses. Moreover, As the secondary actors who are employed by companies, 3PL and ERP system providers are both involved in custom warehouse cases in an indirect way. Compared with ERP system providers, 3PL may be more concerned about the logistics management issues. Therefore, 3PL is categorised into interested actors group.

3.3. Inventory record inaccuracy in custom warehouses

3.3.1. Faults analysis in custom warehouses

Based on the different causes of specific faults, the potential faults can be classified into three fault categories: transaction, shrinkage and misplacement faults. All these faults may lead to inaccurate inventory records, namely the deviation between actual inventory levels and the recorded or expected values. But their effects differ from each other. These three fault categories are presented in a graphic way in figure 3.2 .

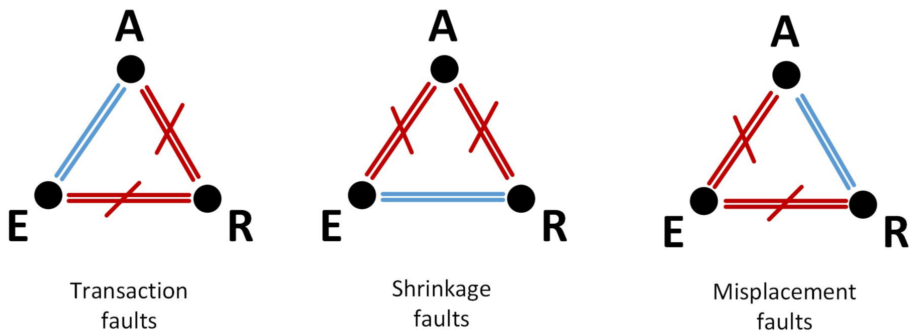


Figure 3.2: Composition of delivered products (A: Actual value; E: Expected value; R: Recorded value)

- Transaction faults: Transaction faults usually happen when ERP systems fail to correctly and completely track inventory movements. Transaction faults do not affect actual inventory conditions but the recorded value in ERP systems. Common transaction faults are incorrect manual inputs, ICT system failures, compliance failures and so on. In custom warehouse management cases, transaction faults are one of the most frequently recognized faults. As introduced before, custom warehouses utilize computer-based declaration systems. Transaction faults may cause the mismatches between the recorded data in custom declaration systems and the actual inventory situation. These discrepancies can be accumulated into a huge duty gap and cause troubles in declaration clearance processes.

- Shrinkage faults: Shrinkage faults stand for the faults changing actual values while recorded values are corresponding to expected values, such as spoilage, employee theft and shoplifting. In principle, the changes can lead to the mismatch between actual and recorded values. In custom warehouse cases, the normal shrinkage phenomena like spoilage and damaged components are taken into considerations. The inventory change caused by normal shrinkage reasons needs to be reported as scraps in the declaration systems. As for the shrinkage faults caused by human issues, companies should take the responsibility for all the loss.

- Misplacement faults: When misplacement faults happen, the recorded inventory position at the objective location will be different from the actual value. This will cause a decrease in the available inventory, but this decrease is temporary and the misplaced inventory can be recovered. In theory, if no transaction fault happens during this period, the expected inventory position will be the same as the actual one. These faults usually happens when the goods is placed in warehouses. These faults are forbidden according to custom regulations. The occurrence of misplacement in custom warehouses can cause uncleared duties and declaration troubles.

Different stakeholders may regard specific faults in different ways. Their involvements on specific fault issues are shown in the table 3.2. Here, the stakeholder involvement includes two cases. In other words, the involved actor either is affected by the faults or have the power to affect the faults. In the table, the check mark means this actor is involved in the corresponding fault category.

Table 3.2: Stakeholder involvement for different faults (✓:involved, X: not involved)

	Transaction Faults	Shrinkage	Misplacement
Executive directors	✓	✓	X
Trade & Customs	✓	✓	✓
Warehouse workers	✓	✓	✓
Customs	✓	X	✓
3PL	✓	X	X
ERP system providers	✓	X	X
Supplier and Customers	X	X	X

From the table, it is found that the transaction faults involves a larger variety of actors compared with other two fault categories. And the Trade & Customs department and warehouse workers are involved in all these fault issues. More specifically, executive directors concern about faults leading to direct financial losses such as transaction and shrinkage faults. Meanwhile, as the actual manager and operator of custom warehouses, T&C employees and warehouse workers are closely involved in all these fault issues. The customs mainly care about the faults related with tax affairs including transaction and misplacement faults. Moreover, 3PL and ERP system providers are only involved in transaction fault issues, while suppliers and customers are not directly involved in these fault issues.

A better understanding on stakeholders' involvement in different fault issues may help in identifying fault sources and making fault control plans. When transaction faults are recognized, the relevant managers can directly contact the corresponding stakeholder with a clear awareness of stakeholders' involvement. For example, if the faults are caused by software bugs in ERP systems, ERP system providers should be consulted and informed. If the faults are caused by wrongly inputs of movement codes, warehouse workers should be enquired and even the master data from 3PL should be checked. However, for shrinkage and misplacement faults, less actors mainly T&C employees and warehouse workers need to be involved in addressing fault issues.

3.3.2. Influence factor analysis from different stakeholder perspectives

In previous literature reviews, several critical factors for inventory record inaccuracy issues are identified in the relevant hypotheses. In this part, these factors will be analysed from different stakeholder perspectives. As shown in the table 3.3, the red check marks indicate that the actor have the power to affect the corresponding factor, while the blue ones means the actor is affected by the factor.

Table 3.3: Influence factor analysis from different stakeholder perspectives ($\color{red}{\checkmark}$:affecting, $\color{blue}{\checkmark}$:affected)

	Transaction frequency	Audit frequency	Item value	Distribution structure	Inventory density and variety
Executive directors	$\color{red}{\checkmark}$	$\color{red}{\checkmark}$		$\color{red}{\checkmark}$	$\color{red}{\checkmark}$
Trade & Customs	$\color{blue}{\checkmark}$	$\color{red}{\checkmark}\color{blue}{\checkmark}$	$\color{blue}{\checkmark}$	$\color{blue}{\checkmark}$	$\color{blue}{\checkmark}$
Warehouse workers	$\color{red}{\checkmark}\color{blue}{\checkmark}$	$\color{blue}{\checkmark}$	$\color{blue}{\checkmark}$		$\color{blue}{\checkmark}$
Customs	$\color{blue}{\checkmark}$	$\color{red}{\checkmark}\color{blue}{\checkmark}$	$\color{blue}{\checkmark}$		
3PL	$\color{blue}{\checkmark}$		$\color{blue}{\checkmark}$		$\color{blue}{\checkmark}$
ERP system providers					
Customers & Suppliers					

The transaction frequency is closely related with different inventory management decisions, such as replenishment and production plans. These inventory decisions are usually determined by the executive directors. The actual transactions are implemented bu warehouse workers. Their actual activities may also change the transaction frequency. Meanwhile, T&C and customs can be affected by this factor. With the increasing transaction frequency, it will be harder for T&C and customs to trace the material movements in the logistics system. Additionally, in custom warehouse management, auditing processes are usually conducted by T&C. All the findings should be timely reported to customs and executive directors. According to the rule, the auditing should under the supervision of customs. Therefore, audit frequency is determined by T&C, customs and executive directors. Even though increasing the audit frequency is beneficial to improve accuracy of inventory records, it may also increase the workload of T&C employees, custom officers and warehouse workers. Moreover, the item value is determined by the specific production requirement and marketing issues which is not controlled by any of the identified actors. However, the item with high value does attract more attention from T&C, customs 3PL and warehouse workers than normal goods. And distribution structure is decided by executive directors based on specific distribution and marketing strategies. It may influence the management approaches of T&C. Besides, inventory density and variety is also determined by the strategies made by executive directors. However, because the auditing difficulty is related with it, more actors are affected by this factor.

It can be summarised from the table that, as the top management layer of the company, executive directors have more powers in terms of the factors which they can affect. Besides, the key actors, T&C and customs can influence the inventory record inaccuracy level by changing the audit frequency. It is also noted that T&C is concerned about all these influencing factors. Their feedback to executive directors may also change the inventory record inaccuracy issues in an indirect way. Among these factors, changing the frequency of auditing activities seems to be a good method to control the inventory record inaccuracy levels.

These results are helpful in enhancing the communication and cooperation among different stakeholders to promote auditing (FDD in this dissertation) efficiency on inaccuracy issues. For example, increasing the audit frequency is know as a useful way to prove warehouses' reliability. However, the increased audits may increase the workload of warehouse workers and cause additional costs. Meanwhile, the goods with lower transaction frequency own a lower inaccuracy level. Therefore, the company may negotiate with the customs to lower the audit frequency on the goods with low transaction frequency to boost warehouse efficiency meanwhile maintain its reliability.

4
Model-based Fault Detection and Diagnosis Methodology

From previous literature reviews on model-based fault detection and diagnosis (FDD), two parallel research directions are found, fault detection and isolation (FDI) based on control theory and diagnosis (DX) based on artificial intelligence. Even though each direction has its own concepts, framework and methodology, their fundamental ideas are the same. Both of them apply a model either in a qualitative (DX) or quantitative (FDI) way to predict expected behaviours, and then compare the predicted results with corresponding observations in order to detect the occurrence of faults. Additionally, by distinguishing specific fault patterns, the categories and locations of these faults can be diagnosed as well. Even though FDI methods detect faults in a direct and efficient way, they highly rely on the accuracy of models and are sensitive to noise, interference and model uncertainty. While DX methods are more reliable based on underlying causal relationship, but the diagnosis process is always time consuming and requires additional information.

In order to apply DX methods for FDD in general logistic systems, detailed movement records and real-time inventory check are required. However, the inventory components are always massive and complicated. The check of material flows and inventory levels are costly and time-consuming. Therefore, only implementing DX methods is not sufficient to timely detect faults occurrence. On the other hand, logistic systems in reality are always complex and dynamic. It is hard to design a precise model in a quantitative way which significantly influence the performance of FDI methods. Considering the strength and limitation of both methods as well as characters of logistic systems, a combined model-based FDD framework is developed in this paper for inventory management in general logistic systems with ERP. The FDI methods with Kalman filter are used for fault detection. Once any fault is detected, a further research for fault diagnosis with DX methods will be triggered. In order to do so, a case-specific process model which can be transformed into a quantitative model is designed in advance. The results are regarded as expected values. While ERP systems measure and record movements and state values in a computer-based environment as recorded values. The actual state values are measured through site inspections and cycle counts either manually or automatically. By comparing the corresponding expected, actual and recorded state values and tracing specific movement patterns, the occurrence of faults can be detected and diagnosed.

This framework mainly consists of three different sections: modelling, fault detection and fault diagnosis. Firstly, a process model is developed in order to simulate the normal procedures based on case-specific circumstances. Secondly, considering the increasing uncertainty over time, Kalman filter is applied to filter out the normal states (expected values) with historical records and updated observations. And then the residuals between the expected and recorded values are statistically tested in order to detect the occurrence of faults. Lastly, once the occurrence of faults is detected, further investigations will be triggered for fault diagnosis including empirical tests, movement sequence check and so on.

4.1. General methodology framework

In this chapter, the developed model-based FDD methodology is applicable for multiple logistics systems which can be modelled in terms of logistic processes such as custom warehouses. The general methodology framework can be briefly divided into three steps.

- Firstly, the logistics system is conceptualized and simplified into process models based on its specific situations. The material flows from on process state to another are modelled as input and output variables for corresponding processes. It is assumed that all the material flow variables are constantly recorded in ERP systems and the inventory position can be calculated based on these material flow variables. Additionally, the faults are modelled as abnormal material flows in this model. For instance, transaction faults can be modelled as abnormal material flows affecting the input or output variables of certain processes. Shrinkage faults can be modelled as additional output variables from the certain processes, while misplacement faults are modelled as abnormal material flows from one process to another.
- Secondly, the occurrence of faults is detected by comparing the recorded states (inventory position in this case) with the expected states predicted by the developed model. Kalman filter-based method is used for residual generation, while the residuals are then analysed through statistical hypothesis tests. In this case, the recorded inventory position is fixed for each time point. Therefore, normal statistical hypothesis tests based on confidence intervals are sufficient in fault detection.
- Lastly, a comprehensive research on the potential faults should be conducted. A series of simulations about the identified faults will be conducted on the developed model. The effects and function mechanisms of different faults can be distinguished. based on the fault patterns identified from simulation results, the faults leading to inaccurate records can be preliminarily detected and diagnosis by comparing the expected, actual and recorded values. Moreover, with the assistance of ERP systems, a technique of movement sequence check can be applied for fault diagnosis in this case.

In summary, based on case-specific process models, faults in logistics systems are detected by Kalman filter-based FDI approaches and then diagnosed by DX approaches such as preliminary test and movement sequence check. This methodology not only takes the advantages of FDI approaches' high fault detection efficiency but also maintain the reliability in fault diagnosis by applying DX approaches.

4.2. Modelling

The process model is developed based on fundamental material flows. As shown in figure 4.1, the general life cycle for individual materials, from unloading to finally delivering to customers, can be refined and dismantled into basic activities including uploading, storing, processing/assembling, disassembling, returning, delivering and scraping. It is noted that both processing and assembling are production processes transferring raw materials into intermediate or final products. Processing represents the irreversible production process after which the raw materials are difficult or impossible to be recycled, such as chemical reaction and mechanical cutting. While assembling mainly represents the combination of detachable components. Some of these activities are accompanied with time delay and costs. As these activities taking place, the corresponding attributes of each object (materials or products) will change. These changes will be simulated in the model and used for further fault detection and diagnosis processes. In order to simplify the model, it is assumed these time delays have constants values in long-term equilibrium situations. It is assumed that all the movements and inventory positions is continuously recorded in computer-based ERP systems.

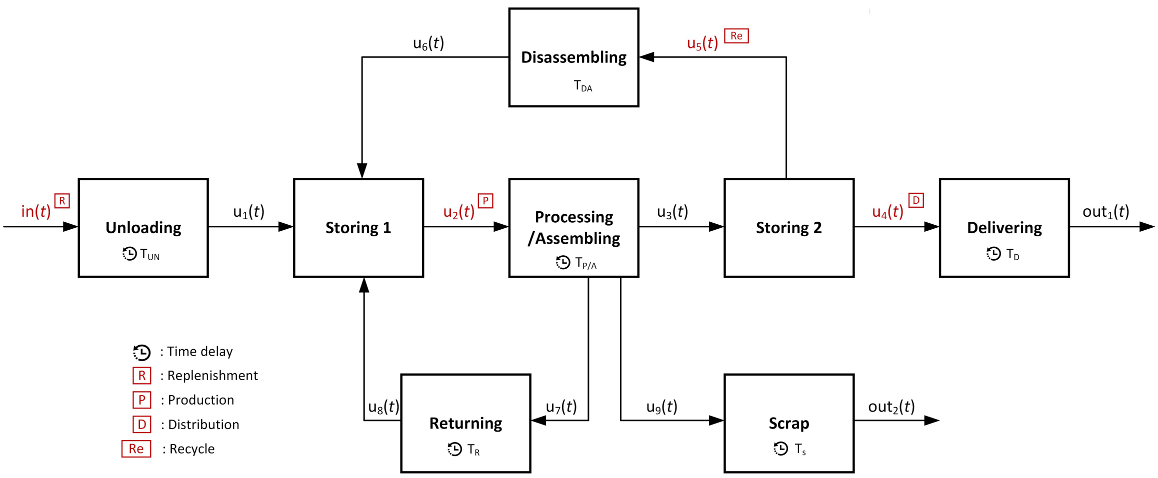


Figure 4.1: Simplified model of a general logistics system

In figure 4.1, the rectangles indicate the basic activities during the production life of a specific material. The arrows denote the material flows from one activity status to another. These flow variable are discrete variables. The flow variables have two colors. Excluding the input ($in(t)$) and output ($out_1(t)$ and $out_2(t)$) variables, the ones in black are normal internal variables, while the ones in red are policy-determined internal variables influenced by external factors like customer demands and inventory management policies. The superscripts in rectangles indicate the specific inventory policy applied. A more detailed description about them will be introduced later.

It is noted that the variables used in this model are vectors that contain the corresponding attributes of each material/component. More specifically, $S_1(t)$, $S_2(t)$ are the vectors that contain the inventory positions of each material/component in the condition of Storing 1 and Storing 2 respectively, while the vectors of $in(t)$, $u_i(t)$ and $out_i(t)$ denote the material flows. Moreover, $T_i(t)$ is the vector contain the delay times of corresponding process for each material/component.

- Unloading

  The 'Unloading' activity block represents the process from the moment when materials arrive at the entrance to the moment these materials are accepted and put into warehouses. In this case, it is simulated as a delay block with one input and one output. The input ($in(t)$) is also the input variable of the whole system, which is determined by replenishment decisions. In general, replenishment decisions are made based on previous replenishment recordings ($in(t-1)$), current inventory positions ($S_1(t)$, $S_2(t)$) and current exiting customer orders ($d(t)$).

  Namely,

  $$in(t) = f(in(t-1), S_1(t), S_2(t), d(t))$$

  The 'Unloading' activity block is a delay block, the activity output ($u_1(t)$) can be calculated from input variable.

  Namely,

  $$u_1(t) = in(t - T_{UN})$$

- Storing

  The 'Storing' activity block represents the process from the moment when materials enter warehouses to the moment these materials are transported out from warehouses. In this simplified process model, there are two storing blocks. 'Storing 1' indicates the inventory stored in raw material warehouses, while 'storing 2' indicates the inventory of materials stored in product warehouses as parts of products.

  For 'storing 1' block, there are three inputs ($u_1(t)$, $u_6(t)$ and $u_8(t)$) and one output ($u_2(t)$). $u_1(t)$ denotes the material flow from suppliers entering raw material warehouses. $u_6(t)$ denotes the material flow recycled from disassembled products. $u_8(t)$ denotes the materials flow returning from workshops to raw material warehouses. While the stock output $u_2(t)$ is influenced by different production decisions, which are usually determined by current inventory positions in different warehouses ($S_1(t)$ and $S_2(t)$) and exiting customer orders ($d(t)$).

  Namely,

  $$u_2(t) = g(S_1(t), S_2(t), d(t))$$

  For 'storing 2', there are one input ($u_3(t)$) and two outputs ($u_4(t)$ and $u_5(t)$). $u_3(t)$ denotes the material flow as parts of products after processing/assembling. While $u_5(t)$ denotes the material flow recycled from disassembled products which is determined by recycle decisions. $u_4(t)$ denotes the material flow as parts of products delivered to customers which is related with distribution decisions.

  According to general recycle and distribution policies,

  $$u_5(t) = r(S_1(t), S_2(t), d(t))$$

  $$u_6(t) = h(S_2(t), d(t))$$

  With the available material flow variables, the inventory positions of raw material and product warehouse $S_1(t)$ and $S_2(t)$ can be calculated by following equations:

  $$S_1(t) = S_1(t-1) + u_1(t) + u_6(t) + u_8(t) - u_2(t)$$

  $$S_2(t) = S_2(t-1) + u_3(t) - u_4(t) - u_5(t)$$

- Processing/Assembling

  The 'Processing/Assembling' activity block represents the production process of raw materials into intermediate or final products. In this model, it is simulated as a delay block ($T_{P/A}$) with one input ($u_2(t)$) and three outputs ($u_3(t)$, $u_7(t)$, $u_9(t)$). $u_2(t)$ denotes the material flow from raw material warehouses to production workshops. After Processing/Assembling process, the materials transported into workshops have three destination options. $u_3(t)$ denotes the material flow to product warehouse as part of the products. $u_7(t)$ denotes the unused material flow returning to raw material warehouse. While $u_9(t)$ denotes the damaged material flow to be scraped. In the long-term equilibrium situation, the ratio of the material flow to different destinations reaches a stable level. The ratio may be estimated from historical data in the information system.

  In this general process model,

$$\begin{cases} u_3(t) = p_1(t) \times u_2(t - T_{P/A}) \\ u_7(t) = p_2(t) \times u_2(t - T_{P/A}) \\ u_9(t) = p_3(t) \times u_2(t - T_{P/A}) \end{cases}$$

  Where, $p_i(t)$ denotes the corresponding percentage of material flows to different process states after processing/assembling in the equilibrium condition. It is noted that $p_1(t) + p_2(t) + p_3(t) = 1$.

- Disassembling

  The 'Disassembling' activity block represents the disassembling process to recycle materials from finished products back to raw material warehouses again. In this case, it is simulated as a delay block (T_{DA}) with one input ($u_5(t)$) and one output ($u_6(t)$). $u_5(t)$ denotes the material flow from products warehouse to be disassembled. $u_6(t)$ denotes the disassembled material flow to raw material warehouses. It is noted that

$$u_6(t) = u_5(t - T_{DA})$$

- Returning

  The 'Returning' activity block represents the process of returning unused materials back to raw material warehouses. In this model, it is simulated as a delay block (T_R) with one input ($u_7(t)$) and one output ($u_8(t)$). $u_7(t)$ denotes the unused material flow from workshops. $u_8(t)$ denotes the material flow back to raw material warehouse. It is noted that

$$u_8(t) = u_7(t - T_R)$$

- Delivering

  The 'Delivering' activity block represents the delivery process of finished products to customers. In this case, it is simulated as a delay block (T_D) with one input ($u_4(t)$) and one output ($out_1(t)$). $u_4(t)$ denotes the material flow to be delivered after processing/assembling. While $out_1(t)$, known as one of the output variables for whole system, denotes the materials have already been delivered to customers. It is noted that

$$out_1(t) = u_4(t - T_D)$$

- Scrap

  The 'Scrap' activity block represents the abandon process of damaged or spoiled materials. In this model, it is simulated as a delay block with one input (u_9) and one output ($out_2(t)$). $u_9(t)$ indicates the materials to be scrapped. While the $out_2(t)$, also known as one of the output variables for whole system, indicates the materials have already been scrapped. It is noted that

$$out_2(t) = u_9(t - T_s)$$

This 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 detect and diagnose faults. In order to simplify the model it is assumed that all the material flow variables are random variables following Gaussian Distribution and the disturbances are white noises.

4.3. Fault detection

As mentioned before, both FDI analytical redundancy approach and DX consistency logical approach detect faults by tracing discrepancies between observed behaviours and expected behaviours predicted from models. The observed behaviours refer to the inventory attributes which are assumed to be continuously recorded and monitored. In this dissertation inventory positions are set as the observed variables. Moreover, the observed inventory position of specific materials is a fixed number at each time point which should be available in ERP systems. While the corresponding expected inventory position from previous developed models is a random distributed variable as shown in the figure.

In this framework, the fault detection process is conducted through statistical hypothesis tests on whether expected inventory position equals the recorded value.

H0: No faults have occurred (expected inventory position equals recorded inventory position)

H1: Uncertain faults have occurred (expected inventory position does not equal recorded inventory position)

If the null hypothesis H0 is accepted (condition 1 in figure 4.2), it is highly likely that no faults have occurred and the system is functioning in a normal and healthy way. If H0 is rejected (condition 2 in figure 4.2), there is a high likelihood that certain faults have occurred. It is noted that the reliability of results is highly dependent on the choice of confidence levels.

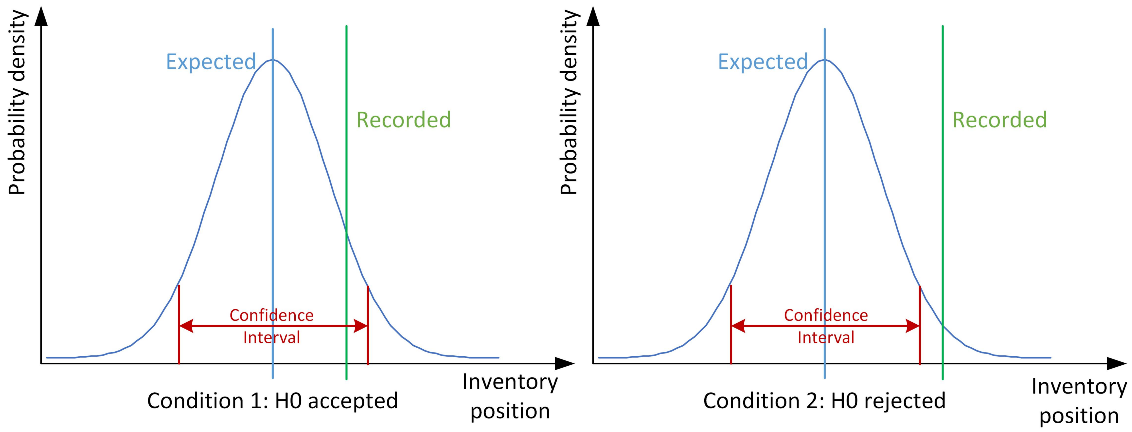


Figure 4.2: Illustration of different conditions in statistical hypothesis tests

However, as time goes on, the uncertainty of expected values will keep on increasing since the addictive effects of model uncertainty and disturbances. In other words, the variance of expected values will be significantly increased as shown in figure 4.3. Under this situation, the sensitivity of this fault detection approach will become weaker and the system may bear higher risk for fault detection failures.

In order to address this problem, Kalman filter is introduced into this fault detection framework. Kalman filter can be considered as a special stochastic optimization approach in linear quadratic systems. The approach applies iteration procedures with historical state data and current observations to calculate the optimized estimations of system states with less uncertainty.

In Kalman filter algorithm (as shown in figure 4.4), it is assumed that the real system states $x(k)$ at time point k are derived from historical states $x(k-1)$ at previous time point $k-1$.

$$x(k) = F(k)x(k-1) + B(k)u(k) + w(k)$$

Where,

$F(k)$ is the state-transition model linking current and past states

$B(k)$ is the control input model linking current states with current inputs

$u(k)$ is the input variable at time point of k

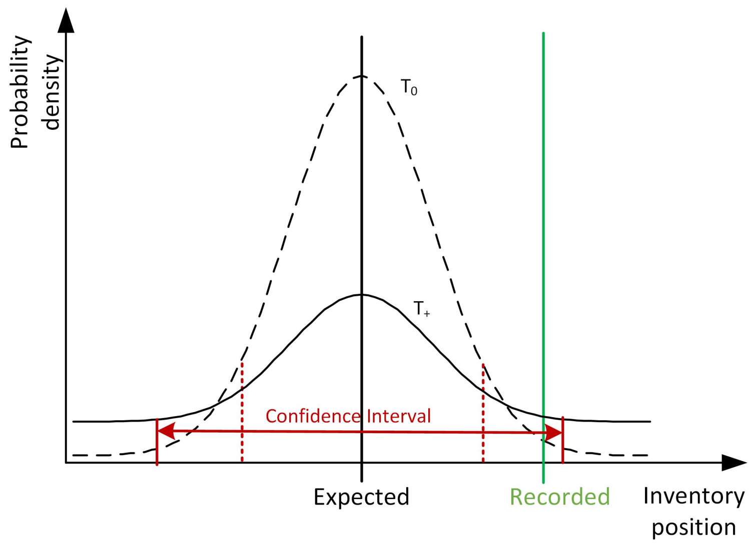


Figure 4.3: Illustration of uncertainty increase in statistical hypothesis tests

$w(k)$ is the process noise following normal distribution $N(0, Q(k))$, while $Q(k)$ denotes the covariance of the process noise.

For the observation $(z(k))$ of system states

$$z(k) = H(k)x(k) + v(k)$$

It is denoted that

$H(k)$ is the observation model linking observed and real states

$v(k)$ is the observation noise following normal distribution $N(0, R(k))$, while $R(k)$ denotes the covariance of the observation noise.

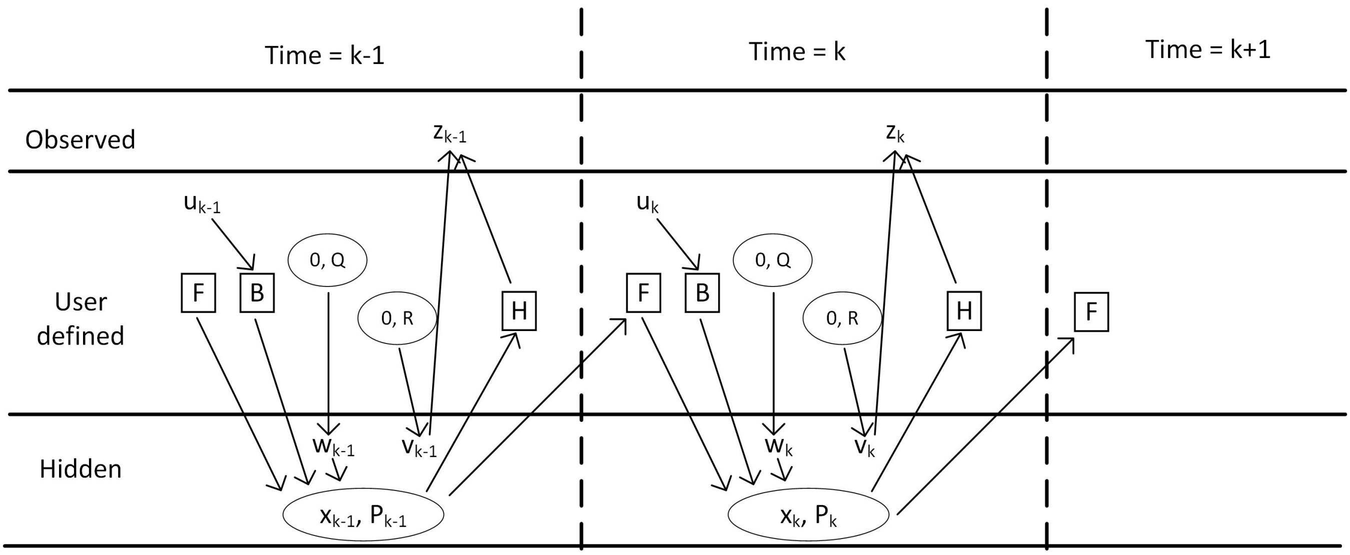


Figure 4.4: Illustration of Kalman filter algorithm

The application procedures of Kalman filter can be mainly divided into two steps. It is denoted that $\hat{x}(n|m)$ represents the estimate of x at time point n given observation at time m.

- Estimation: Estimate current states based on last updated results

With the past predicted states ($\hat{x}(k-1|k-1)$) updated at time $k-1$, the estimate of states ($\hat{x}(k|k-1)$) at time point k can be calculated.

$$\hat{x}(k|k-1) = F(k)\hat{x}(k-1|k-1) + B(k)u(k)$$

And the predicted estimate covariance is,

$$P(k|k-1) = F(k)P(k-1|k-1)F(k)^T + Q(k)$$

- Update: Update estimated states with current observations

  In order to fulfil the implementation of iteration cycles, the predicted states ($\hat{x}(k|k-1)$) and corresponding estimate covariance ($P(k|k-1)$) are updated based on current observations ($z(k)$).

$$\hat{x}(k|k) = \hat{x}(k|k-1) + K(k)(z(k) - H(k)\hat{x}(k|k-1))$$

$$P(k|k) = P(k|k-1) - K(k)H(k)P(k|k-1)$$

  It is noted that $K(k)$, known as optimal Kalman gain, determines how state estimates can be influenced by observations.

$$K(k) = P(k|k-1)H^T(k)(H(k)P(k|k-1)H^T(k) + R(k))^{-1}$$

In the process model developed before, taking the inventory positions of raw material and product warehouses as states variables, the state system equation and observation system equation will be,

$$\begin{bmatrix} S_1(k) \\ S_2(k) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} S_1(k-1) \\ S_2(k-1) \end{bmatrix} + \begin{bmatrix} 1 & -1 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & -1 & -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} u_1(k) \\ u_2(k) \\ u_3(k) \\ u_4(k) \\ u_5(k) \\ u_6(k) \\ u_8(k) \end{bmatrix} + \begin{bmatrix} w_1(k) \\ w_2(k) \end{bmatrix}$$

$$\begin{bmatrix} z_1(k) \\ z_2(k) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} S_1(k) \\ S_2(k) \end{bmatrix}$$

Through substitution of relative parameters and variables. The Kalman filter algorithm can be applied for the optimization of fault detection framework.

In summary, with the developed model and observed states, Kalman filters are applied to filter out the normal system behaviours. This is done by comparing the predicted states from previous models and the updated states observed from relevant ERP systems. After filtering, the residuals are tested through statistical hypothesis testing in order to detect the occurrence of faults. Namely, if the residuals between the observed and the expected states are beyond a certain level of confidence intervals, the null hypothesis that the system is working in a normal state without faults will be rejected. This result will then triggered a series of fault diagnosis procedures in order to distinguish which specific faults have happened.

4.4. Fault diagnosis

The application of Kalman filter based FDI approaches is effective and efficient in fault detection. However, FDI approaches are not suitable for fault diagnosis purposes in logistics management because it is sensitive to model uncertainty and system dynamics. In order to avoid this problem, instead of FDI approaches, the proposed method framework utilized DX approaches for fault diagnosis which is more reliable. The faults are traced by distinguishing their varied behaviour patterns with preliminary tests as well as further investigations on movement sequences from a artificial intelligence perspective.

4.4.1. Preliminary test

With the developed quantitative model, mathematical simulations on the possible behaviours of specific logistics systems under different scenarios can be conducted. The results are expected values which are regarded as standard values in normal patterns. The actual values can be acquired through periodical physical auditing. While in this case, the recorded values are from the information systems like SAP/ERP. In order to identify the specific patterns of different faults, a series of simulations on the possible effects will be conducted. The fault effects are calculated in multiple measurable criteria. Because of different function mechanisms, the effects of varied faults will be distinguishable. In this way by comparing the corresponding expected, actual and recorded values, the occurrence of faults can be preliminarily detected and diagnosed.

For example, as indicated in section 3.1.1, transaction faults may cause the recorded inventory position different from its expected and actual value. Therefore, if only transaction faults have happened, the actual and expected inventory position should be almost the same, while the recorded inventory position will be different from them. Once this pattern is distinguished in the logistics system, it is highly likely that transaction faults have occurred. With similar ideas, shrinkage and misplacement faults can also be preliminarily diagnosed.

4.4.2. Movement sequence check

Currently, computer-based ERP systems have been widely applied in modern logistics management. These applications provide possibility to trace the material flow of a uniquely identified materials in terms of movement records. In other word, the movement sequence is with respect to a certain identifiable component. In general, all the movements of material flows are required to be recorded in ERP system database by corresponding movement codes with predefined formats. As shown in figure 4.5, the movement codes are presented as MOV i for this simplified general logistic model. It is noted that the process model 4.5 used in movement sequence check is a bit different from fault detection part 4.1, where the process model is applied for a specific kind of component in terms of quantitative variables. However, for movement sequence check, the process model present the logistics system by qualitative codes. Moreover, it is assumed that the complete movement sequence history for a specific component is accessible for the implementation of this DX approach.

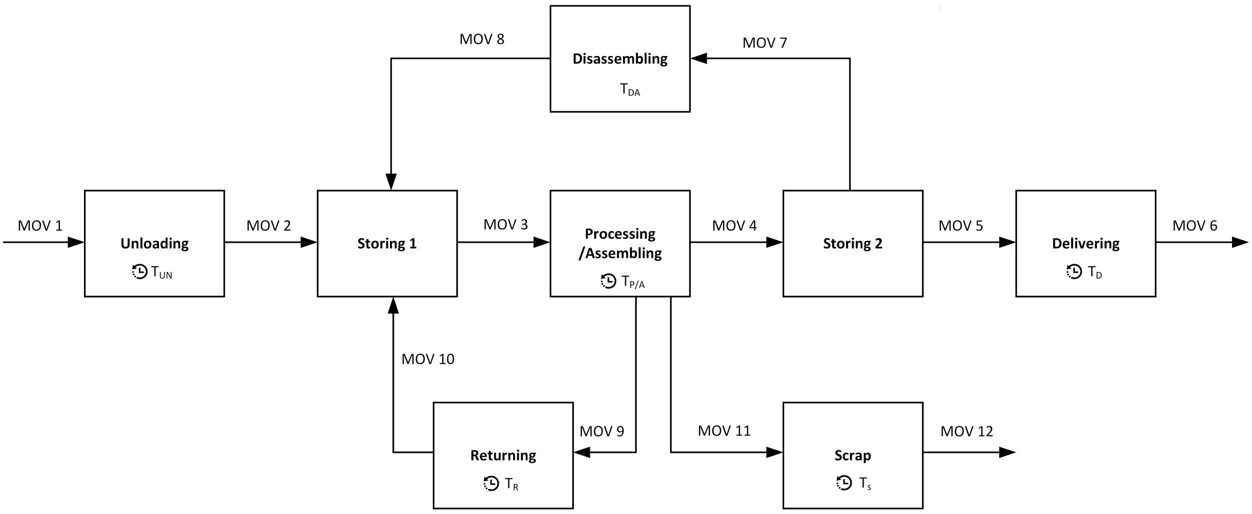


Figure 4.5: Process model with movement sequences

In figure 4.5, it is illustrated that even though there are multiple material flow possibilities, there are certain regulations and patterns in movement sequences. For example, movement code MOV 8 should be after MOV 7, while movement code MOV 10 should be after MOV 9. figure 4.6 is the movement sequence diagram designed for this simplified model to explicate the sequence patterns of specific movements in a direct way. The arrows direct from the previous movement state to next movement possibilities. In this way, faults can be diagnosed by tracing the movement history of specific materials in ERP systems.

With the developed movement sequence diagram (figure 4.6) in this research, a large number of faults, like improper operations and inventory misplacements, can be detected and diagnosed by tracing their specific movement sequence patterns in ERP systems. In practical, these records are input manually into ERP systems by workers or carriers at working sites, when the movement orders are being implemented.

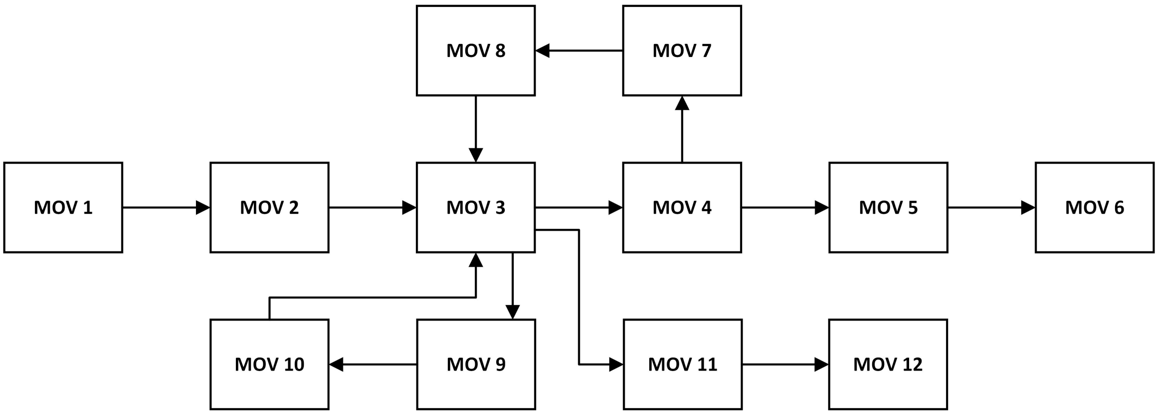


Figure 4.6: Normal movement sequence diagram

The normal sequence of movements should follow a certain pattern as shown in the figure 4.6. In this figure the arrows show all the possible sequence combination of movements in terms of movement codes. Even though some specific movement code (such as MOV3 and MOV4) can be followed by multiple movement choices, the movement sequence should follow some certain patterns or rules. Take the wrong movement code input error as an example. If workers wrongly input MOV10 instead of MOV 8 into the ERP system, when returning the disassembled materials into raw material warehouses. In reality, this fault may cause chain reaction leading to unnecessary duty and troubles in inventory management. This fault can be addressed by tracing the abnormal movement sequence patterns in the history data of ERP system. In this case, the movement history of these wrongly recorded goods will contain code sequence "...- MOV7-MOV10-MOV3-...", which is forbidden in normal possibilities.

This method applies model-based diagnosis techniques based on computer science and AI theories. Through tracing these abnormal movement sequence patterns, a large number of faults can be distinguished. This method can be applied in ERP system as an active fault detection module. Once the system detect abnormal code input, it can generate an alert immediately and directly to the relevant managers. If these fault can be found in the early period, it is more likely and much easier to timely correct them in order to eliminate or minimize their negative effects.

5

Case study

In order to demonstrate the application process of proposed model-based FDD method, a case study has been conducted on a Custom Warehouse in the Netherlands. The information for this case study is collected from interviews, conferences and company periodical documents.

5.1. Case Description

This case study is conducted on the Custom Warehouse of ABC in the Netherlands. ABC is one of the world's leading manufacturers and head-quartered in the Netherlands. As part of its supply chain operations ABC is running a Customs Warehouse under license. Goods in such a warehouse are formally under customs supervision and payment of import duties is suspended until a final customs destination is known. 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 products their customs status (re-export outside the EU as "in transit", entering into the EU as "free circulation", etc.) is known (accuracy). Every month ABC prepares a so called Electronic Periodic Declaration (EPD): an audit file with evidence of the warehouse movements, so customs can supervise at a distance. Before granting a license, customs must make sure that the processes and information systems that feed the EPD can be relied on.

In this case, we focus on possible deficiencies that hidden in the logistic processes, that may lead to inaccurate inventory records, based on the ERP systems (like SAP and TonT) that generates the electronic reports, and the inbound process where goods are delivered by a third-party logistics provider (3PL) and entered into inventory. Some trade documents (e.g. transit documents) are prepared by a freight forwarder (FF). Every month, the TonT system is used to generate an Electronic Periodic Declaration in the form of an audit file and sent to customs on CD-ROM. The audit file is a large data file in pre-defined format.

The ERP system of ABC records a stream of movements: transactions that represent a status update. TonT interfacing ERP generates the EPD, so it should correctly declare those movements which are relevant for the customs procedures. Customs experts have determined in advance which types of movements in ERP are customs relevant, for example when involving goods from foreign origin. So those movements are filtered out. If goods are mistakenly categorized as customs related, it should trigger a control response in information systems.

Initial analysis has revealed that many errors can be attributed to the inbound process, where goods are entered into the warehouse. Once goods have entered into the warehouse, it is much harder to trace errors. As a result ABC had to implement several additional control measures related to the inbound process, 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. Executing these additional controls is costly. In the long run, ABC would like to reduce these additional manual controls and rely on automated controls.

5.2. Process Model

As indicated in the general framework, modelling is the first step of model-based FDD method. Based on the information from interviews and relevant documents, the logistics activities of custom warehouses in company ABC are simplified and modelled into a process model. It is noted that expert consultation plays an important role in the development process of this model. In this case study, the preliminarily developed model is validated by experts from ABC during interviews.

As shown in the figure 5.1, there are three kinds of raw materials: A, B and C. According to their different sources, storing locations, these materials are further divided into six groups. For the model used with Kalman filter, this would lead to one set of inventories per group (e.g. In this case, S1 for A, S2 for C2, and S3 for C3). More specifically, A and C (C2 and C3) are unique materials from EU and non-EU suppliers respectively. The fundamental differences between C2 and C3 is their different targeted customers. Materials C2 are targeted at non-EU customers, while materials C3 can be delivered to EU customers after levying all the necessary duties. Moreover, materials C2 are stored at bonded warehouse and materials C3 are stored at free warehouse. While for replaceable materials B, there are three groups of materials B1, B2 and B3. Materials B are usually standard materials from either EU or non-EU suppliers. But their storage locations are different. B1 are materials from EU suppliers stored at free warehouses. While B2 and B3 are materials from non-EU suppliers stored at bonded and free warehouses respectively. B2 can be transformed into B3 and delivered to EU customer after levying all the duties.

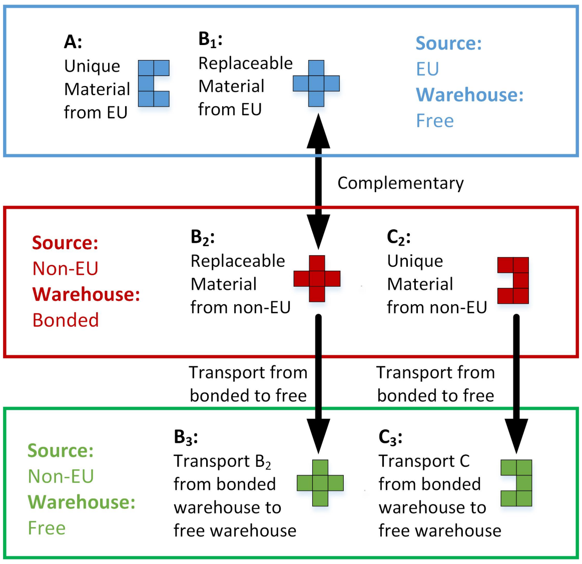


Figure 5.1: Classification of materials from different suppliers

After classifying materials into groups based on their different attributes, the structure of the Custom Warehouse in this case is comprehensively analysed in order to build a case-specific process model. As shown in the figure 5.2, the Custom Warehouse structure mainly consists of suppliers, free warehouse, bonded warehouse, production workshop and clients. The arrows indicate the material flows from one location or state to another and the cross lines on the arrows represent which kind of ERP system is used to record the material flows.

The whole material flow process can be divided into five sub-processes, inbound process, storage process, production process, recycle process and outbound process. More specifically, inbound process is from suppliers to warehouses mainly including unloading cargo from tracks to warehouse entrance, recording inbound materials in ERP systems and storing them at preassigned locations. Materials A and B1 are from EU suppliers to free warehouse, while Materials B2 and C2 are from non-EU suppliers to bonded warehouse. Materials B2 and C2 can be stored at free warehouse as Materials B3 and C3 after all the necessary duties are levied. The materials are stored at warehouse until a production order is implemented. The materials are transported into production workshop and are assembled or processed into products. The left ones are returned back to warehouses. Finally, the assembled or processed materials are delivered to customers as part of products. It is noted that the products with bonded materials (B2 and C2) are forbidden to be delivered to EU customers without levying the duties.

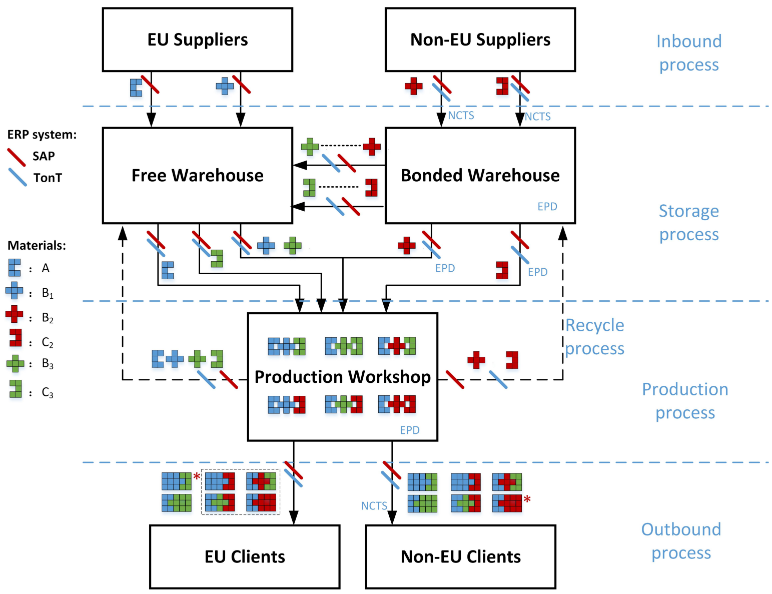


Figure 5.2: Structure diagram of Custom Warehouse

Based on the analysis before, process models can be developed from this Custom Warehouse structure as shown in figure 5.3 and figure 5.4.

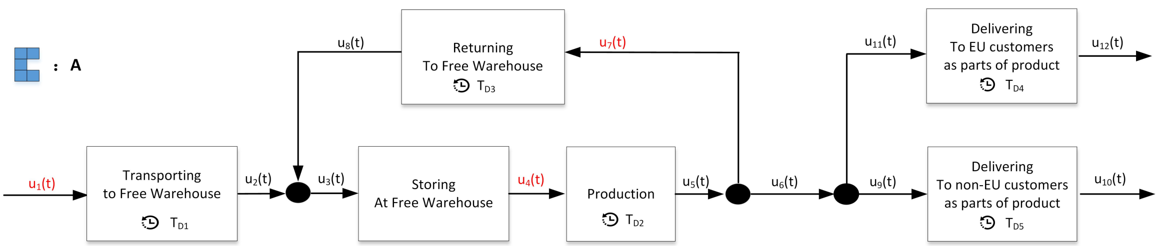


Figure 5.3: Process model for materials from EU suppliers

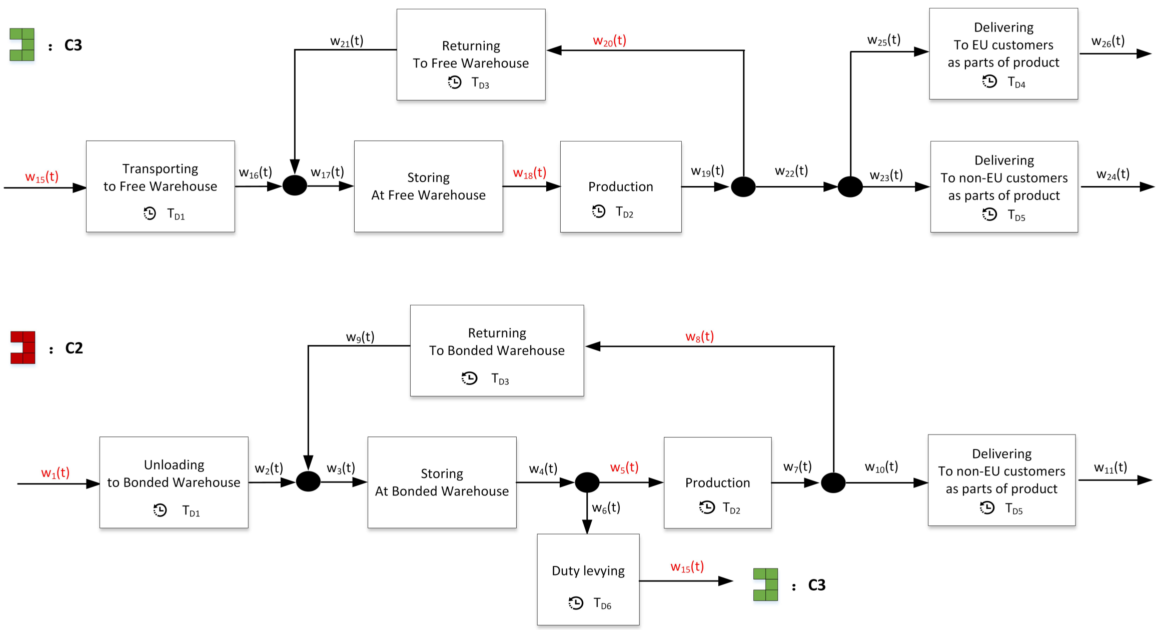


Figure 5.4: Process model for materials from non-EU suppliers

5.3. Risks leading to inventory record inaccuracy

According to the internal control report of ABC in 2013, inaccurate inventory records issues had caused a huge duty gap to be paid for the declaration clearance. The potential amounts of duties that ABC should pay if they would "clean" these inaccurate inventory records were up to 11.3 million. In order to address this huge duty gap and prevent these issues from happening again, The custom experts in ABC conducted a comprehensive analysis on all the possible risks and summarised these identified risks in a risk matrix. These risks are the potential causes for faults leading to inventory record inaccuracy.

In this case study, the potential faults regarded as risks by ABC are identified and classified into three groups. If common faults are identified, additional solutions or controls can be set up in advance. Based on the risk matrix developed by custom experts and the feedback from interviews, 16 risks are summarised as possible sources for inaccurate inventory records as show in table 5.1. In order to fulfil custom's requirements and maintain custom license, ABC arranges regular IT audits to verify whether these internal controls are operational in ERP.

Table 5.1: Risks leading to inaccurate inventory records

No.	Risk topic	Risk Name	Risk description
1	General	New Movement (TonT to GPA)	Using new Movement types (MvT) which are not determined for Track on Trade will not end up or end up wrong in GPA.
2	General	Incomplete or incorrect GPA by 3PL in SAP	Incomplete or incorrect GPA relevant data entered manually by 3PL in SAP/Error portal Track on Trade.
3	General	Incomplete or incorrect master data	Incomplete or incorrect master data caused by access security, change management and new master database.
4	General	ERP system failure	Emergency procedure SAP/Track on Trade down (data no longer available).
5	General	Compliance failure between different ERP systems	Possible mismatch records from different ERP systems like SAP and Track on Trade in this case.
6	Inbound	Discharge of MRN in NCTS	No Goods Receipt entry (GR) in SAP resulting in removal from customs supervision MRN number not processed in SAP.
7	Inbound	Incomplete or incorrect movement records in ERP systems	Incomplete or incorrect movement records in ERP systems in inbound processes.
8	Inbound	Wrongly classified components	During inbound processes, the component are recorded under a wrong inventory category.
9	Inbound	Misplacement of inbound components	When entering warehouses, the inbound components are placed at wrong locations in warehouse.
10	Storage	Shrinkage issues	Missing inventory during storage processes caused by multiple reasons.
11	Storage	ERP system failure	Missing data caused by the shutdown of ERP systems.
12	Production	Production delays or cancellations	Production delays or cancellations may lead to a significant inventory change.
13	Production	Damaged components and scraps	Damaged components and scraps may cause a loss of inventory.
14	Recycle	Incomplete or incorrect movement records in ERP systems	Incomplete or incorrect movement records in ERP systems in recycle processes.
15	Recycle	Misplacement of returned components	After the production, unused components are recycled back to wrong locations in warehouse.
16	Outbound	Incomplete or incorrect movement records in ERP systems	Incomplete or incorrect movement records in ERP systems in outbound processes.

In the table, the colour of risk number indicates its specific fault category. The red represents the transaction fault, the green represents the shrinkage fault and the blue represents the misplacement fault. It is found that there are a large variety of risks contributing to transaction faults. Most of them are general risks which may happen at any time in the logistics system. Besides, shrinkage faults mainly occur during the storage and production processes, while misplacement faults usually happen in the inbound and recycle process when the goods are placed in the relevant warehouses. It is noted that fault detection process will be simulated and demonstrated in Chapter 6.

5.4. Fault diagnosis in terms of movement sequence check

In this case study, all the movements are recorded as predefined code in ERP systems. These fundamental records of material flows provide necessary data for the implementation of fault diagnosis methods. Among these methods, movement sequence check is a useful tool to diagnose what fault is happening and where it is which is widely applied in real custom warehouse management. In this section, the diagnosis process on the misplacement of materials from bonded warehouses is presented to demonstrate the implementation process of movement sequence check.

With the developed process model in this research, some kinds of faults, like the misplacement of materials from bonded warehouses, can be diagnosed by tracing the specific sequence pattern of Movement in ERP systems. According to customs regulations, all the movements of custom related goods should be recorded in terms of the standard movement types (three-digit number). The detailed introduction of standard movement types is included in Appendix 1. In practice, these records are input manually into ERP systems by workers or carriers at working sites. For goods in Bonded Warehouse, the process model is shown as in figure 5.5 . The more detailed introduction about the construction of this model will be explicated in mid-term presentations.

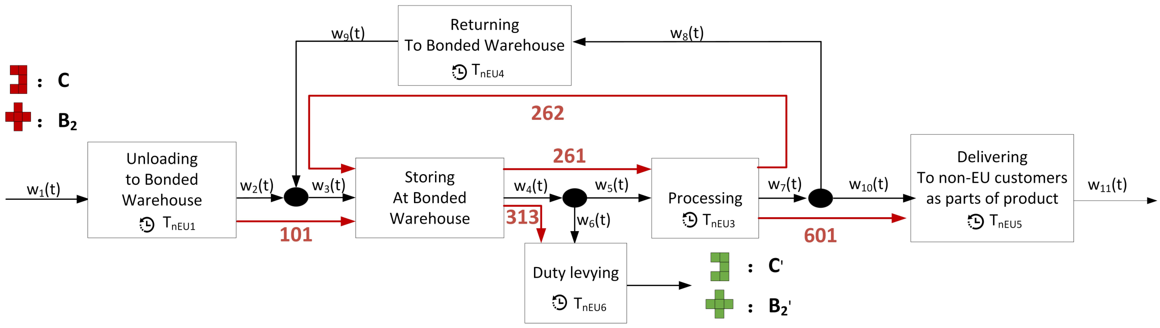


Figure 5.5: Process model with movement sequences

The normal sequence of movements should follow a certain pattern as shown in the Figure 2. In this figure the arrows show the possible sequence combination from one movement code to another. Even though for some specific movement code (such as 101 and 262) can be followed by multiple choices, the possible sequence should also follow some certain patterns or rules. For example, code 261 can be shown after code 101, but code 262 cannot.

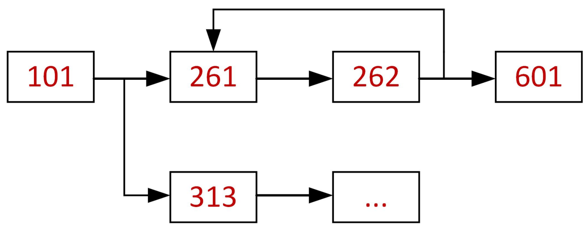


Figure 5.6: Normal movement sequences diagram

Sometimes, when the goods are returned back to bonded warehouse, the workers may confuse the use of code 261 and 101 because of carelessness or unawareness. Instead of type 262 into ERP system, they type 101. The movement sequence history of these specific goods will show an abnormal pattern. In this case, the history of these goods will contain code sequence "...- 261-101-261-..." which is different from the normal possibilities. This fault may cause unnecessary repeated duty levied on the same goods, because code 101 may trigger a duty levy process in customs system automatically. Through tracing these kinds of abnormal movement sequence pattern, a lot of faults can be distinguished. This method can be applied in ERP system as an active fault detection module. Once the system detect abnormal code input, it can generate an alert immediately and directly to the relevant managers.

6 Simulation

Based on the process models developed in the case study, quantitative simulations can be conducted tracing material flows in the custom warehouse of company ABC. These process models can be further developed into quantitative models for simulations. In this paper, a series of simulation tests are implemented on the system behaviours under different scenarios. The simulation results not only provide insights for the theoretical researches of logistics management, but also are useful for internal control and auditing processes in practice. The simulation may help deepening the understanding of policy functions and fault effects, which are important for inventory and logistics management. Meanwhile, with the assistance of relevant results, the managers can take a better control of inventory situations and monitor possible faults in an active way. Moreover, the developed model and relevant simulations can be easily extended into case-specific and user-defined tools, which can be emerged into ERP systems as an automatic FDD component.

In this work, the simulation is implemented for multiple purposes.

- To demonstrate and understand the functions of different inventory management policies;
- To evaluate the performance of different inventory management policies;
- To illustrate the potential effects of specific faults under predefined policy scenarios
- To identify possible fault patterns for specific faults;
- To predict the expected system behaviours under different scenarios which can be used in model-based FDD method.
- To induce understanding on faults situations for the communication between different stakeholders

In order to realize all these purposes, three set of simulation tests are designed and implemented based on the previous case study. Firstly, the system behaviours with three different inventory policies are simulated and the policy performances are compared and analysed in terms of the fluctuation level of inventory positions. Secondly, under the inventory policy selected from previous policy tests, the different effects of distinguished faults are simulated with the model. The simulation experiments can be divided into three groups based on its different categories, transaction, shrinkage and misplacement faults. Lastly, to demonstrate the application process of the proposed model-based FDD method and preliminarily verify its effectiveness in detecting faults, a simulation of fault detection process is conducted based on the transaction faults simulation results. It is noted that inventory positions have been selected as key inventory performance indicators in the simulations.

In this paper, the simulations are conducted through Simulink, a powerful graphical programming environment for simulation in the Matlab. With the help of Simulink, material flows can be easily simulated in terms of discrete signals and inventory positions can be directly calculated through the integration of input and output flows. Due to the lack of time and data, the movement sequence will not be simulated in this work.

6.1. Simulation settings

To transfer process models into quantitative models for simulation, several simulation setting procedures are necessary. Firstly, the previous developed process models are simplified and quantified by making assumptions. Secondly, inventory management policies are designed and applied in the programmed quantitative model. Thirdly, all the relevant parameters are assigned. After all these setting procedures, process models can be developed into quantitative models which are programmable in Simulink and further simulation tests can be implemented.

6.1.1. Assumptions

To transfer the process models into quantitative models which can be programmed in Simulink, several important assumptions are made as follows.

Assumption 1: All the simulation tests start from a equilibrium state and the initial inventory positions of different material are the same.

The storage in warehouses are not empty at the starting point of simulation. The initial inventory position should be a certain value $S_{initial}$ which is usually regarded as safety stock position. The safety stock is prepared in order to avoid the fluctuation caused by changing demands and delayed deliveries. Therefore, safety stock should keep the inventory position above predefined minimum line S_{min} with a certain range of demand fluctuation.

Namely,

$$S(0) = S_{initial} \neq 0$$

.

Assumption 2: The composition of outbound materials to customers as part of products should follow a certain distribution rate.

As indicated before, based on their different material sources and targeted customers, the materials are classified into six groups (A, B1, B2, B3, C2 and C3). It is assumed that there are two set of composition patterns (EU_i and $NonEU_i$) for each customer location as shown in the table 6.1.

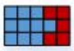
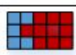
Pattern Name	Figure	Composition	Percentage
EU1		A + B1 + C3	P_{EU1}
EU2		A + B3 + C3	P_{EU2}
NonEU1		A + B1 + C2	P_{NEU1}
NonEU2		A + B2 + C2	P_{NEU2}

Figure 6.1: Composition of delivered products

Assumption 3: The customer demands from different locations are assumed to be random variables with normal distribution.

In this quantitative model, the customer demands $D_{EU}(t)$ and $D_{nonEU}(t)$ are simulated as a combination of fix values and white noises. The average of the demands for EU and non-EU customers are D_{EU} and D_{nonEU} respectively.

Assumption 4: The production capacity is assumed to be infinite.

In reality, the production capacity is highly limited by available human labours and finite production resources. The production process has its maximum daily production quantity. Once the customers' orders exceeds this limitation, the extra order will be put into waiting lists until the production line is available again. In order to simplify the production process in this simulation, it is assumed that the production capacity is assumed to be infinite. In other words, all the received orders at one time point are addressed at the same time, regardless of its amount.

Assumption 5: Most of the processes (unloading, transporting, returning, production and delivering) are modelled as delay blocks with fixed process delays.

As indicated in the general model-based FDD framework in chapter 4, the logistics process is modelled as a block with input and output flows. The implementation of each process may take a certain amount of time which is usually a random parameter. Generally speaking, apart from the storing process, the time of each process may follow certain patterns or random distributions and reach an equilibrium average in the long-term run. In this simulation, all the process except for the storing process are modelled as delay blocks with fixed process delays.

Therefore, the inputs and outputs of these processes follow the formula,

$$output_{processi}(t) = input_{processi}(t - T_{processi})$$

Assumption 6: The storing process is modelled as an integration block.

As introduced in Assumption 5, the storing process is different from other processes in this simulation. This is because the input and output of storing process are all policy related variables. The input variable is determined by replenishment policy, while the output variable is influenced by production policy. And the storing process is modelled as an integration block to continuously calculate the inventory positions.

6.1.2. Inventory management policy settings

As an important part of simulation settings, inventory management policy settings significantly influence the possible system behaviours. The inventory management policies mainly consist of replenishment, production, recycle and distribution policies. It is noted that in the custom warehouse case, the assembled products are assumed to be directly sent to customers. Therefore, the distribution policy will not be discussed here.

Literately, replenishment is the restoration of a stock to a targeted level or condition. Generally, the movement of inventory is from upstream suppliers to the storage locations of downstream actors. The purpose of replenishment activities is to keep inventory flowing in a sustainable and relatively stable way through the supply chain. The process is helpful in eliminating costly inventory overstocking and alleviating bullwhip effects. The most important decisions of replenishment policy are when to trigger a new round of replenishment and how much to be replenished. Typically, replenishment is triggered when the inventory level reaches a predefined reorder point. It is noted that it is usually too late to trigger a new order when stocks are depleted. Therefore, the reorder point should be set at a reasonable level not only to prevent shortages but also to avoid overstocking. The decision of replenishment amount is more flexible. The simplest way is to order fixed amount materials every time or restore the stock to a predefined level. However, with this replenishment policy, the inventory level will keep on fluctuating even with a fixed demand, which may increase the difficulty in inventory management. Therefore, when making replenishment decisions recently, most companies will take historical data as well as existing and predicted demands into consideration. Actually, a number of options are available for companies to make replenishment policies.

Besides, production refers to the action of manufacturing components from raw materials to part of intermediate or final products. During the production process, the value of components will be changed because of labour cost and additional value. In other words, production process may combine and emerge tangible inputs (raw materials, semi-finished goods, sub-assemblies) and intangible inputs (labour, ideas, information, knowledge) together into new goods or services. Generally speaking, there are two kinds of production categories, assembling and processing. Assembling stands for the mechanical permutation and combination of separate component parts into a machine or intermediate object. While processing refers to the chemical reaction by mixing multiple reagents and materials. The main differences between assembling and processing are that it is usually hard to recycle components back to raw materials after processing and that the assembling requires more labour. Generally, the decisions of production policy are highly dependent on customer demands and marketing strategies.

As for recycling, it is usually regarded as the process converting idle or wasted objects into reusable materials. Nowadays, because of environmental concerns and cost saving purposes, recycling has become a heated topic in modern industries. The underlying idea is to make maximum use of every components. In this case, the recycling activities are mainly limited on the left materials after manufacturing from workshops back to warehouses.

As shown in the figure, the red variables are policy related ones. More specifically, $u_1(t)$, $w_1(t)$ and $w_15(t)$ are replenishment policy related variables. $u_4(t)$, $w_5(t)$ and $w_{18}(t)$ are production policy related variables. While $u_7(t)$, $w_8(t)$ and $w_{20}(t)$ are recycle policy related variables. It is noted that A, C2 and C3 are selected as representatives for simultion in this paper.

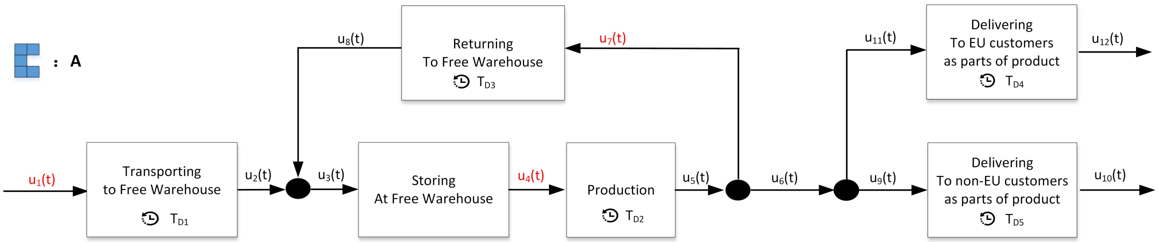


Figure 6.2: Process model for materials from EU suppliers

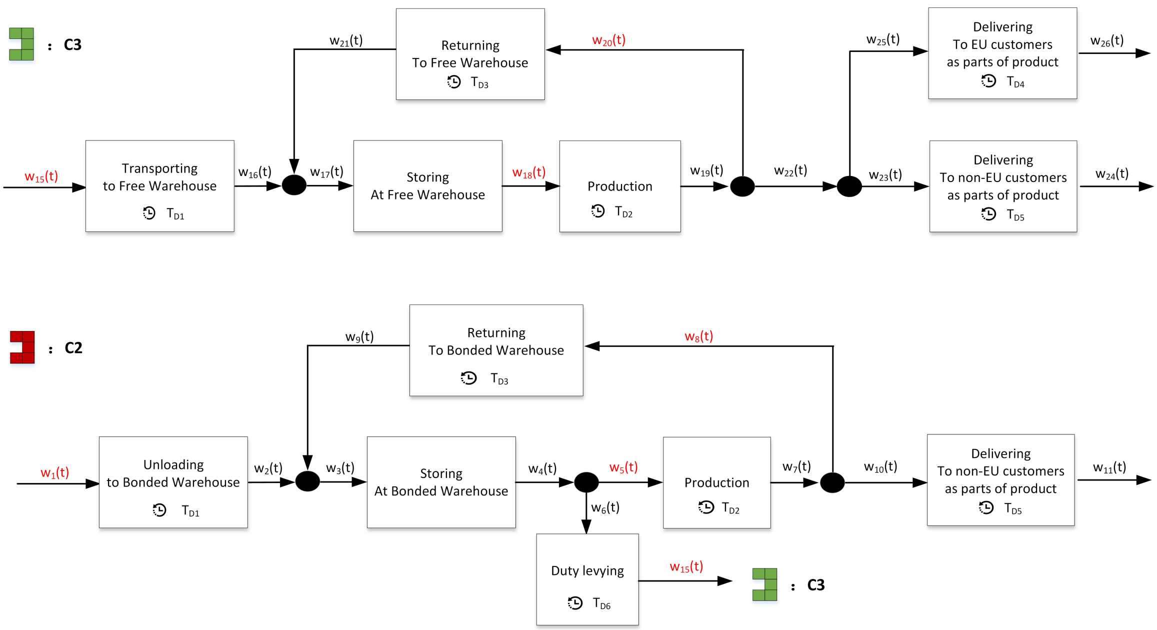


Figure 6.3: Process model for materials from non-EU suppliers

Apart from the inventory management policy scenario test, the other simulation test are all under the same inventory management policy scenarios.

- Replenishment policy: Continuous replenishment orders are implemented based on historical outputs. In addition to continuous replenishment orders, when the inventory position is under certain level (Inventory threshold S_{imin}), an urgent replenishment order with fixed amount U_i or W_i will be implemented.

  Namely,

$$u_1(t) = \begin{cases} u_6(t-1), & S_{fw}(t) > S_{fwmin} \\ U_1, & S_{fw}(t) \leq S_{fwmin} \end{cases}$$

$$w_1(t) = \begin{cases} w_{10}(t-1) + w_6(t-1), & S_{bw}(t) > S_{bwmin} \\ W_1, & S_{bw}(t) \leq S_{bwmin} \end{cases}$$

$$w_{15}(t) = \begin{cases} w_{22}(t-1), & S'_{fw}(t) > S'_{fwmin} \\ W_2, & S'_{fw}(t) \leq S'_{fwmin} \end{cases}$$

- Production policy: After a short delay, the received demands will be addressed initiating corresponding production processes. It is assumed the workshop has an unlimited production capacity with a fixed lead-time.

  Namely,

$$u_4(t) = D_{EU}(t) + D_{nonEU}(t)$$
$$w_5(t) = D_{nonEU}(t)$$
$$w_{18}(t) = D_{EU}(t)$$

- Recycle policy: $P_{irecycle}$ of the materials after production will be recycled to warehouse.
  Namely,

$$u_7(t) = P_{1recycle} * u_4(t - T_{EU3})$$
$$w_8(t) = P_{2recycle} * w_5(t - T_{nEU3})$$
$$w_{20}(t) = P_{3recycle} * w_{18}(t - T_{nEU9})$$

6.1.3. Parameter assignment

The assumptions and policy settings clarified the causal relation between all the input and output flow variables of each process. If the input variable is known, the output variable can be calculated. This output variable is the input variable for next process. In this way, all the material flows in this case can be calculate as long as the material flow from upstream suppliers and the initial states are known. Since the confidential agreement with the company, the parameters in this simulation are assigned in an approximate way. These important parameters are presented in table 6.1.

Table 6.1: Important parameter assignment

Parameter	Description	Value/unit
$P_{1recycle}$	Percentage of the left materials after production recycling to warehouse (A)	0.1/100%
$P_{2recycle}$	Percentage of the left materials after production recycling to warehouse (C2)	0.1/100%
$P_{3recycle}$	Percentage of the left materials after production recycling to warehouse (C3)	0.1/100%
D_{EU}	Average product demand from EU customers	5/unit
D_{nonEU}	Average product demand from non-EU customers	10/unit
T_{D1}	The delay time for inbound process	1/unit
T_{D2}	The lead-time for production	2/unit
$TD3$	The delay time for returning materials back to warehouses	1/unit
T_{D4}	The delivery time for to EU customers	1/unit
T_{D5}	The delivery time for to nonEU customers	2/unit
T_{D6}	The delay time for duty levying	1/unit
S_{fwmin}	Predefined minimum inventory position (A in free warehouse)	10/unit
S'_{fwmin}	Predefined minimum inventory position (C3 in free warehouse)	10/unit
S_{bwmin}	Predefined minimum inventory position (C2 in bonded warehouse)	50/unit
U_1	Urgent replenishment order quantity (A in free warehouse)	20/unit
W_1	Urgent replenishment order quantity (C2 in bonded warehouse)	20/unit
W_2	Urgent replenishment order quantity (C3 in free warehouse)	20/unit
$S_{initial}$	Initial inventory position	100/unit

6.2. Simulation results

Based on the assumptions and inventory management policy arrangement, the process models are transferred into quantitative models in Simulink as shown below. With these quantitative models, a series of simulation tests are conducted, including inventory management policy scenario test, fault pattern tests and an application example of model-based FDD method.

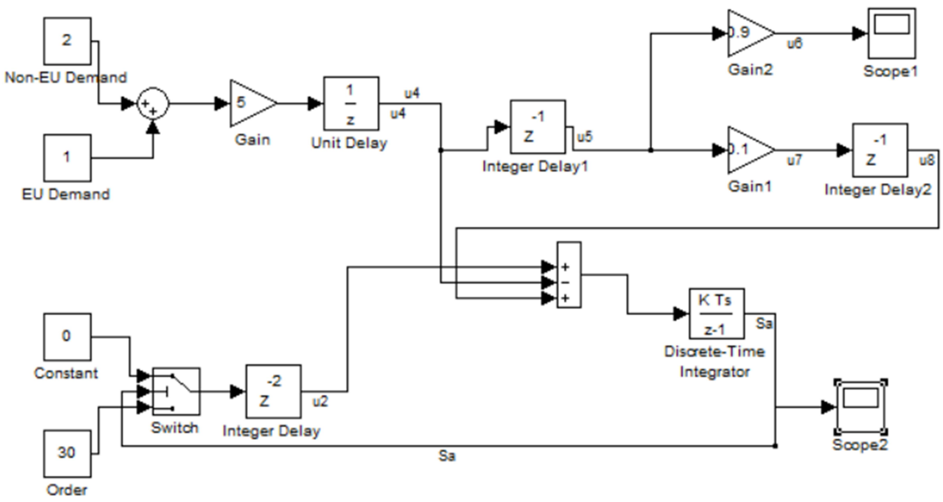


Figure 6.4: Control diagram of materials from EU suppliers

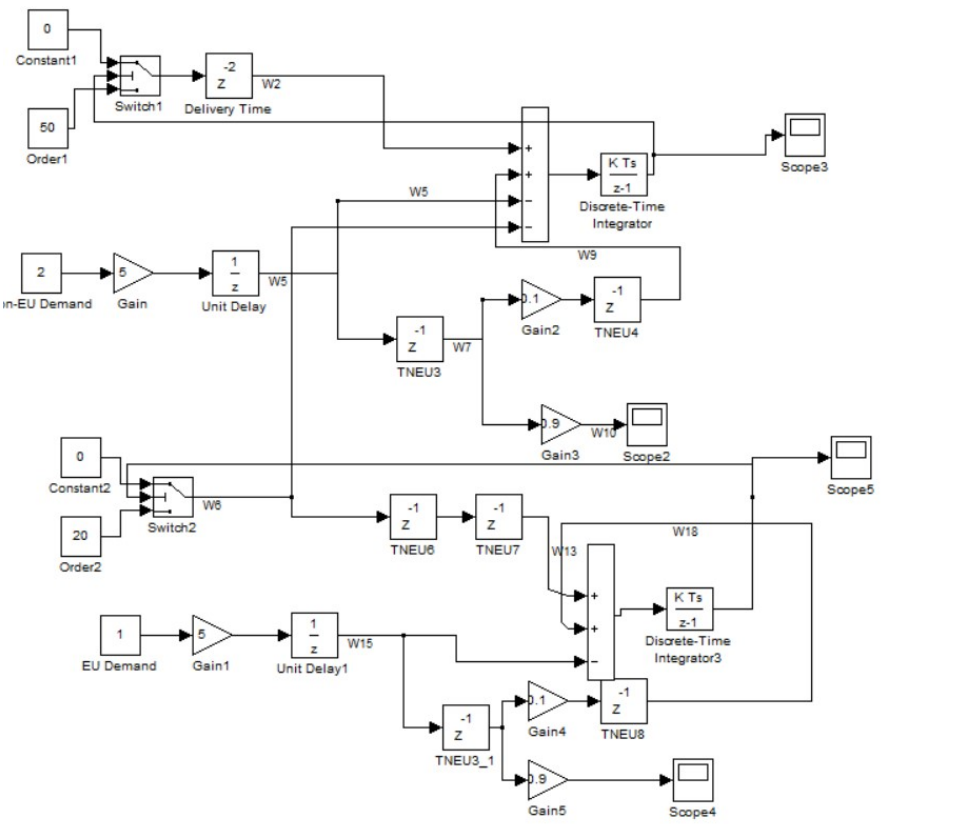


Figure 6.5: Control diagram of materials from non-EU suppliers

6.2.1. Inventory management policy scenario test

As mentioned before, the possible system behaviours highly depend on the inventory management policies, including replenishment policy, production policy and recycle policy. In this test, the inventory position of material A in free warehouse under different replenishment policies are simulated. The other policies follow the standard settings as mentioned before.

- Replenishment policy 1 (Fixed replenishment): When the inventory position is under certain level (Inventory threshold), a replenishment order with fixed amount will be implemented.
- Replenishment policy 2 (Fixed + Cycled replenishment): In addition to the fixed replenishment policy, this policy applies periodical cycled replenishment orders based on the equilibrium of the inventory system.
- Replenishment policy 3 (Fixed + Historical outputs based): In addition to the fixed replenishment policy, this policy involves the historical outputs into the replenishment decisions.

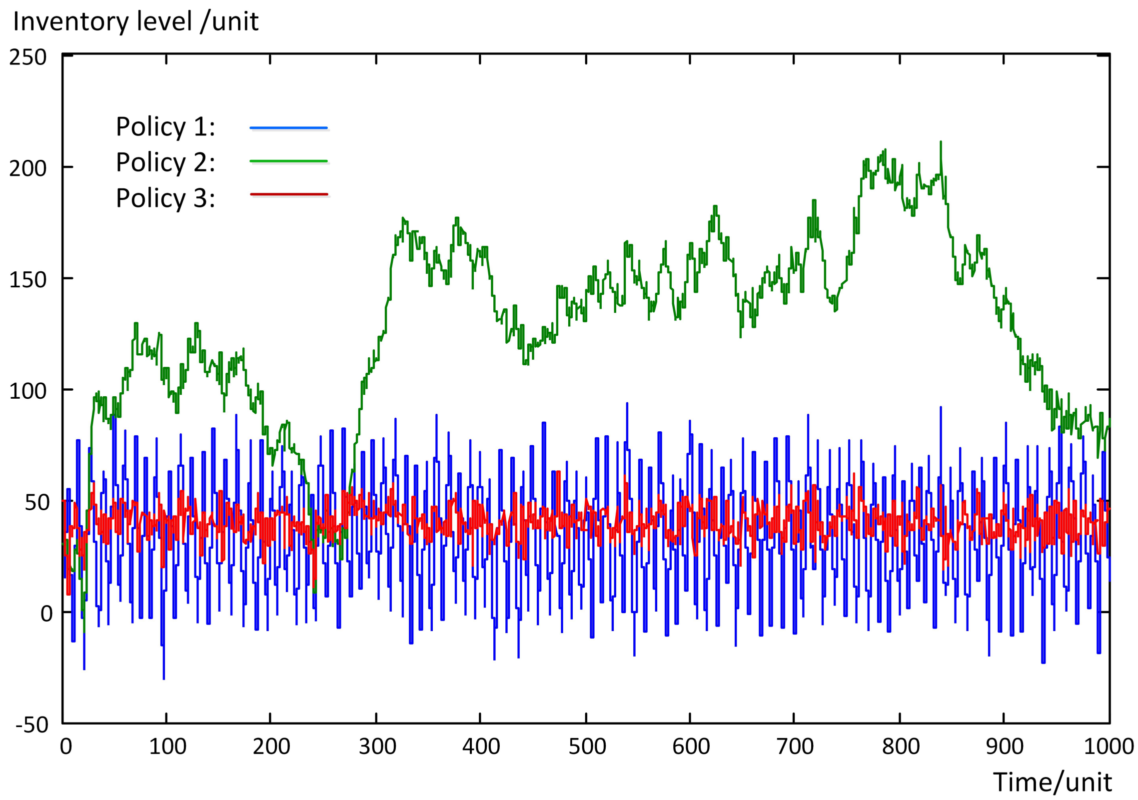


Figure 6.6: Inventory positions under different inventory management policy scenarios

This simulation shows the behaviours of inventory position (A) in free warehouse under different policy scenarios with unstable demands. It is notable that even with fixed demand, the fixed replenishment policy always leads to a constant oscillation. Meanwhile as for the other two policies, the inventory systems will become stable after a short-term adjustment.

From the picture, it is illustrated that for the unstable demands, the fixed + Cycled replenishment policy (Policy 2) will cause a larger scale of oscillation which is even larger than the pure fixed replenishment policy (Policy 1). It is also found that the Fixed + Historical outputs based replenishment policy (Policy 3) is with better inventory management performance in this case in terms of the oscillation level.

6.2.2. Fault pattern tests

The identification of specific fault patterns for different faults is helpful for FDD. According to the classification of the identified faults, the fault pattern tests are also divided into three separate simulation experiments.

Transaction faults As discussed before, transaction faults are usually caused by misidentification or miscount of the items leading to the discrepancy between recorded values and real stock. Even though the functions of transaction faults are varied, their effects on inventory positions can be summarised in two ways. In some situations, transaction faults may increase the outflows of materials or decrease the inflows, declining the inventory position in warehouses and vice versa. In this simulation, transaction fault A indicates the recording failure of a specific set of inbound materials. The inflow of material A into free warehouse is reduced. Although transaction fault B indicates the one-off recording failure of outbound materials.

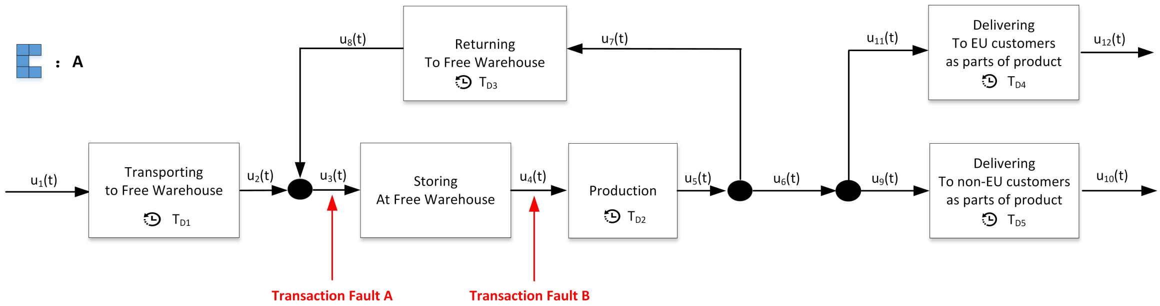


Figure 6.7: Process model for materials from EU suppliers

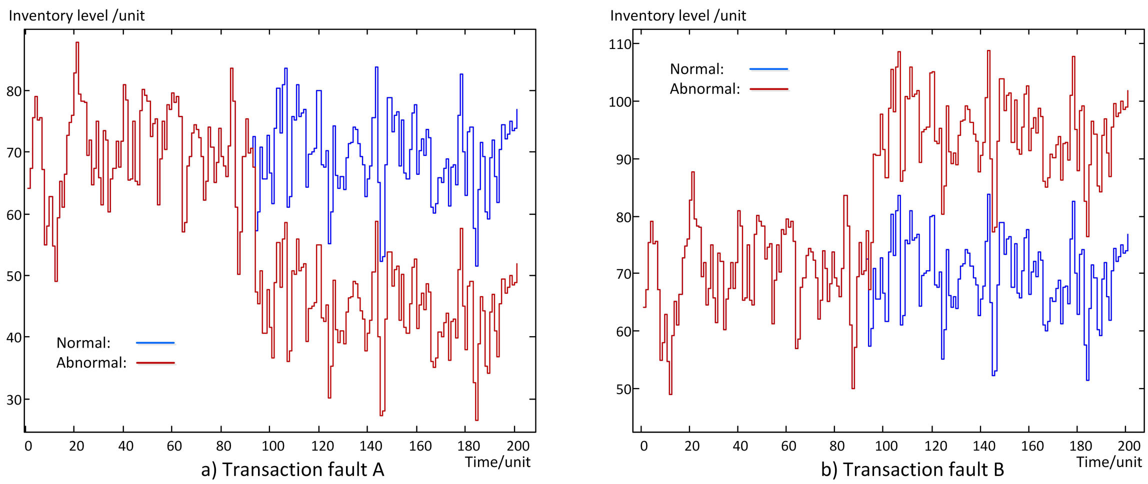


Figure 6.8: Inventory positions in free warehouse under different transaction faults scenarios

The simulation results are illustrated in figure 6.8. It is found that transaction fault A may lead to a decrease of the inventory position. While transaction fault A may increase the inventory position. The magnitude equals the specific material amounts which are failed to be recorded.

Shrinkage faults Shrinkage faults, known as stock loss, can be caused by either human factors (such as employee theft and shoplifting) or natural attributes (like spoilage). The employee theft and shoplifting usually happen intermittently . However, spoilage is a continuous shrinkage fault which is determined by the storage time of specific inventory. In this simulation, shrinkage fault A represents the occasional faults like employee theft and shoplifting. While shrinkage fault B stands for the continuous faults.

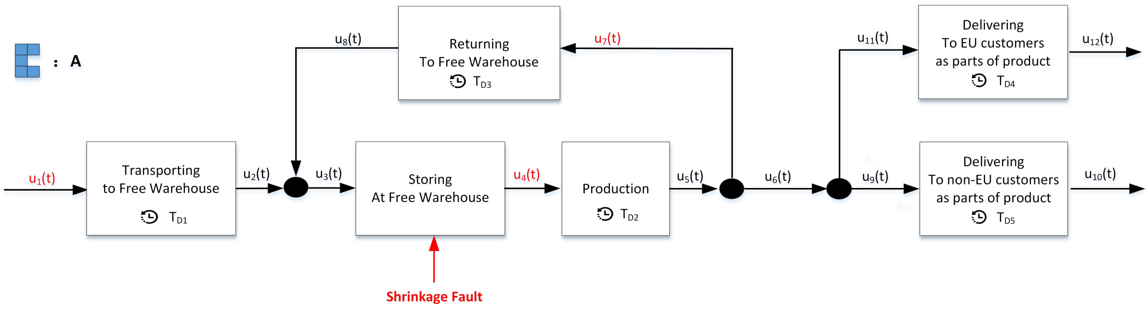


Figure 6.9: Process model for materials from EU suppliers

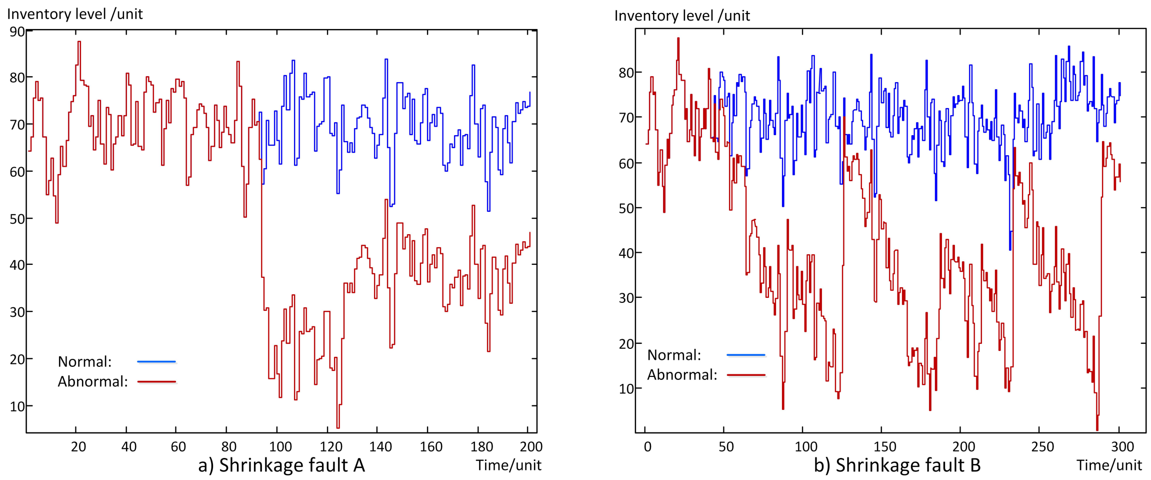


Figure 6.10: Inventory positions in free warehouse under different Shrinkage faults scenarios

According to the simulation results shown in figure 6.10, it is found that occasional shrinkage faults (shrinkage fault A) may decrease inventory positions in a fixed magnitude, while continuous shrinkage faults (shrinkage fault B) may lead to continuous decline of inventory positions. When the inventory position drops below the predefined minimum line, emergency replenishment is triggered causing a jump of the inventory position.

Misplacement faults Misplacement faults result in the inaccessible inventories which are not placed at the right locations and are temporarily unavailable for further operations. In this case, the misplacement of bonded materials into free warehouse will cause not only missing duties but also troubles in declaration processes. Misplacement fault A represents occasional misplacement fault, while misplacement fault B represents continuous misplacement fault.

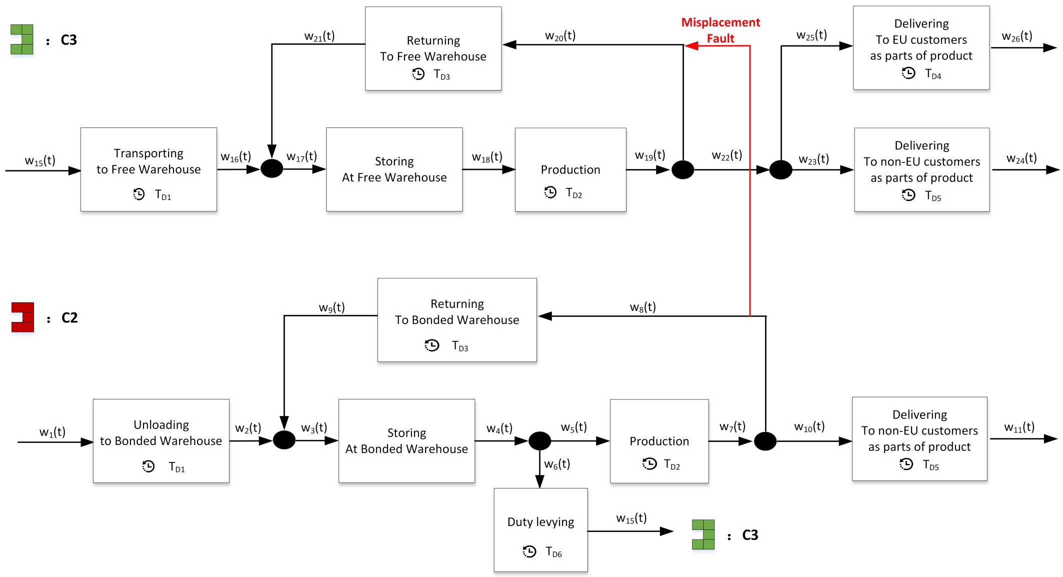


Figure 6.11: Process model for materials from non-EU suppliers

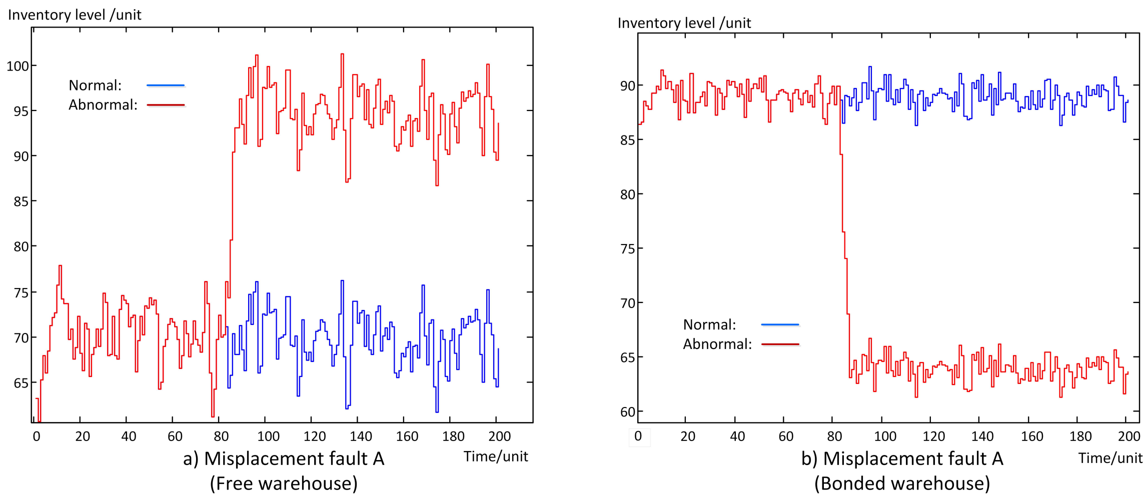


Figure 6.12: Inventory positions in different warehouse with accidental misplacement

This simulation shows the behaviours of inventory position with unstable demands with both the normal condition and misplacement faults. In this case, the misplacement is accidental and only happens once. It is noted that the system applies the Fixed + Historical outputs based replenishment policy in this fault test. Similar as the analysis before, the results show a decrease in bonded warehouse inventory position and a corresponding increase in free warehouse inventory position.

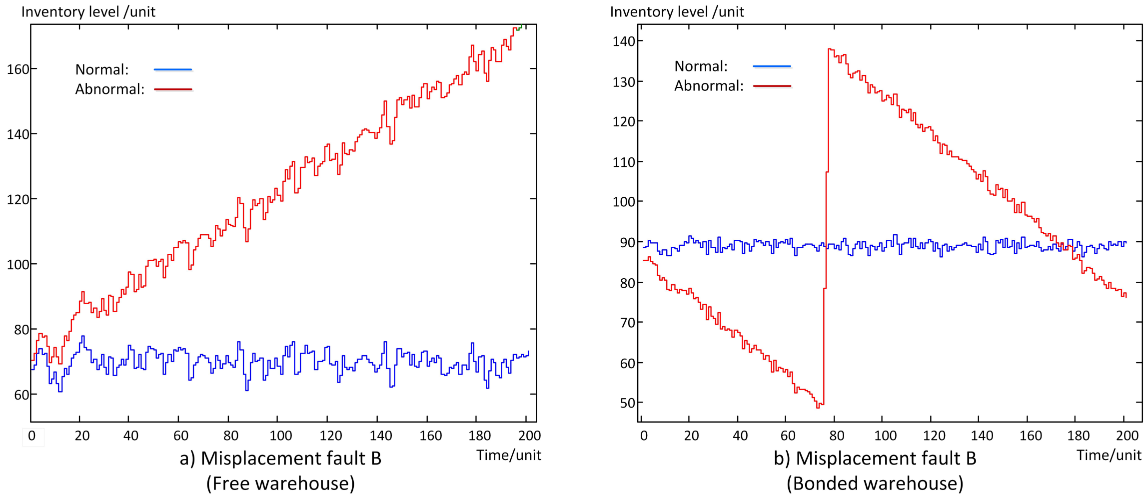


Figure 6.13: Inventory positions in different warehouse with constant misplacement

This simulation shows the behaviours of inventory position with unstable demands with both normal conditions and misplacement faults. In this case, the misplacement is continuous. More specifically, half of the recycled bonded materials will be misplaced to free warehouse . In this condition, the free warehouse inventory position will continuously increase. While the inventory position of bonded warehouse has shown a periodical decrease until the inventory position reaches the inventory threshold and triggers emergence replenishments.

6.2.3. An application example of model-based FDD method

In order to demonstrate the application process of the proposed methodology in detecting faults and preliminarily verify its effectiveness, the proposed model-based FDD method has been applied on the quantitative model with transaction fault A.

As introduced in section 4.3, the uncertainty of expected values predicted by models keeps on accumulating with time. And the fault detection sensitivity is reduced as the weakening power of statistical tests. In order to solve this problem Kalman filter is introduced. The simulation results of fault detection before and after the application of Kalman filter are shown in figure 6.14.

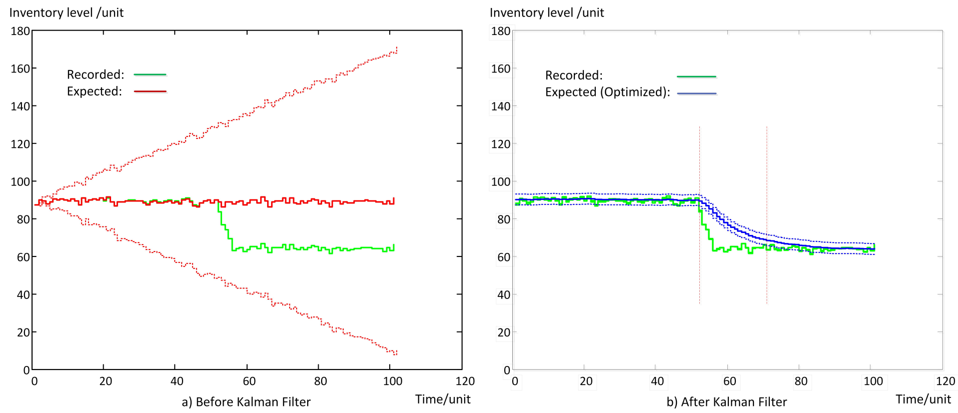


Figure 6.14: Comparison between normal model-based FDD method and optimized method with Kalman filter

The simulation results are shown in figure 6.14. The green line indicates the recorded inventory position. While the red and blue lines represent the expected inventory positions before and after the application of Kalman filter respectively. The areas between the dotted lines indicate the confident intervals for statistical tests. If the recorded inventory position is outside the confident area, it means the occurrence of faults is claimed and a further fault diagnosis is triggered.

As shown in figure 6.14 a), before the application of Kalman filters, the statistical test may lose its power in detecting the fault occurrence as the time goes on, because of accumulated system uncertainty. It is noted the power of statistical test is positively related with the confidence level. However, the rise of confidence level may also lead to the error rate in fault detection because of the normal demand oscillations. Figure 6.14 b) shows that the fault occurrence is identified after the application of Kalman filter as proposed in general framework.

7 Conclusion and Recommendation

7.1. Conclusion

In order to address inventory record inaccuracy issues in custom warehouses, this dissertation proposes an innovative model-based FDD methodology combining previous FDI approaches and DX approaches. The proposed methodology is applied and tested in a real custom warehouse case in the Netherlands. A series of simulations have been conducted based on the case study to test system behaviours under different inventory and fault scenarios as well as to demonstrate the application process of the proposed methodology. The simulation results are helpful for the identification of specific fault patterns for different fault scenarios. Meanwhile, the effectiveness of the proposed methodology is also preliminarily verified in the simulation. Moreover, considering the complexity of stakeholder involvement, a comprehensive stakeholder analysis has been implemented as well. Multiple actors with varied interests and powers have been involved in the inventory record inaccuracy issues of custom warehouses. A better understanding of their roles and perspectives in custom warehouse management may assist the application of the proposed methodology in reality.

All the research work is conducted to answer the main research question, **"How can faults leading to inventory record inaccuracy be detected and diagnosed considering multiple stakeholder involvement in custom warehouse management?"**. In general, an innovative model-based FDD methodology combining FDI and DX approaches has been designed, analysed and tested in this dissertation. Meanwhile, considering the complexity of custom warehouse, a comprehensive stakeholder analysis has been conducted to enhance their communication and cooperation in addressing inventory record inaccuracy issues. More specifically, the main research question is answered in separate researches on different sub-research questions.

I. What are the common faults leading to inaccurate inventory records in logistics management and what are their characteristics?

The common faults contributing to inaccurate inventory records are identified and summarized through literature reviews and expert consultations which are classified into three groups in this work. Firstly, transaction errors, are the events caused by the misidentification and miscount of items during inbound or outbound processes. There are multiple causes for transaction errors such as human errors and ERP system failures in this case. The impact of this fault can be two-sided on inventory records. Secondly, shrinkage, also known as stock loss, is found to be one of the major causes for recording inaccuracies. It may be caused by multiple reasons including employee theft, shoplifting, vendor fraud and spoiled or damaged inventory. Once it happens, it may lead to less available inventories in actual storage than the recorded inventory position in the ERP systems. Thirdly, misplaced inventory, refers to the materials or products physically existing but at incorrect locations. The misplaced inventory is temporarily unavailable but still has the possibility to be recovered as normal inventory. Misplaced inventories may decrease the actual available inventory at the target location.

II. How is the inventory record inaccuracy situation in custom warehouses considering multiple stakeholder involvement?

The inventory record inaccuracy is a critical issue in the management of custom warehouses. Different from normal logistics system, custom warehouses involve multiple stakeholders including different departments inside the company, customs, 3PL, ERP system providers, suppliers and customers. The involved actors share different interests and play varied roles in the management process of custom warehouse. Their different perspectives on inventory record inaccuracy may lead to their different activities in the decision making processes of custom warehouse. Based on the evaluation of these actors in terms of interests and powers, the department responsible for custom affairs in the company and customs are identified as key stakeholders in this case.

III. How can we develop a model-based fault detection and diagnosis methodology which is applicable in multiple circumstances?

Based on the identification of common faults for inventory record inaccuracy in custom warehouses, a general model-based fault detection and diagnosis methodology has been developed. The methodology framework can be briefly divided into three steps, including the logistics process modelling, the detection of fault occurrences and the diagnosis of fault categories and locations. Firstly, the logistics system is modelled through generalizing the complex processes into separate activity stages with different objectives and attributes. Secondly, the faults in this case can be detected by conducting statistical tests on the differences between the recorded data and the actual or expected values based on Kalman filers. Thirdly, with the application of ERP systems in modern logistics management, the diagnosis of fault categories and locations is implemented by DX approaches such as movement sequence check in this case. Thanks to the case-specific and user-define modular design of this framework, the model-based fault detection and diagnosis developed in this work can be applied in multiple circumstances in addition to custom warehouse management.

IV. How can the model-based fault detection and diagnosis methodology be applied in specific cases considering actual application situations?

In order to explicate how to apply the model-based FDD methodology in real cases, a case study of Custom Warehouse in the Netherlands together with relevant simulations have been conducted in this work. Firstly, specific process models have been developed which are corresponding to the real logistics situations inside the custom warehouse. And then the faults identified from the case study are analysed and classified as discussed in the previous work. At last, based on the case-specific process models, an application example of the proposed methodology is demonstrated through quantitative simulations. The results show that the application of the model-based FDD methodology needs certain adjustments and is effective in detecting faults of inventory record inaccuracy in real custom warehouse cases.

V. What are the possible logistics behaviours under different fault and inventory scenarios and how can the developed model-based fault detection and diagnosis methodology be preliminarily verified?

This question is answered through a series of simulations based on the developed models in the case study. The simulations in this work mainly consist of three sections, including system performance tests under different inventory policies, fault pattern tests and a application example of the developed methodology. The first section simulates the system behaviours under varied inventory policy scenarios. The results are used to evaluate the performance of different inventory policies. It is found that inventory policies have significant influences on the behaviours of logistics systems. In the second section, the specific fault patterns for different faults are analysed in terms of inventory positions. It is found that transaction errors may change the inventory records in two directions, while shrinkage and misplacement issues may cause the decrease of available inventories. At last, the simulation in the third section shows that the application of Kalman filter in model-based FDD methodology may significant enhance the fault detection sensibility as time goes by. The simulation result may preliminarily verify the developed model-based FDD methodology.

In summary, through literature reviews, interviews and expert consultations, a variety of faults have been found contributing to inventory record inaccuracy. Theses faults are classified into three groups, transaction, shrinkage and misplacement. Each fault group has its own causes and varied effects on inventory conditions. By tracing their specific fault patterns, these fault can be detected and diagnosed. Considering the limitation of physical auditing, an innovative model-based fault detection and diagnosis methodology has been developed and tested, which compares recorded inventory information with its expected values predicted from models. The methodology combined fault detection and isolation (FDI) approaches from control theory and diagnosis (DX) approaches from computer science. Because of its cost-efficiency and fast response, FDI approach with Kalman filter is utilized for fault detection. Considering the complex and dynamic reality, the more reliable DX approach of movement sequence check are applied for fault diagnosis. In addition, from interviews and expert consultations, multiple stakeholders are identified in custom warehouse issues, including different departments of the company, customs, third party logistics, software providers, suppliers and customers. The involved stakeholders play varied roles in detecting and diagnosing faults which contribute to inventory record inaccuracy in custom warehouses. Their communication and cooperation can not only assist in fault detection and diagnosis but also enhance the efficiency of custom warehouse management.

The research results in this dissertation are not only beneficial to the theoretical researches in fault analysis and logistics management but also helpful for the practical management of custom warehouses. From theoretical perspectives, the proposed methodology is an innovative model-based FDD method combining previous researches on FDI with DX approaches. The proposed methodology is more reliable than empirical auditing methods and more cost-efficient compared with physical auditing methods. For practical applications, this work may help in addressing the un-cleared duties and declaration troubles in custom warehouse management. Meanwhile, the stakeholder analysis in this work may enhance the communication and cooperation between different stakeholders leading to healthy and efficient custom warehouses.

7.2. Reflection

In order to better understand the model-based FDD methodology developed in this dissertation and shed light on relevant researches in the future, the methodology together with the relevant stakeholder analysis is analysed and reflected in the end. Moreover, the research processes of this thesis project are also briefly reflected in terms of the applied research approaches.

- Modelling limitation

  As mentioned in section 2.1.3 , the performance of model-based auditing is significantly influenced by the accuracy and reliability of applied models. The previous modelling approaches are highly limited because of their strict application requirements. Most of them are only suitable for specific cases in ideal circumstances. Therefore, this dissertation proposed a case-specific and user-define modelling approach based on the fundamental material flows of logistics systems. The proposed modelling approach can be applied in multiple logistics systems and circumstances. However, the proposed modelling approach in this dissertation is mainly focused on material flows and requires for the complete awareness of logistics processes. In order to model logistics systems into quantitative models, the input and output of each process should follow certain causal patterns or regulations. Namely, if the logistics system inputs are known, the possible outputs and inventory attributes should be able to be estimated through statistical calculations.

  Moreover, the multiple stakeholder involvement also sets barriers on the modelling approach. Different stakeholders may accept varied performance indicators and targeting at differed management objectives. In this dissertation, inventory positions are selected as the main logistics performance indicator which is concerned by most of the involved stakeholders. The future researches may study multiple criteria such as lead time and tax from different stakeholder perspectives.

- FDI and DX approaches

  As discussed in section 2.3, FDI approaches can avoid time-consuming and costly physical auditing and are efficient in addressing faults issues, but their effectiveness is greatly affected by external discrepancies and model uncertainties. On the other hand, DX approaches based on underlying causal links are more reliable, but they requires for complete and accurate inventory information which cause time-consuming and costly auditing processes. In this dissertation, an innovative model-based FDD methodology has been proposed integrating FDI and DX approaches together. Considering its efficiency in detecting faults, FDI approaches have been applied in fault detection which is more tolerant for the external discrepancies and model uncertainties. Once fault occurrence has been recognised, DX approaches are applied to diagnose which fault is happening and where it is. In this way, the logistics systems are maintained in a reliable situation, while the logistics management and maintenance cost can be saved since the reduced time-consuming and costly auditing processes. Therefore, in theory, the proposed model-based FDD methodology draw on the strong points of both FDI and DX approaches to make up for their different weak points.

  However, in practice, the application of this methodology may still face several challenges. For example, even though the introduction of Kalman filter has relieved the effects of accumulated uncertainty, the small discrepancies which are accumulating with time can still bring the inventory system to a risky situation in a long-term perspective. Moreover, the DX approaches such as movement sequence check are usually complicated and time-consuming because of the dynamic and complex circumstance and their success in fault diagnosis is also greatly dependent on the auditors' skills.

- Stakeholder analysis

  Considering the complexity of fault detection and diagnosis in custom warehouse management, a stakeholder analysis is conducted in this dissertation. A better understanding of different stakeholder involvement is helpful in enhancing their communication and cooperation to build a reliable and efficient custom warehouse. The stakeholder analysis in this dissertation is implemented based on interviews and group discussions. Because of the quantity and experience limitation of respondents, the results may be not suitable for some special custom warehouse cases. However, it is beneficial for general custom warehouse management and heuristic for future researches.

- Research approaches

  In this dissertation, the design, analysis and test processes of the developed model-based FDD methodology are mainly exploratory research activities, while the relevant analysis on custom warehouses belongs to analytical research activities. Accordingly, the applied research approaches are also mixed and serve for different research purposes. Qualitative approaches like stakeholder analysis and case study are applied in analytical research activities, while quantitative approaches including quantitative modelling (part of the methodology design) and simulation are used for exploratory research activities. In this way, different research purposes of this dissertation are fulfilled by corresponding research approaches. It is noted that the model in simulations is built in a quantitative way based on the qualitative process information from case study. However, because of time limitation and data privacy issues, the model parameters and variables are estimated and assumed in a principle way. Therefore, if the real logistics database is available in future researches, it is highly recommended to apply the real data in simulations and the verification of proposed methodology.

7.3. Limitation

Because of multiple restricting factors such as limited research time and data accessibility, there are several limitations not only for the proposed model-based FDD methodology in this work but also the research work itself.

The limitations of the proposed model-based FDD methodology:

(1) The application of the proposed model-based FDD methodology requires complete and detailed information about every movement in the logistics system. In the custom warehouse cases, the records in ERP systems provide all the necessary information. However, in the logistics system without modern recording methods, it is usually difficult to constantly track and trace the material flows. Therefore, the application of the proposed model-based FDD methodology is limited to the systems with sufficient logistics information.

(2) The application of the proposed model-based FDD methodology is highly dependent on modelling accuracy. The difficulty of modelling is dramatically raised as the increase of system complexity and dynamic. In reality, the logistics management is usually complicated and full of changes. Under this circumstance, the application of the proposed model-based FDD methodology is limited by how close it is between the develop models and reality.

The limitations of this research work:

(1) In this research work, the logistics system is analysed mainly focusing on material flows and part of information flows. The relevant information about financial flows is not discussed which is a important component in auditing processes. Moreover, the information flows are only utilized as a resource for relevant inventory information. However, the detailed recording procedures and characteristics of information flows are not involved in this research work.

(2) In order to simplify the simulation process, a lot of assumptions have been designed and applied in the construction of simulation programs. However, the idealization of the simulation model inevitably limits the generalization and effectiveness of the relevant simulation results.

(3) Because of information privacy issues and research time limitations, the analysis with the actual inventory database is not available in this work. Even though the simulation result can partly verify the proposed model-based FDD methodology, further verification and validation with real data are still needed. In addition, without the access to actual database, the last step of the proposed methodology, fault diagnosis, is not tested in this work.

7.4. Future Research

Considering the limitations of the research work in this paper, several suggestions for future researches are presented in this paper.

(1) This paper mainly focuses on the fault detection and diagnosis in logistics management. After the faults are detected and diagnosed, future researches may conducted on how to control these faults in a cost-efficient

and time-efficient way.

(2) In this paper, a model-based FDD methodology has been developed and applied for the inaccurate inventory records in the custom warehouse management. Actually, the proposed methodology can also be applied in multiple logistics occasions to address other issues, such as compliance problems and tax issues. These issues can be studied in future researches.

(3) As mentioned before, because of the data limitation in this paper, the proposed model-based FDD methodology is only preliminarily tested. Therefore, a comprehensive verification and validation analysis with real logistics data is highly recommended in future researches.

(4) The research in this paper mainly focuses on analysing material flows. However, the function of information and financial flows is also important in logistics management, which can be analysed in future researches.

Bibliography

[1] C Angeli. Diagnostic expert systems: from expert's knowledge to real-time systems. *Advanced knowledge based systems: Model, applications & research*, 1:50–73, 2010.

[2] JR Tony Arnold, Stephen N Chapman, and Lloyd M Clive. Introduction to materials management. 2001.

[3] Aykut Atali, Hau L Lee, and Özalp Özer. If the inventory manager knew: Value of visibility and rfid under imperfect inventory information. *Available at SSRN 1351606*, 2009.

[4] RW Backes. Cycle counting–a better method for achieving accurate inventory records. *Production and Inventory Management*, 21(2):36–44, 1980.

[5] Karen Lynn Basinger. *Impact of inaccurate data on supply chain inventory performance*. PhD thesis, The Ohio State University, 2006.

[6] Richard Vernon Beard. Failure accomodation in linear systems through self-reorganization. 1971.

[7] P Bernard. Cycle counting: The missing link. *PROD. INVENT. MANAGE.*, 26(4):27–41, 1985.

[8] JW M Bertrand and HPG Van Ooijen. Workload based order release and productivity: a missing link. *Production Planning & Control*, 13(7):665–678, 2002.

[9] Peter Bolstorff and Robert G Rosenbaum. *Supply chain excellence: a handbook for dramatic improvement using the SCOR model*. AMACOM Div American Mgmt Assn, 2007.

[10] Valérie Botta-Genoulaz and Pierre-Alain Millet. A classification for better use of erp systems. *Computers in Industry*, 56(6):573–587, 2005.

[11] Donald J Bowersox, David J Closs, and M Bixby Cooper. *Supply chain logistics management*, volume 2. McGraw-Hill New York, NY, 2002.

[12] JW Brault and OR White. The analysis and restoration of astronomical data via the fast fourier transform. *Astronomy and Astrophysics*, 13:169, 1971.

[13] Roger B Brooks and Larry W Wilson. *Inventory record accuracy: unleashing the power of cycle counting*, volume 18. John Wiley & Sons, 2007.

[14] Robert Goodell Brown. Decision rules for inventory management. 1967.

[15] Bruce G Buchanan, Edward Hance Shortliffe, et al. *Rule-based expert systems*, volume 3. Addison-Wesley Reading, MA, 1984.

[16] AZ Camdereli and JM Swaminathan. Coordination of a supply chain under misplaced inventory. *University of North Carolina Working Paper OTIM-2005–02*, 2005.

[17] Gavin Chappell, David Durdan, Greg Gilbert, Lyle Ginsburg, Jeff Smith, and Joseph Tobolski. Auto-id in the box: the value of auto-id technology in retail stores. auto-id center, 2009.

[18] Andrew J Clark and Herbert Scarf. Optimal policies for a multi-echelon inventory problem. *Management science*, 6(4):475–490, 1960.

[19] Robert N Clark. A simplified instrument failure detection scheme. *IEEE Transactions on Aerospace and Electronic Systems*, (4):558–563, 1978.

[20] Robert N Clark, Douglas C Fosth, and Vincent M Walton. Detecting instrument malfunctions in control systems. *IEEE Transactions on Aerospace and Electronic Systems*, (4):465–473, 1975.

[21] M-O Cordier, Philippe Dague, François Lévy, Jacky Montmain, Marcel Staroswiecki, and Louise Travé-Massuyès. Conflicts versus analytical redundancy relations: a comparative analysis of the model based diagnosis approach from the artificial intelligence and automatic control perspectives. *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)*, 34(5):2163–2177, 2004.

[22] Randall Davis. Diagnostic reasoning based on structure and behavior. *Artificial intelligence*, 24(1):347–410, 1984.

[23] Kleer J De, AK Mackworth, and R Reiter. Characterizing diagnosis and systems. *Artificial Intelligence*, 56 (2-3):197–222, 1992.

[24] Nicole DeHoratius and Ananth Raman. Inventory record inaccuracy: an empirical analysis. *Management Science*, 54(4):627–641, 2008.

[25] Johan DEKleer. Local methods for localizing faults in electronic circuits. Technical report, DTIC Document, 1976.

[26] CK Dillon. Stretching toward enterprise flexibility. *APICS The Performance Advantage*, 9(10):38–43, 1999.

[27] ECR Europe. Introducing a collaborative approach to reducing stock loss in the supply chain. *ECR Europe. Brussels, Belgium*, 2001.

[28] Mitchell J Feigenbaum, Leo P Kadanoff, and Scott J Shenker. Quasiperiodicity in dissipative systems: a renormalization group analysis. *Physica D: Nonlinear Phenomena*, 5(2):370–386, 1982.

[29] Benito E Flores and D Clay Whybark. Implementing multiple criteria abc analysis. *Journal of Operations Management*, 7(1-2):79–85, 1987.

[30] Srinagesh Gavirneni, Roman Kapuscinski, and Sridhar Tayur. Value of information in capacitated supply chains. *Management science*, 45(1):16–24, 1999.

[31] Janos J Gertler. Survey of model-based failure detection and isolation in complex plants. *IEEE Control systems magazine*, 8(6):3–11, 1988.

[32] Jaap Gordijn and JM Akkermans. Value-based requirements engineering: exploring innovative e-commerce ideas. *Requirements engineering*, 8(2):114–134, 2003.

[33] Peter D Hanlon and Peter S Maybeck. Multiple-model adaptive estimation using a residual correlation kalman filter bank. *IEEE Transactions on Aerospace and Electronic Systems*, 36(2):393–406, 2000.

[34] Mark Hanna and W Rocky Newman. *Integrated operations management: adding value for customers*, volume 1. Prentice Hall, 2001.

[35] H Sebastian Heese. Inventory record inaccuracy, double marginalization, and rfid adoption. *Production and Operations Management*, 16(5):542, 2007.

[36] Richard Hollinger and Jason L Davis. National retail security survey. *Report, Department of Sociology and the Center for Studies in Criminology and Law, University of Florida*, 2001.

[37] Inseok Hwang, Sungwan Kim, Youdan Kim, and Chze Eng Seah. A survey of fault detection, isolation, and reconfiguration methods. *IEEE Transactions on Control Systems Technology*, 18(3):636–653, 2010.

[38] Donald L Iglehart and Richard C Morey. Inventory systems with imperfect asset information. *Management Science*, 18(8):B–388, 1972.

[39] Rolf Isermann and Peter Ballé. Trends in the application of model-based fault detection and diagnosis of technical processes. *Control engineering practice*, 5(5):709–719, 1997.

[40] Rudolph Emil Kalman. A new approach to linear filtering and prediction problems. *Journal of basic Engineering*, 82(1):35–45, 1960.

[41] Y Kang and R Koh. Applications research. *Auto-ID Centre*, 2002.

[42] Yun Kyu Kang. *Information inaccuracy in inventory systems.* PhD thesis, Massachusetts Institute of Technology, 2004.

[43] Jens Kappauf, Bernd Lauterbach, and Matthias Koch. *Logistic Core Operations with SAP: Inventory Management, Warehousing, Transportation, and Compliance.*

[44] AT Kearney. Meeting the retail rfid mandate—a discussion of the issues facing cpg companies. *Chicago: AT Kearney*, 2003.

[45] W Knechel, S Salterio, and B Ballou. Auditing: Assurance and risk: Thomson learning, 2007.

[46] A Gürhan Kök and Kevin H Shang. Evaluation of cycle-count policies for supply chains with inventory inaccuracy and implications on rfid investments. *European Journal of Operational Research*, 237(1):91–105, 2014.

[47] Lee J Krajewski, Barry E King, Larry P Ritzman, and Danny S Wong. Kanban, mrp, and shaping the manufacturing environment. *Management science*, 33(1):39–57, 1987.

[48] Young M Lee, Feng Cheng, and Ying Tat Leung. Exploring the impact of rfid on supply chain dynamics. In *Proceedings of the 36th conference on Winter simulation*, pages 1145–1152. Winter Simulation Conference, 2004.

[49] Young M Lee, Feng Cheng, and Ying Tat Leung. A quantitative view on how rfid will improve a supply chain. *IBM Research Division*, 2005.

[50] Michael Levy and Barton A Weitz. Retailing management. the irwin, 2001.

[51] Marvin B Lieberman, Susan Helper, and Lieven Demeester. The empirical determinants of inventory levels in high-volume manufacturing. *Production and Operations Management*, 8(1):44, 1999.

[52] Anne Lightburn. 2002 unsaleables benchmark report. *Report, Joint Industry Unsaleables Steering Committee, Food Distributors International, Food Marketing Institute and Grocery Manufacturers of America*, 2002.

[53] Ruopeng Lu, Shazia Sadiq, and Guido Governatori. On managing business processes variants. *Data & Knowledge Engineering*, 68(7):642–664, 2009.

[54] Durga P Malladi and Jason L Speyer. A generalized shiryayev sequential probability ratio test for change detection and isolation. *IEEE Transactions on Automatic Control*, 44(8):1522–1534, 1999.

[55] Raman K Mehra and J Peschon. An innovations approach to fault detection and diagnosis in dynamic systems. *Automatica*, 7(5):637–640, 1971.

[56] Steven Nahmias and Ye Cheng. *Production and operations analysis*, volume 6. McGraw-Hill New York, 2009.

[57] Parley S Neeley. A framework for cycle counting. *Production and Inventory Management*, 24(4):23–32, 1983.

[58] Igor V Nikiforov. A generalized change detection problem. *IEEE Transactions on Information theory*, 41 (1):171–187, 1995.

[59] Ryumduck Oh and Jeyh Park. A development of active monitoring system for intelligent rfid logistics processing environment. In *Advanced Language Processing and Web Information Technology, 2008. ALPIT'08. International Conference on*, pages 358–361. IEEE, 2008.

[60] ES Page. Continuous inspection schemes. *Biometrika*, 41(1/2):100–115, 1954.

[61] RJ Patton and J Chen. A review of parity space approaches to fault diagnosis. In *IFAC Safeprocess Conference*, pages 65–81, 1991.

[62] Ron J Patton, CJ Lopez-Toribio, and FJ Uppal. Artificial intelligence approaches to fault diagnosis. In *Condition Monitoring: Machinery, External Structures and Health (Ref. No. 1999/034), IEE Colloquium on*, pages 5–1. IET, 1999.

[63] AK Pradhan, A Routray, and SR Mohanty. A moving sum approach for fault detection of power systems. *Electric Power Components and Systems*, 34(4):385–399, 2006.

[64] Ananth Raman. Retail-data quality: Evidence, causes, costs, and fixes. *Technology in Society*, 22(1):97–109, 2000.

[65] Ananth Raman, Nicole DeHoratius, and Zeynep Ton. Execution: The missing link in retail operations. *California Management Review*, 43(3):136–152, 2001.

[66] Raymond Reiter. A theory of diagnosis from first principles. *Artificial intelligence*, 32(1):57–95, 1987.

[67] Yacine Rekik, Evren Sahin, and Yves Dallery. Analysis of the impact of the rfid technology on reducing product misplacement errors at retail stores. *International Journal of Production Economics*, 112(1):264–278, 2008.

[68] Evren Sahin and Yves Dallery. A literature review on the impact of inventory data record inaccuracies on inventory management and the potential of the rfid technology to tackle this issue. *RFID Eurasia, 1st Annual*, pages 1–7, 2007.

[69] Evren Sahin and Yves Dallery. Assessing the impact of inventory inaccuracies within a newsvendor framework. *European Journal of Operational Research*, 197(3):1108–1118, 2009.

[70] Aysegul Sarac, Nabil Absi, and Stéphane Dauzère-Pérès. A literature review on the impact of rfid technologies on supply chain management. *International Journal of Production Economics*, 128(1):77–95, 2010.

[71] Robert W Scapens and Mostafa Jazayeri. Erp systems and management accounting change: opportunities or impacts? a research note. *European accounting review*, 12(1):201–233, 2003.

[72] DA Schrady. Operational definitions of inventory record accuracy. *Naval research logistics quarterly*, 17 (1):133–142, 1970.

[73] Jeremy Shapiro. *Modeling the supply chain*. Nelson Education, 2006.

[74] JA Silvoso. Report of the committee on basic auditing concepts. *The Accounting Review*, 47:15–74, 1972.

[75] Augustin Soule, Kavé Salamatian, and Nina Taft. Combining filtering and statistical methods for anomaly detection. In *Proceedings of the 5th ACM SIGCOMM conference on Internet Measurement*, pages 31–31. USENIX Association, 2005.

[76] Jason L Speyer and John E White. Shiryayev sequential probability ratio test for redundancy management. *Journal of Guidance, Control, and Dynamics*, 7(5):588–595, 1984.

[77] Sridhar Tayur, Ram Ganeshan, and Michael Magazine. *Quantitative models for supply chain management*, volume 17. Springer Science & Business Media, 2012.

[78] Christian Tellkamp. The auto-id calculator: an overview. 2003.

[79] Elisabeth J Umble, Ronald R Haft, and M Michael Umble. Enterprise resource planning: Implementation procedures and critical success factors. *European journal of operational research*, 146(2):241–257, 2003.

[80] D van Schrick. Remarks on terminology in the field of supervision, fault detection and diagnosis. pages 959–964, 1997.

[81] George Wald and Donald R Griffin. The change in refractive power of the human eye in dim and bright light. *JOSA*, 37(5):321–336, 1947.

[82] Hans Weigand and Philip Elsas. Model-based auditing using rea. *International Journal of Accounting Information Systems*, 13(3):287–310, 2012.

[83] Yuan-bao WEN and Dan TANG. Design and realization of the web-based erp logistics management system [j]. *Computer Engineering & Science*, 11:007, 2006.

[84] Alan S Willsky. A survey of design methods for failure detection in dynamic systems. *Automatica*, 12(6): 601–611, 1976.

[85] J Wünnenberg and PM Frank. Sensor fault detection via robust observers. In *System fault diagnostics, reliability and related knowledge-based approaches*, pages 147–160. Springer, 1987.

A

Appendix 1:Description of Movement Types

Below you will find a short description of the standard movement types. The reversal movement type is the movement type + 1 (reversal of 101 = 102).

101 Goods receipt for purchase order or order If the purchase order or order has not been assigned to an account, a stock type (unrestricted-use stock, stock in quality inspection, blocked stock) can be entered during goods receipt. If the purchase order or order has been assigned to an account, the goods receipt is not posted to the warehouse, but to consumption.

In the case of non-valuated materials, the goods receipt is posted to the warehouse, although the purchase order has not been assigned to an account. Possible special stock indicators:

K Goods receipt for purchase order to consignment stock

O Goods receipt for purchase order to stock of material provided to vendor

E GR for purchase order or order to sales order stock

Q GR for purchase order or order to project stock.

Goods receipt for subcontract order: at goods receipt, the consumption of the components is posted at the same time (see movement type 543) Goods receipt for stock transport order: at goods receipt the transported quantity is posted in the receiving plant from stock in transit into unrestricted-use stock (stock in quality inspection or blocked stock).

103 Goods receipt for purchase order into GR blocked stock You cannot receive goods into goods receipt blocked stock for stock transport orders. Possible special stock indicators: K, O, E, Q

105 Release from GR blocked stock for purchase order Movement type 105 has the same effects as 101. Possible special stock indicators: K, O, E, Q

121 Subsequent adjustment for subcontracting This movement type cannot be entered manually. With a subsequent adjustment for a subcontract order it is possible to correct the consumption of components. In this case, the material produced by the supplier is credited with the excess consumption / under-consumption. For this reason, if there is a subsequent adjustment, an item is generated for the produced material using movement movement type 121. Movement type 121 does not have a reversal movement type. Possible special stock indicators: O, E, Q

122 Return delivery to supplier or to production Using movement type 122, you can distinguish real return deliveries for a purchase order or order from cancellations (102). In the standard version, you must enter a reason for the return delivery if you are using movement type 122. This enables you to carry out evaluations for return deliveries. The effects of movement type 122 correspond to a cancellation of movement type 101. Possible special stock indicators: K, O, E, Q

123 Reversal of return delivery If you returned a goods receipt using movement type 122, you can reverse the return delivery using movement type 123. This movement type has the same effects as movement type 101. Possible special stock indicators: K, O, E, Q

124 Return delivery to vendor from GR blocked stock Using movement type 124, you can return a goods receipt to GR blocked stock (103). Movement type 124 has the same effects as movement type 104. Possible special stock indicators: K, O, E, Q

125 Return delivery from GR blocked stock - reversal If you returned a goods receipt to GR blocked stock using movement type 124 , you can reverse the return delivery using movement type 125. Movement type 125 has the same effects as movement type 103. Possible special stock indicators: K, O, E, Q

131 Goods receipt for run schedule header This movement type cannot be entered manually. It is generated automatically at notification of goods receipt for a run schedule header. Possible special stock indicators: E, Q

141 Goods receipt for subsequent adjustment for active ingredient This movement type cannot be entered manually. It is generated automatically upon subsequent adjustment for a proportion/product unit . Subsequent adjustment is necessary if the system finds that there has been excess consumption or under-consumption after a goods receipt posting. Possible special stock indicators: K, O, E, Q

161 Return for purchase order If a purchase order item is marked as a returns item, the returns to vendor are posted using movement type 161 when the goods receipt for purchase order (101) is posted. Movement type 161 has the same effects as movement type 122. Possible special stock indicators: K, O, E, Q

201 Goods issue for a cost center The goods can only be withdrawn from unrestricted-use stock. Possible special stock indicators: K: Goods withdrawal from consignment stock P: Goods withdrawal from the pipeline If you have withdrawals from consignment stock and from pipeline, payables to suppliers ensue.

221 Goods issue for a project The goods can only be withdrawn from unrestricted-use stock. Possible special stock indicators: K, Q

222 Goods issue for . . . .

231 Goods issue for a customer order (without Shipping) You use this movement type if you want to process the delivery without Shipping. The goods can only be withdrawn from unrestricted-use stock. Possible special stock indicators: E, K, Q

241 Goods issue for an asset The goods can only be withdrawn from unrestricted-use stock. Possible special stock indicators: K

251 Goods issue for sales (without customer order) Use this movement type if you have not entered a customer order in SD. In the standard system, the movement is assigned to a cost center. The goods can only be withdrawn from unrestricted-use stock. Possible special stock indicators: K

261 Goods issue for an order This refers to all withdrawals for orders with the exception of customer orders. Possible special stock indicators: E, K, P, Q, W The goods issue can be posted manually in Inventory Management or automatically when an order is confirmed or via a delivery in Shipping.

281 Goods issue for a network The goods can only be withdrawn from unrestricted-use stock. The goods issue can also be posted via a delivery in Shipping. Possible special stock indicators: E, K, P, Q

291 Goods issue for any arbitrary account assignment With this movement type, all account assignment fields are ready for input. You can assign the movement to any arbitrary account assignment object. The goods can only be withdrawn from unrestricted-use stock. Possible special stock indicators: E, K, P, Q

301 Transfer posting plant to plant in one step The quantity is transferred from unrestricted-use stock in the issuing plant to unrestricted-use stock in the receiving plant. Possible special stock indicators: E, O, Q, V, W

303 Transfer posting plant to plant in two steps - removal from storage The quantity is transferred from unrestricted-use stock of the issuing plant tostock in transfer in the receiving plant. For technical reasons, you cannot carry out transfer postings from plant to plant in two steps for split valuation materials. Removal from storage can be posted with movement type 603 via Shipping. Possible special stock indicators: None

305 Transfer posting plant to plant in two steps - placement in storage The quantity is posted from stock in transfer to unrestricted-use stock in the receiving plant. The movement is not valuated. You can use movement type 605 in Shipping to post the goods receipt with reference to the delivery. Possible special stock indicators: None

309 Transfer posting material to material The quantity is posted from unrestricted-use stock of the issuing material into unrestricted-use stock in the receiving material. Prerequisite: both materials have the same stockkeeping unit. Possible special stock indicators: E, O, Q, V, W

311 Transfer posting storage location to storage location in one step The quantity is transferred from unrestricted-use stock of the issuing storage location to unrestricted use in the receiving storage location. Possible special stock indicators: E, K, M, Q See also 321, 343, 349, and 455 for other stock types

313 Stock transfer storage location to storage location in two steps - removal from storage The quantity is transferred from unrestricted-use stock of the issuing storage location to stock in transfer in the receiving storage location. Possible special stock indicators: None

315 Transfer posting storage location to storage location in two steps - placement in storage In the receiving storage location, the quantity is transferred from the stock in transfer to the unrestricted-use stock. Possible special stock indicators: None

317 Creation of a structured material from constituent components (Retail) A material split into its components using movement type 319 can be rejoined using movement type 317. Movement type 317 has the same effect as a cancellation of movement type 319. Possible special stock indicators: None

319 Split structured material into components (Retail) You can enter the splitting of a structured material manually using movement type 319. You can configure Customizing so that a structured material (for example, aset, prepack, or display is automatically split into its components at goods receipt. The system posts the split using movement type 319. In this process, the BOM header material is posted and each of the component stocks are increased. You can also use this function if you use the Warehouse Management System (LE-WM). Possible special stock indicators: None

321 Transfer posting stock in quality inspection - unrestricted-use stock The quantity is transferred from stock in quality inspection into unrestricted-use stock. Here you can post the quantity to another storage location. You cannot use this movement type for QM-managed materials since transfer posting for these materials takes place via the usage decision. Possible special stock indicators: E, K, O, Q, V, W

323 Transfer posting storage location to storage location - stock in quality inspection The quantity is transferred from stock in quality inspection in the issuing storage location into stock in quality inspection in the receiving storage location. Possible special stock indicators: E, K, Q

325 Transfer posting storage location to storage location - blocked stock The quantity is transferred from blocked stock in the issuing storage location into blocked stock in the receiving storage location. Possible special stock indicators: E, K, Q

331 Withdrawal of sample from stock in quality inspection The sample is destructive, that is, the withdrawal has the same effects as scrapping. Possible special stock indicators: E, K, Q, V, W

333 Withdrawal of sample from unrestricted-use stock The sample is destructive, that is, the withdrawal has the same effects as scrapping. Possible special stock indicators: E, K, Q, V, W

335 Withdrawal of sample from blocked stock The sample is destructive, that is, the withdrawal has the same effects as scrapping. Possible special stock indicators: E, K, Q

340 Revaluation of batch Using this movement type, you can change a batch's valuation type. The system automatically calls up this movement type when you want to revaluate a batch by choosing Logistics -> Central Functions -> Batch Management -> Batch -> Change (transaction code MSC2N). There is no reversal movement type. Possible special stock indicators: E, Q

341 Change in status of a batch (available to unavailable) This goods movement is automatically created when there is a change in thestatus of a batch and it is also used to transfer the unrestricted-use stock into restricted-use stock. Possible special stock indicators: E, K, M, O, Q, V, W

343 Transfer posting blocked stock - unrestricted-use stock The quantity is transferred from blocked stock to unrestricted-use stock. You can also post the quantity to another storage location. Possible special stock indicators: E, K, Q

349 Transfer posting from blocked stock to stock in quality inspection The quantity is transferred from blocked stock to stock in quality inspection. Here you can transfer the quantity to another storage location. Possible special stock indicators: E, K, Q

351 Goods issue for a stock transport order (without Shipping) The quantity is transferred from unrestricted-use stock in the issuing plant tostock in transit in the receiving plant. Movement type 351 is only used if the goods issue is posted without a delivery in Shipping. A goods issue for a stock transport order with delivery in Shipping is posted using movement types 641, 643, 645, or 647. The transfer posting is also possible for materials with split valuation. The goods issue for a stock transport order takes place using movement type 101. Possible special stock indicators: E, Q For special stock indicators E and Q and for purchase orders assigned to an account, ensure that the quantity is not posted to the stock in transit in the receiving plant.

411 Transfer posting of special stocks E, K, and Q to company's own stock The quantity is transferred from unrestricted-use special stock E (sales order stock), unrestricted-use stock K (consignment stock) and unrestricted-use special stock Q (project stock) to unrestricted-use storage location stock. The corresponding special stock indicator is required for this movement. If you do not use the special stock indicator, the system uses this movement type and movement type 311. For sales order stock, you can change the material number for this movement if you manage the material in your company's own stock under a different material number (for example, for configurable materials). Consignment stock is transferred to valuated stock, thus resulting in a vendor liability.

413 Transfer posting to sales order stock You can use this movement type to carry out a transfer posting from your own unrestricted-use stock, other sales order stock, consignment stock, and project stock to a sales order stock. Possible special stock indicators: E, K, Q

415 Transfer posting to project stock You can use this movement type to carry out a transfer posting from your own unrestricted-use stock, consignment stock, and other project stock to a project stock. Possible special stock indicators: E, K, Q

441 Transfer posting non-tied to tied empties Part of the stock of an "empties" material assigned to a full product is managed in the stock type "tied empties". Empties stock not assigned to a full product forms part of the stock type "unrestricted-use". Using movement type 441, you can make a transfer posting for an empties material from the stock type "unrestricted-use" to the stock type "tied empties". Movement type 442 reverses this transaction.

451 Returns from customer (without Shipping) Using movement type 451, you post customer returns without a returns delivery in Shipping into blocked stock returns. Possible special stock indicators: None See also: 453, 651, 653

453 Transfer posting blocked stock returns to unrestricted-use stock The quantity is transferred from blocked stock returns to unrestricted-use stock and thereby transferred to valuated stock. With this movement you can transfer the quantity to another storage location at the same time. Possible special stock indicators: None

455 Transfer posting storage location to storage location - blocked stock returns The quantity is transferred from blocked stock returns of the issuing storage location to blocked stock returns of the receiving storage location. Possible special stock indicators: None

457 Transfer posting blocked stock returns to quality inspection stock The quantity is transferred from blocked stock returns to quality inspection stock and thereby transferred to valuated stock. With this movement you can transfer the quantity to another storage location at the same time. Possible special stock indicators: None

459 Transfer posting blocked stock returns to blocked stock The quantity is transferred from blocked stock returns to blocked stock and thereby transferred to valuated stock. With this movement you can transfer the quantity to another storage location at the same time. Possible special stock indicators: None

501 Goods receipt without purchase order - unrestricted-use stock This movement type is used for deliveries from vendors that are not based on a purchase order. Invoice verification is not possible for these goods receipts. For a goods receipt for purchase order (101), the receipt of returnable transport packaging can be entered using movement type 501 and special stock indicator M. Possible special stock indicators: E, K, M, Q

503 Goods receipt without purchase order - stock in quality inspection This movement type is used for deliveries from vendors that are not based on a purchase order. Invoice verification is not possible for these goods receipts. Possible special stock indicators: E, K, Q

505 Goods receipt without purchase order - blocked stock This movement type is used for deliveries from vendors that are not based on a purchase order. Invoice verification is not possible for these goods receipts. Possible special stock indicators: E, K, Q

511 Free-of-charge delivery from vendor The quantity is posted to unrestricted-use stock. If there is a material with moving average price, the moving average price is reduced accordingly. Possible special stock indicators: None

521 Goods receipt without order - unrestricted-use stock This movement type is used for deliveries from production that are not based on an order. Possible special stock indicators: E, Q

523 Goods receipt without order - stock in quality inspection This movement type is used for deliveries from production that are not based on an order. Possible special stock indicators: E, Q

525 Goods receipt without order - blocked stock This movement type is used for deliveries from production that are not based on an order. Possible special stock indicators: E, Q

531 Goods receipt from by-product from the order The goods receipt of a by-product usually refers to an order, but it can be entered without a reference. If a component is entered with a negative quantity in the order, a reservation item is created with 531 (instead of 261). The receipt of a by-product can be entered when the component for the order is withdrawn from stock or it can be entered as an 'other goods receipt'. Possible special stock indicators: E, Q See also: 545 and 581

541 Transfer posting unrestricted-use stock - stock of material provided to vendor With this movement type you provide the subcontractor with the components required for subcontract orders. The quantity is posted into unrestricted-use stock of material provided to vendor. If there is a goods receipt for a subcontract order (101) consumption of components is posted from this stock. The transfer posting can be posted via a delivery in Shipping. Possible special stock indicators: None

543 Consumption from stock of material provided to vendor This movement cannot be entered manually. The consumption of components for a subcontract order is posted using goods receipt for purchase order (101). It can be corrected by means of a subsequent adjustment. For special stock indicators E and Q, you must ensure that the quantity is not posted to the stock of material provided to vendor, but to the unrestricted-use sales order or project stock. Possible special stock indicators: E, O, Q

545 Goods receipt from by-product from subcontracting If a component is entered with a negative quantity for the subcontract order, the receipt of the by-product is posted to stock provided to vendor during goods receipt for purchase order or during the subsequent adjustment. For special stock indicators E and Q, you must ensure that the quantity is not posted to the stock of material provided to vendor, but to the unrestricted-use sales order or project stock. Possible special stock indicators: E, O, Q

551 Scrapping from unrestricted-use stock Possible special stock indicators: E, K, O, Q, V, W

553 Scrapping from stock in quality inspection Possible special stock indicators: E, K, O, Q, V, W

555 Scrapping from blocked stock Possible special stock indicators: E, K, Q

561 Initial entry of stock - unrestricted-use stock During initial entry of stock balances, when the R/3 system is active, you enter the physical warehouse stock figures or the book inventory from your old system into the R/3 Materials Management component. This data entry usually takes place by means of batch input. Possible special stock indicators: E, K, M, O, Q, V, W

563 Initial entry of stock - quality inspection During initial entry of stock balances, when the R/3 system is active, you enter the physical warehouse stock figures or the book inventory from your old system into the R/3 Materials Management component. This data entry usually takes place by means of batch input. Possible special stock indicators: E, K, O, Q, V, W

565 Initial entry of stock - blocked stock During initial entry of stock balances, when the R/3 system is active, you enter the physical warehouse stock figures or the book inventory from your old system into the R/3 Materials Management component. This data entry usually takes place by means of batch input. Possible special stock indicators: E, K, Q

571 Goods receipt for assembly order to unrestricted-use This movement cannot be entered in Inventory Management. It can only be entered in repetitive manufacturing using the Goods receipt for sales order function. Possible special stock indicators: E, Q

573 Goods receipt for assembly order to quality inspection This movement cannot be entered in Inventory Management. It can only be entered in repetitive manufacturing using the Goods receipt for sales order function. Possible special stock indicators: E, Q

575 Goods receipt for assembly order to blocked stock This movement cannot be entered in Inventory Management. It can only be entered in repetitive manufacturing using the Goods receipt for sales order function. Possible special stock indicators: E, Q

581 Goods receipt of a by-product from the network The goods receipt of a by-product usually refers to anetwork, but can be entered without reference. If a component is entered with a negative quantity in the network, a reservation is created with 581 (instead of 281). The receipt of a by-product can be entered during the withdrawal for the network or as an ’other goods receipt’. Possible special stock indicators: E, Q

601 Goods issue for delivery (Shipping) In Shipping, this movement type is created automatically with the Goods issue for delivery function. The quantity is taken from unrestricted-use stock. Possible special stock indicators: E, K, Q

603 Goods issue for stock transport order (Shipping) with additional item If you issue goods for a stock transport order in Shipping using movement type 641, you can use this movement type to assign an extra item to the order. The ordered material is transferred to the stock in transit of the receiving plant. The material for the additional item is transferred from unrestricted-use stock in the issuing plant to stock in transfer in the receiving plant. You can also use this movement type without referencing a purchase order. Possible special stock indicators: None See also: 303, 641

605 Goods receipt for a stock transport order (Shipping) with additional item You can use this movement type to transfer into unrestricted-use stock the material you posted into stock in transfer in the receiving plant using movement type 603. You post the goods movement with reference to the purchase order (if available) or the delivery. Possible special stock indicators: None See also: 305 and 641

621 Transfer posting unrestricted-use - returnable packaging (Shipping) The quantity is transferred from unrestricted-use stock to the returnable packaging stock at customer. Possible special stock indicators: none

623 Goods issue from returnable packaging stock at customer (Shipping) This quantity is withdrawn from unrestricted-use returnable packaging stock at the customer. Possible special stock indicators: V

631 Transfer posting unrestricted use - customer consignment stock (Shipping) The quantity is transferred from unrestricted-use stock to consignment stock at customer. Possible special stock indicators: E, Q

633 Goods issue from customer consignment (Shipping) The quantity is withdrawn from unrestricted-use consignment stock at the customer. Possible special stock indicators: W

641 Goods issue for a stock transport order (Shipping) The quantity is transferred using a delivery in Shipping from unrestricted-use stock of the issuing plant to stock in transit of the receiving plant. The goods receipt for the stock transport order takes place using movement type 101 and can, if required, refer to the purchase order or to the delivery. If a purchase order item is flagged as a returns item in the stock transport order, you can post the goods receipt of the returns in the issuing plant with movment type 671. Possible special stock indicators: E, Q For the special stock indicators E and Q and for purchase orders assigned to an account, you must ensure that the quantity is not posted to the stock in transit of the receiving plant. See also: 351, 643, 671

643 Goods issue for a cross-company stock transport order (Shipping) It is used only for cross-company stock transport orders with SD billing and invoice. The quantity is withdrawn from the unrestricted-use stock of the issuing plant. No stock in transit is created here. In the second step, the goods receipt must be entered in the receiving plant. If a purchase order item is flagged as a returns item in the stock transport order, you can post the goods receipt of the returns in the issuing plant with movment type 673. Possible special stock indicators: E See also: 351, 641, 673

645 Goods issue for a cross-company stock transport order in one step (Shipping) Unlike movement type 643 when a goods issue is posted using movement type 645, a goods receipt line is generated automatically 101). If a purchase order item is flagged as a returns item in the stock transport order, you can post the goods receipt of the returns in the issuing plant with movment type 675. Possible special stock indicators: E See also: 675

647 Goods issue for a stock transport order in one step(Shipping) Unlike movement type 641 when a goods issue is posted using movement type 647, a goods receipt line (movement type 101) is generated automatically in the receiving plant. If a purchase order item is flagged as a returns item in the stock transport order, you can post the goods receipt of the returns in the issuing plant with movement type 677. Possible special stock indicators: E, Q See also: 677

651 Returns from customer (Shipping) Using movement type 651, you post returns from a customer with a return delivery in Shipping to blocked stock returns. Possible special stock indicators: None See also: 451, 453, 653

653 Returns from customer (Shipping) to unrestricted-use stock With this movement type you post returns from the customer with returns delivery via Shipping directly to the valuated stock. Possible special stock indicators: E See also: 451, 453, 651

655 Returns from customer (Shipping) to stock in quality inspection With this movement type you post returns from the customer with returns delivery via Shipping directly to the valuated stock. Possible special stock indicators: E See also: 451, 453, 651

657 Returns from customer (Shipping) to blocked stock With this movement type you post returns from the customer with returns delivery via Shipping directly to the valuated stock. Possible special stock indicators: E See also: 451, 453, 651

661 Returns to vendor via Shipping As with movement type 502, a return delivery to the vendor is entered without reference to the purchase order, but the goods issue is posted via a delivery in Shipping. Possible special stock indicators: E

671 Returns for stock transport order via Shipping If a purchase order item is marked as a returns item in a stock transport order using movement type 641 when a goods receipt for a stock transport order (101) is posted, the return is posted to stock in transit using movement type 161. When the return arrives, the issuing plant posts the goods receipt for the return using movement type 671. Movement type 671 (like movement types 352 and 642) reduces the receiving plant's stock in transit and increases the issuing plant's unrestricted-use stock. Possible special stock indicators: E, Q

673 Returns for cross-company stock transport order (Shipping) If you post a goods issue for a cross-company stock transport order with returns items using movement type 643 via Shipping, the returns are transferred to unrestricted-use stock in the issuing plant in a second step using movement type 673. Possible special stock indicators: None See also: 643

675 Returns for cross-company stock transport order (Shipping) in one step If you use movement type 645 to post a goods issue for a cross-company stock transport order with returns items in one step, the returns are transferred to unrestricted-use stock in the issuing plant using movement type 161 in the receiving plant and movement type 675 in the issuing plant. Possible special stock indicators: None See also: 645

677 Returns for stock transport order in one step (Shipping) If you use movement type 647 to post a goods issue for a stock transport order with returns items in one step, the returns are transferred to unrestricted-use stock in the issuing plant using movement type 161 in the receiving plant and movement type 677 in the issuing plant. Possible special stock indicators: E, Q See also: 647

701 Inventory differences in unrestricted-use stock (MM-IM) This movement is generated automatically during inventory difference posting in Inventory Management. Possible special stock indicators: E, K, M, O, Q, V, W

703 Inventory differences in quality inspection stock (MM-IM) This movement is generated automatically during inventory difference posting in Inventory Management. Possible special stock indicators: E, K, M, O, Q, V, W

707 Inventory differences in blocked stock (MM-IM) This movement is generated automatically during inventory difference posting in Inventory Management. Possible special stock indicators: E, K, M, Q

711 Inventory differences in unrestricted-use stock (LE-WM) This movement is generated automatically when you post inventory differences in the Warehouse Management System. Possible special stock indicators: E, K, M, Q

713 Inventory differences in quality inspection stock (LE-WM) This movement is generated automatically when you post inventory differences in the Warehouse Management System. Possible special stock indicators: E, K, M, Q

715 Inventory differences in blocked stock returns (LE-WM) This movement is generated automatically when you post inventory differences in the Warehouse Management System. Possible special stock indicators: None

717 Inventory differences in blocked stock (LE-WM) This movement is generated automatically when you post inventory differences in the Warehouse Management System. Possible special stock indicators: E, K, M, Q

721 - Sales value receipt - not affecting margins (Retail) The movement is generated automatically when the sales price of a value-only material is changed (total sales price revaluation on the posting date). Possible special stock indicators: None

731 - Sales value receipt - affecting margins (Retail) The movement is generated automatically when the sales price of a value-only material is changed (partial sales price revaluation on the posting date). Possible special stock indicators: None