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A METHOD FOR GENERATING PROCESS TOPOLOGY-BASED CAUSAL MODELS

Master's thesis for the degree of Master of Science in Technology submitted for inspection, Espoo, 6 June, 2013.

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Preface

This Master's Thesis was carried out in the Research Group of Process Control and Automation at the School of Chemical Technology, Aalto University. It was written in the period from November 2012 to May 2013. My work was obtained substantial support from many people around me during this period.

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School of Chemical Technology Abstract of Master's Thesis
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A Method for Generating Process Topology-based Causal Models

Abstract

Process disturbances always spread along the connected equipment in a plant and are detected in many places. In order to identify the root disturbance, many data-based fault detection and diagnosis (FDD) methods have been developed in recent years. However, most of these methods can generate spurious solutions. Several authors have observed that FDD methods are enhanced if topology information about the causal relationships of a process is considered as well. Generally, this topology information is manually created by using the process knowledge. However, such a way is always time-consuming and the result is imprecise. Hence, there is a requirement for an automated generation of effective topology-based causal models.

This thesis developed a thorough approach to implement two types of causal models, i.e., a connectivity matrix and a causal digraph, based on piping and instrumentation diagrams (P&IDs). As the core development tools, AutoCAD P&ID and object-oriented programming (OOP) of MATLAB were used. The development included three procedures: generate topology data, define the class for generating causal models, and obtain the causal models by instantiating the class with the topology data.

In conclusion, it appears that both the connectivity matrix and causal digraph manifest the internal relationship between different process components caused by material flows and signal flows in a clear way. Therefore, these models can play an important role in the research associated with the FDD methods.

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ABBREVIATIONS

AP	Application Protocol
API	Application Programming Interface
BM4	Board Machine 4
BSI	British Standards Institution
CAD	Computer Aided Design
CAEX	Computer Aided Engineering Exchange
DLL	Dynamic-link Library
FDD	Fault Detection and Diagnosis
GUI	Graphical User Interface
ISA	International Society of Automation
LC	Level Controller
LV	Level Valve
OOP	Object-oriented Programming
P&ID	Piping and Instrumentation Diagram
PCA	Principal Component Analysis
	POSC Caesar Association
PC	Pressure Controller
PDC	Pressure Difference Controller
PFD	Process Flow Diagram
PIP	Process Industry Practices
PLS	Partial Least Square
PV	Pressure Valve
QCS	Quality Control System
QSIM	Qualitative Simulation
QTA	Qualitative Trend Analysis
RDBMS	Relational Database Management System

RDL	Reference Data Library
SDG	Signed Directed Graph
SG	Steam Group
STEP	Standard for the Exchange of Product Model Data
W3C	World Wide Web Consortium
XLS/XLSX	Microsoft Excel File Format
XML	Extensible Markup Language

1 INTRODUCTION

Modern industrial processes present complicated structures with a large number of control loops and equipment which are interlinked. Hence, process disturbance occurring at one point always propagates along the plant and leads to the variances in many other variables. The term fault refers to the variance exceeds the acceptable scope of a variable. The procedure to determine the faults and further locate the origin of faults is called fault detection and diagnosis (FDD). In several decades, many data–based FDD methods have been proved their effectiveness in finding the root cause from numerous potential fault points. However, such methods tend to create spurious solutions. In other words, there are always more than one root cause calculated and these methods do not have a satisfied precision.

Diagnosis of the root cause of plant-wide faults is improved when process topology is considered together with the results of traditional data-based FDD methods (Thomhii, 2006). Generally, the process topology information, for instance, the connections between process equipment can be identified from a process drawing, such as a piping and instrumentation diagram (P&ID) (Di Geronimo Gil, 2011). However, this type of drawing is always designed for engineering applications, e.g. construction and maintenance. It is, therefore, complicated and contains a large amount of information unrelated to the FDD research, which only requires the connecting information of process components without their geometric shape and size. This provides the motivation to simplify the P&ID drawing and create a brief and readable topology-based model for the FDD research. There are two types of topology-based causal models including the topology-based causal digraph and the connectivity matrix, which can be considered as a graphical representation and a numerical representation of process schematics, respectively.

In recent years, more and more researchers have employed topology-based causal models to eliminate the spurious solutions generated from data-based methods

(Thomhii, 2006; Yim, 2006; Thambirajah, 2007 ; Benabbas, 2009). Thomhii et al. (2006) proposed a prototype software, which combines XML representations of process schematics with the results of a signal analysis tool to locate the root causes. Thambirajah et al. (2007) offered a strategy which utilizes a connectivity matrix created from an XML description of the process diagram to reduce the spurious solutions generated from a data-driven analysis called transfer entropy. Further, Benabbas et al. (2009) converted the results of transfer entropy method to a cause-and-effect matrix with the aid of a connectivity matrix to diagnose the root cause. All these articles indicate the root cause can be more effectively located by data-based methods when the topology information about plant connectivity is considered.

In all the above work, though extensive attention has been given to confirm the validity of topology-based causal models applied in data-based methods, the detailed procedures and methodologies that are used to develop these models have not been studied. This provides the intention of this thesis, which proposes a systematic way to convert process schematics to topology-based causal models.

This thesis proposes a convenient method to extract causal models from a kind of process schematic, P&ID. As the core development tools, AutoCAD P&ID and object-oriented programming (OOP) of MATLAB are used to generate the two kinds of causal models, i.e., a connectivity matrix and a causal digraph. The development includes three procedures. The first step is to employ AutoCAD P&ID software to generate an electronic P&ID drawing and export the topology data, such as the names and coordinates of process items, and the connections between them. In the second step, a problem solving class is established by MATLAB OOP. Finally, the topology data is imported to the class and the connectivity matrix and digraph are obtained by invoking corresponding methods defined in the class. The remainder of the thesis is arranged as follows:

The literature part consists of three chapters. Chapter 2 briefly introduces the traditional FDD methods and gives an overview of the graphical models

employed in promoting the performance of data-based FDD methods. Chapter 3 presents the graphical representation of process topology and introduces a series of symbol standards which are used in a P&ID drawing. Some common application software used for drawing the P&IDs are also specified. Chapter 4 mainly focuses on the electronic representation of the P&ID drawing. Two types of industrial standards for topology data exchanges are introduced.

The experimental part specifies the thorough procedures for generating topology-based causal models. It briefly introduces relevant techniques, such as AutoCAD P&ID and MATLAB OOP, before describing how they are applied in the formation of the causal models. Then, the drying section of a board machine is used as the case study to present the application of the proposed method. The thesis ends with the summary and conclusion.

LITERATURE PART

2 FAULT DETECTION AND DIAGNOSIS AND GRAPHICAL MODELS

Process disturbance occurring at one point always propagates along the plant and causes the process faults of many other variables. Such a feature of the process disturbance increases difficulties in the maintenance work. In several decades, many fault detection and diagnosis methods have been proved their effectiveness in finding the root cause from numerous potential fault points. However, such methods tend to create spurious solutions and do not have a satisfied precision. Several authors have recognized the advantages of utilizing a graphical qualitative model, which reflects the relationships between process variables, to improve the the results of traditional FDD methods.

This chapter provides the background and motivation of the whole thesis. Firstly, it gives an overview of traditional FDD methods and their classification. Then, the shortages of FDDs are proposed and the definition and motivation of graphical models are introduced. As the graphical model that the thesis focuses on, the concept of the topology-based causal model is highlighted.

2.1 Definition of the FDD

The malfunctions of a process are usually characterized by process abnormalities in process variables, such as flow, pressure, level or temperature. This type of abnormality is also called a fault (Himmelblau, 1978). More specifically, the term fault refers to an unallowable deviation of one or more characteristic properties of the system from the normal and acceptable state. The unallowable deviation is the variance between the fault value and the violated threshold of a tolerance zone for its normal value (Isermann, 2011).

The root cause or basic event refers to an underlying cause of faults. The root

cause is also known as a malfunction or a failure (Venkatasubramanian, 2003). Venkatasubramanian et al. further divides failures occurring in industrial systems into three types, namely process parameter changes, structural changes, actuator and sensor problems. The parameter changes indicate a disturbance entering the process through exogenous variables (Huang, 2002). For instance, an alteration in the flow rate of the feed stream is typically such a case. Structural changes mean that changes occur within the process. They are mainly caused by hard failures in equipment such as a controller failure or a broken pipe, etc. (Venkatasubramanian, 2005). Actuator and sensor problems, which result from a fixed failure, a constant bias or an out of range failure, refer to the incorrect measurements and wrong implementation of the controller commands (Venkatasubramanian, 2003).

The process supervision loop, as shown in Figure 1, explicitly describes the concept and function of FDD. A process fault can be identified by timely checking if particular measurements are within a tolerable scope of the normal value. The fault message will be determined if this check is not passed and that process is called fault detection. Once a fault is detected, the following step named fault diagnosis will be taken, where the root cause is identified and located. In the rest stages, the hazard grade of the fault cause is assessed and corresponding actions are taken. If it is tolerable, the operation continues, otherwise, a series of changes will be performed to the operation. Typically, the operation must be stopped and the fault must be eliminated when the fault is intolerable (Isermann, 1984).

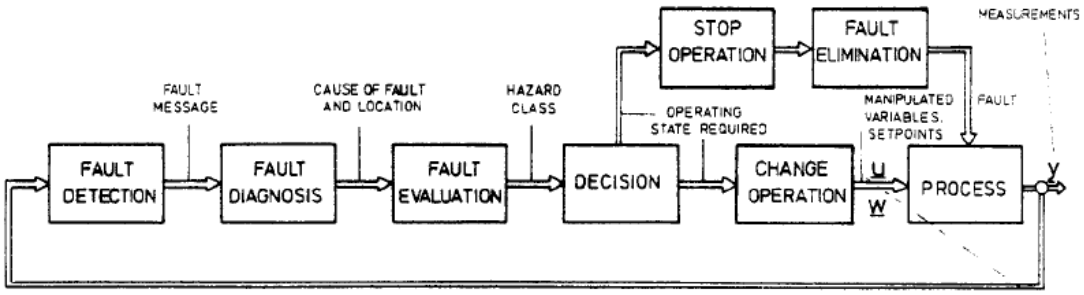

Figure 1: Process supervision loop (Isermann, 1984)

FDDs are essential in the process industry. Traditionally, operators are required to detect and find out the root cause of process faults by their experience and knowledge. Next some actions are made to correct the fault which could result in innumerous damages to the plant due to its chain reaction (Kokawa, 1983). However, these tasks are very difficult for human labor as the scale of modern process industries is becoming increasingly complicated.

A modern typical chemical process is always composed of a large number of components, such as equipment, instrumentation, and valves, which are interconnected by pipes and signal lines through which the mass and signals flow. The connectivity of a continuous process means that faults usually spread between subsystems. The root cause cannot be determined by a single fault since it might be aroused by an upstream fault. Hence, it is time-consuming and difficult to locate the source of a fault by observing vast abnormal signals by human labor (Thambirajah, 2009). Moreover, disturbances that propagate plant-wide have an extremely large impact on product quality and running costs, and even cause serious accidents which damage the facility and threaten the personal safety (Thornhill, 2003). Finally, if the root cause can be early found and removed, the propagation will be limited at an early stage so as to reduce the workload of further problem solutions. These considerations provide the motivation for the development of effective FDD methods when an abnormal measurement is detected.

2.2 Classification of the FDD

The process of FDD can be considered as a set of transformations, which is shown in Figure 2, based on process measurements (Venkatasubramanian, 2003). The feature space contains a series of functions about measurement variables, and such functions are derived from a priori process knowledge. Furthermore, the transformation from the feature space to the decision space is achieved by utilizing discriminant functions to calculate if the differences between measurements and expected values obtained from the feature space meet specific objective values. This step determines if some variables are out of normal states

so as to realize the fault detection. Lastly, the root cause is decided through the comparison between the decision variables and the fault symptoms stored in the class space.

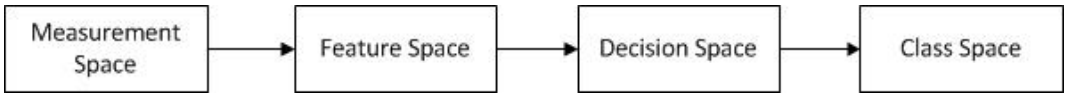

Figure 2 : FDD flow from the perspective of transformations on measurements (Venkatasubramanian, 2003)

Based on the FDD flow discussed above, a priori process knowledge is the first section of the FDD and plays a key role to decide the effects of the fault diagnosis. The basic a priori knowledge for fault diagnosis is divided into model-based knowledge and history-based knowledge. Model-based knowledge can be either mathematical relationships between the inputs and outputs of a process (quantitative model) or qualitative functions based on different units (qualitative model). In contrast, the history-based knowledge means the features extracted from historical process data (Venkatasubramanian, 2003). Venkatasubramanian et. al. further classified the FDD methods into the three categories including quantitative model based methods, qualitative model based methods, and process history based methods, according to the a priori knowledge which they use. Figure 3 shows the classification diagram.

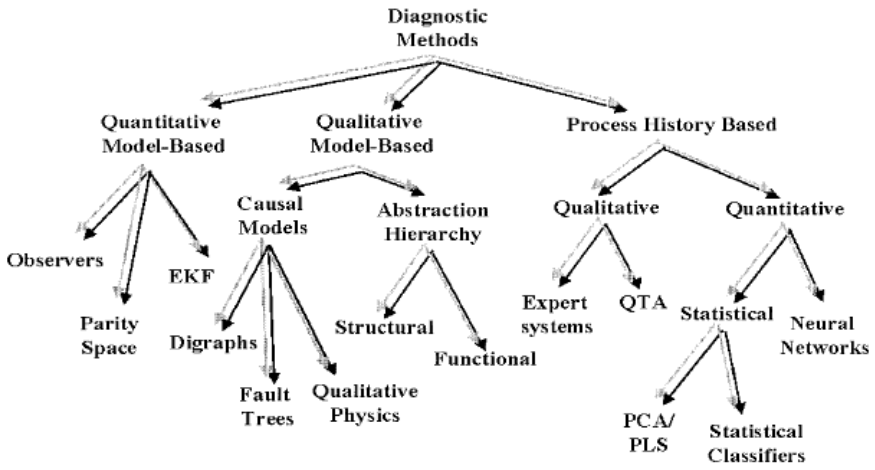

Figure 3: Classification of the diagnostic algorithms (Venkatasubramanian, 2003)

Quantitative model-based methods are applied by searching for residuals between measurements and estimated values predicted by a specific mathematical model, which can be derived either from physical understanding or a black-box scheme. The models used for residuals generation mainly includes diagnostic observers, parity relations, Kalman filters, and parameter estimation (Ding, 2008). However, an accurate mathematical model is always hard to develop for a complicated process which is characterized by complexity and nonlinearity. Hence, quantitative model-based methods are not suitable for a large-scale process system (Venkatasubramanian, 2003).

Qualitative model-based methods capture cause-effect relationships between variables and failures based on understanding of the physics and chemistry of the process (Venkatasubramanian, 2005). Qualitative models do not depend on precise expressions and numerical models about the process. The most typical qualitative model-based methods contain signed directed graph (SDG), fault trees, and qualitative simulation (QSIM) (Venkatasubramanian, 2003). A typical qualitative method, such as SDG, involves the connecting information of process variables, with which the fault propagation path can be readily identified. Hence, qualitative models are suitable for locating root causes in a large-scale process (Jamsa-Jounela, 2012).

Process history based methods exploit the internal connections between process variables from measurements. This kind of method can be either qualitative or quantitative according to the extracted information. Specifically, the methods that extract qualitative information, called qualitative methods for short, include expert systems and qualitative trend analysis (QTA). The quantitative methods involve non-statistical methods (e.g. neural networks) and statistical methods, which can be further classified as principal component analysis (PCA) and partial least squares (PLS) (Venkatasubramanian, 2003).

However, the diagnostic effect becomes restricted when the FDD method mentioned above is applied alone in the large-scale process system. Maurya et al.

have noticed that signed direct graph (SDG) methods can create several spurious candidates when it is used alone for diagnosis (Maurya, 2007). It is also difficult to judge if a specific variable is the root cause by only analyzing process measurements since there are more than one candidate root causes calculated (Chiang, 2003; Jiang, 2009; Benabbas, 2009). Hence, a combination of two or more diagnosis methods is commonly applied in actual cases.

2.3 Graphical Models Used for the FDD

Several authors have recognized the advantages of utilizing a graphical qualitative model, which reflects the relationships between process variables, to improve the process data based analysis. Such a model usually contains process understanding and offers an explanation of the means by which a fault propagates from the root cause to other positions (Thornhill, 2003).The most typical graphical qualitative models include variable-based SDGs and process topology-based causal models (Yang, 2010).

2.3.1 An Overview of the SDG

The SDG is a graph where the nodes denote the process variables and the edges correspond to the direct influences between the variables. Additionally, both nodes and edges consist of signs associated with them. These signs indicate variations of variables and the influence of these variations on other variables (Iri, 1979). The SDG can be derived from either mathematical equations or process knowledge. Chiang (2003) applied SDGs in multivariate statistical analysis to improve the fault diagnosis. Lee et al. (2003) used a SDG to decompose a process into subprocesses and applied partial least-squares for each measured variable in each subprocess so as to promote the diagnostic precision. Maury et al. (2007) employed a SDG method to reduce spurious solutions generated by a data-based analysis of QTA for the fault diagnosis.

2.3.2 An Overview of the Process Topology-based Causal Models

Topology-based causal models are a type of qualitative model, which indicates the physical connections of process items including equipment, valves, and instrumentations. Such a model can be derived from a process schematic without the request for first principles (Di Geronimo Gil, 2011). Different from the SDG which directly reveals the relationships of process variables, topology-based causal models indirectly show interactions between variables in different components, which have resulted from physical or signal flows along the components in a system.

Topology-based models are readily to be developed, since the topology data which is required to build such models can be easily exported from computer aided engineering tools, such as AutoCAD P&ID, SmartPlant P&ID and ComosPT, in the form of XML (extensible markup language) or XLS/XLSX format (Microsoft Excel file format).

There are two types of topology-based causal models including the topology-based causal digraph and the connectivity matrix, which can be considered as a graphical representation and a numerical representation of process schematics, respectively. The topology-based causal digraph uses nodes and directional arcs to represent the positional information of process items and their connections. The connectivity matrix, the other form of the causal model, is a matrix which represents the relationships between components with binary numbers. Elements in the matrix can be either ‘1’ or ‘0’ according to whether there is a directional connection from the row header to the column header, which represents a specific process component (Benabbas, 2009). The detailed concept of the topology-based causal models will be specified in the Section 6.1.1 of the experimental part.

3 GRAPHICAL REPRESENTATION OF PROCESS TOPOLOGY - P&ID

The process topology refers to positions of process components and their connections. Piping and instrumentation diagrams (P&IDs), which are usually applied to plant design, construction, and maintenance, clearly reflect such topology information. In order to guarantee the consistency of the P&IDs, a series of the P&ID standards for graphical symbols and lettering abbreviations are published. The most common ones comprise the PIP, ISA, ISO, BS, and DIN standards. The graphical symbols and their identifications defined by different standards always vary; hence, a thorough understanding of these representations and the differences between them is very essential. With the development of information technology, the traditional printed P&ID drawings are being gradually replaced by the more effective electronic P&IDs which present huge advantages in the design, maintenance and data exchange of the P&ID drawings.

Based on the above introduction, this chapter first presents the definition of the P&IDs and their applications. Next, some common standards used for P&IDs are described. Section 3.3 mainly concentrates on the identification of the various component symbols and lettering abbreviations. The last section introduces several intelligent P&ID design applications.

3.1 Definition of the P&ID

A process layout or topology in a plant is usually presented by a series of the process components such as equipment and instrumentation, and the piping between them. In the engineering applications such as project designing and construction, the process drawings are commonly used to describe such a process topology. The most ordinary process drawings applied in the process industry include a process flow diagram (PFD) and a piping and instrumentation diagram (P&ID) (Bumble, 2000).

The PFD is a process sketch which uses standard symbols to represent the process equipment and reveal the general flow of the plant processes. The PFD depicts the connecting information about the primary piping between the major plant equipment so that it only identifies physical flows, i.e., gas and liquid flows along the process and does not show details about control loops (Matt, 2009).

The P&ID is developed from the PFD and includes the control loops (Dev, 2013). Compared with the PFD, the P&ID is a more detailed graphical description of the plant topology and it displays both the pipe lines and signal lines along with the connected equipment and instrumentation. Hence, the P&ID reflects both process flow and control functions. As an important constituent, the instrumentation in P&IDs refers to a combination of devices in the control loop which are used to measure, display and control a variable. The common instruments include measurement devices (e.g., a transmitter), indication devices (e.g., an indicator), control devices(e.g., a controller) and actuating devices (e.g., a control valve) (Meier, 2007). As shown in Figure 4, in which a PFD (left) and a P&ID (right) based on the same process are presented, the P&ID possesses more control functions such as control valves and controllers, which are not presented on the PFD.

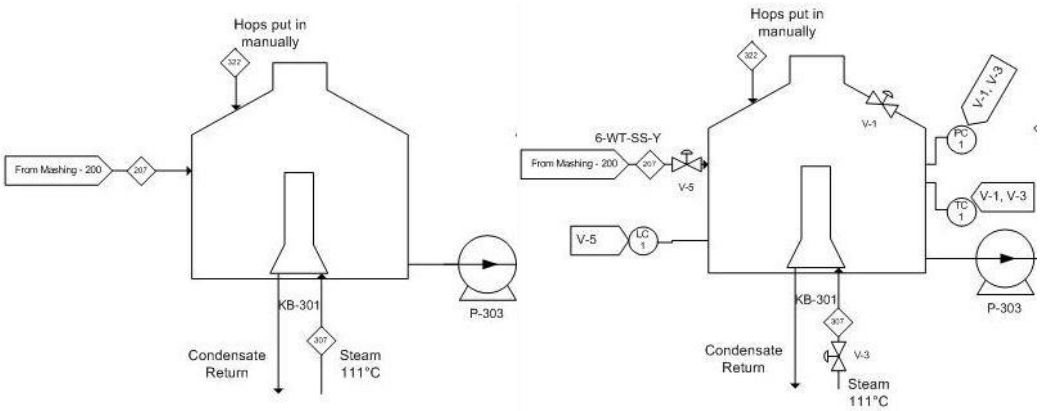

Figure 4: Comparison between the PFD (left) and the P&ID (right) (Matt, 2009)

Besides the graphical symbols, the P&IDs also assign a tagging system to uniquely identify the process items. Such a system includes abbreviations and

numbers of equipment, valves, and instruments, as well as the numbers of piping and control loops. Moreover, the size of piping and valves is also marked.

The P&ID provides essential information required for constructing and operating the process and further conducting the fault diagnosis. It presents detailed information about piping connections between process components so as to provide a feasible foundation for the engineering applications. On the other hand, the connecting lines imply the internal connections such as physical or signal flows between different components. This assists the normal FDD methods to precisely locate the most probable root causes when faults occur (Thambirajah, 2009). Overall, the P&ID realizes the following four functions (Cook, 2010):

1. It provides clear illustration and relative position information of all equipment, piping and instruments to all people who want to understand the process.
2. It is strong evidence upon which engineers conduct process hazards analysis and fault diagnosis.
3. It is an essential guideline for process construction, operation and maintenance.
4. When improvements are applied, the P&IDs can be treated as a project reference and changes can be planned safely and effectively.

Although the P&ID clearly describes the overall process topology and identifies each equipment and instrument, it still lacks some detailed information. For instance, it only generally presents the symbols and relative locations of devices rather than their actual size and real positions. It does not contain operating specifications such as flow rates, compositions, pressure, and temperature (Christopher, 2007). Therefore, other supplementary documents are usually needed to provide more details. Such documents include: the plant layout drawings showing the distance between units, the PFDs providing detailed mass/energy balance data and stream compositions, the material specifications explaining materials needed for construction, and the equipment and instrumentation specifications deeply describing some details about equipment and instruments (Cook, 2010).

For a large process, the structure of the P&ID diagram needs to be broken down into manageable sections according to the areas in the plant, functions or other criteria that affect to the project (Cook, 2010). Correspondingly, each diagram should be equipped with notations directing to the linked diagram. The separation of the P&IDs facilitates the development of the drawing as well as its readability.

3.2 P&ID Standards

P&IDs must be designed systematically and uniformly within a company (Christopher, 2007). Firstly, the development and implementation of a P&ID project always involve professional engineers from various departments. Inconformity can lead to confusion among different participants so as to affect the project implementation. Moreover, the follow-up maintenances and improvements based on the P&IDs are always conducted by different developers. The revisions reflecting the process changes should therefore follow the same form each time. Inconsistent formats of the P&IDs are confusing and misunderstanding by the upstreaming technicians.

Based on above reasons, a thorough set of standards must be determined before the P&ID development either for creating a P&ID by hand or on a computer. These standards define the format of symbol and identification label for each component of the P&ID (Medida, 2007). P&ID symbols are graphical representations for process components, e.g., equipment, piping, and instruments. Identification labels are a combination of letters and numbers used to uniquely recognize a process item. Currently, there are many standards for instrument symbols and lettering abbreviations of the P&IDs. The most common ones comprise the PIP, ISA, ISO, BS, and DIN standards.

3.2.1 An Introduction to the P&ID standards

PIP standard. The industry group Process Industry Practices (PIP) is an association of a series of member companies, with the aim to harmonize the

internal standards of member companies for design, construction, and maintenance. It establishes a set of harmonized documents as "Practices" in various process disciplines such as power, pulp & paper, and pharmaceuticals (PIP, 2012).

The P&ID standard issued by PIP is enclosed in PIP PIC001, Piping and Instrumentation Diagram Documentation Criteria, which defines the P&ID format (drawing size, item layout, tag format, text arrangement, etc.), symbols , drafting rules, and tagging and numbering scheme for the equipment (tanks, exchangers, pumps, reactors, etc.), piping (piping lines, valves, and fittings), and instrumentation and controls (controllers, control valves, transmitters, Interlocks, relief devices) (PIP, 2008).

ISA standard. The latest version of American standard ANSI/ISA-5.1, Instrumentation Symbols and Identification, is approved by Standards and Practices Board of International Society of Automation (ISA) in 2009. It is used to describe instrumentation symbolism, and identification systems. This standard introduces a consistent mechanism that comprises identification schemes and graphic symbols in order to describe and identify instruments and process items and their functions. The ISA standard is widely applied in commercial process software, which is used for measuring, monitoring, and controlling actual process production (ISA, 2009).

ISO 14617 standard. The P&ID standard published by the International Organization for Standardization (ISO) technical committees belongs to the standard series ISO 14617, graphical symbols for diagrams. The purpose of ISO 14617 is to develop a library of the harmonized graphical symbols for diagrams used in technical applications. The sections associated to the P&IDs involve: 14617-3 specifies graphical symbols for functional connections, pipelines, and connection joints; 14617-4 specifies graphical symbols for basic elements in the actuator, complete actuators, and actuating devices in diagrams; 14617-5 and

14617-6 specify graphical symbols for measurement, and control devices and functions; 14617-8 specifies graphical symbols for valves (SFS, 2004).

BS standard. British standard BS 1646 (1-4) has been developed by the Industrial-process measurement and control standards committee of the British Standards Institution (BSI) from 1979 to 1984. This standard provides a set of symbolic representations for process measurement control functions, and instrumentation. The standard is presented in four parts (BSI, 1979-1984): the part 1 and part 2 create a symbol system which involves a series of the graphical representations describing the functions of measurement and control equipment in a process. This system only clarifies the identification of the instrument functions without affording approaches of depicting specific instruments. The part 3 specifies instrument symbols, such as signal lines, measurement devices, for use on interconnection diagrams. The part 4 specifies symbols for the representation of the process computer and/or shared display/control functions in process measurement and control. The symbols can be used in conjunction with the symbols given in the part 1 and part 2 of BS 1646.

DIN standard. DIN 19227-1-1993 and DIN 19227-2-1991 are issued by German Institute for Standardization. This standard applied to the preparation of design documentation for process control engineering incorporates existing measurement, operation, and control instrumentation (DIN, 1993).

The name of DIN 19227-1 is 'Control Technology - Graphical Symbols and Identifying Letters for Process Control Engineering - Symbolic Representation for Functions'. This document defines graphical symbols for the basic representation of process instrumentation and controls including conventional measurement and control equipment. DIN 19227-2, namely 'Control Technology - Graphical Symbols and Identifying Letters for Process Control Engineering - Representation of Details', deals with the detailed representation of the functions as specified in DIN 19227-1.

3.2.2 Comparisons between Different P&ID Standards

The ISA standard is an extension of the PIP standard (PIP, 2008). In other words, the ISA standard is developed from the PIP PIC001. The cross-licensing agreement between ISA and PIP allows ISA to broaden the symbol library of the PIP standard and extend its application beyond the member companies of the PIP (PRNewswire, 2000). Meanwhile, PIP can also get access to the ISA symbols in the PIC001. Hence, the ISA standard possesses more complete symbol libraries than PIP.

The ISO standard is widely employed by the European industries. The BS standard is developed from the ISO standard and it therefore follows the similar expression form and the drawing rule than the ISO standard. However, the BS standard focuses on process control functions and instrumentation sections, but ignores the equipment and pipes (BSI, 1979-1984).

The DIN standard defines special P&ID graphical systems which is different from others. Similar to the BS standard, this standard concentrates on the graphical symbols and identifying letters for instrumentation. Since there exist similarities between different standards, the following section describes the components identification in the P&ID with ISA standard.

3.3 Component Identification in the P&ID

As mentioned in the last section, the development of a P&ID should follow a certain norm. There are two factors, P&ID drawing styles and component identification, which should be considered when an understandable P&ID is developed (Nasby, 2012).

Drawing styles refer to the arrangement of symbols and piping on a P&ID. The ISA standard defines a three-layer hierarchy for a P&ID drawing, which is shown as the field equipment, local control panels, and central control systems, from the bottom to the top. In contrast, the other standards do not propose a specific

drawing style. Normally, the layout of the process components can be determined by the specific design requirements of a company and it should reflect actual positions of the process components.

Component identification refers to the representation of the actual process items in a P&ID. Such a representation refers to a combination of the graphical symbols and identification labels of the process items. The following depicts three of the most important items: equipment, lines, and instrumentation.

3.3.1 P&ID Symbols and Tagging

Different types of process equipment are distinguished by different symbols, while the tag scheme can be applied to differentiate the equipment within the same type. Figure 5 shows some common equipment symbols with corresponding tags based on ISA standard. Equipment tags usually possess a letters-plus-number tagging scheme (ISA, 2009). The letter designates the type of equipment, such as V is vessel, P is pump, and T is tank, while the number is the identifier of a piece of specific equipment. The tag can also involve the type of service which can also be represented with a number. For instance, 30 is process gas and 60 is fuel gas. Hence, the tag TK-60100 means the number 100 tank with fuel gas service.

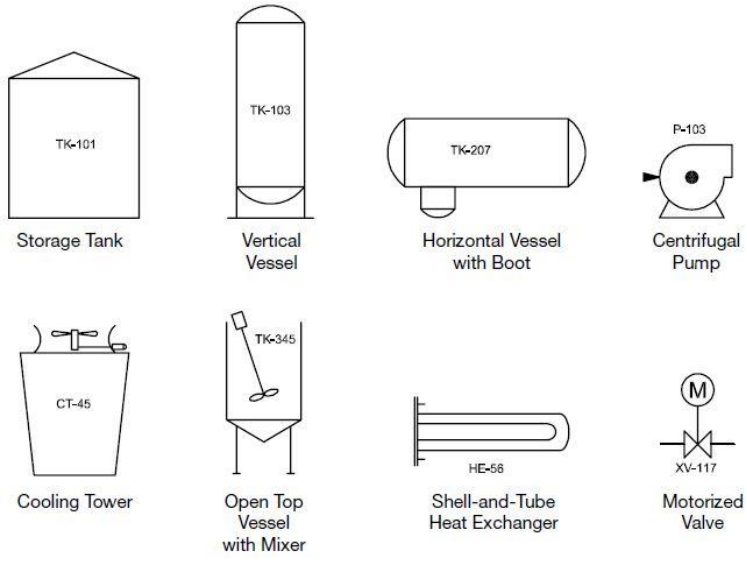

Figure 5: Commonly used equipment symbols with the alphanumeric labels (Nasby, 2012)

Pipes and signal lines are usually denoted by different line symbols, which are used to describe the connectivity between different process components and the internal materials that pipes/lines serve for. Process industry usually involves two types of pipes, primary pipes, and secondary pipes, which are distinguished by lines with a different size. The direction of material flow is usually identified by arrows, and the pipe labels are placed along the lines to provide further information about the pipe, for instance, a diameter of the pipe, the component in the stream, material of the pipe, and insulation. The format of the labels is usually company-specific. Figure 6 shows a case of the pipe line symbols, which represents the number 39 pipe with a 4" diameter. The stream that the pipe carries is denoted 'N', the pipe is made of carbon steel, and there is no insulation.

Figure 6: A pipe line segment with labels (Halley, 2009)

The signal line symbols describe how signals are transmitted within a control loop. This type of lines should be lighter than the process pipe lines. Moreover, the signal types, such as electrical and pneumatic, should be reflected by different forms of lines. Table 1 describes the most common signal lines defined in the ISA-5.1 (Meier, 2011).

Table 1: Commonly used signal line symbols (Halley, 2009)

Connection to process, or instrument supply	
Pneumatic signal	
Electric signal	
Capillary tubing (filled system)	
Hydraulic signal	
Electromagnetic or sonic signal (guided)	
Internal system link (software or data link)	

As shown in Figure 7, the pipe and signal lines, also known as the major and minor lines, should be broken according to the hierarchy in the order of major-minor-primary-secondary lines, when they cross.

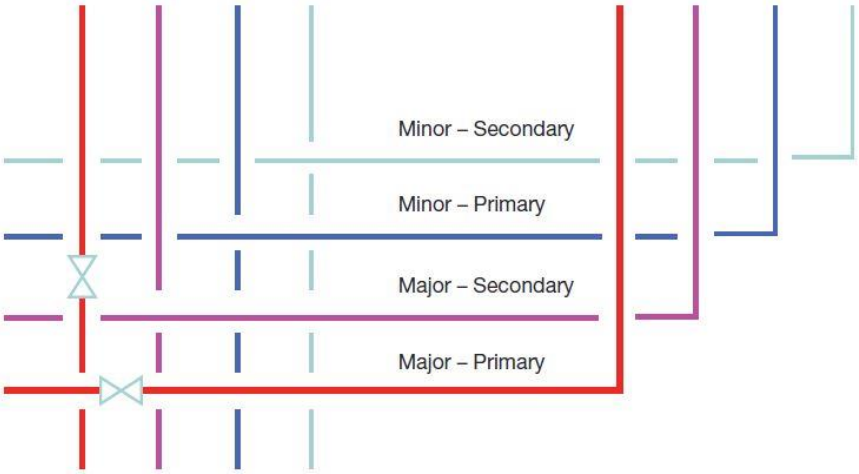

Figure 7: Crossing lines (Walker, 2009)

Instrumentation symbols reflect process instruments, e.g., transmitters, indicators, and controllers. These symbols with the attached tags can easily identify the instrument functions, and their locations. The following figure extracted from the ISA standard document lists the common instrumentation symbols.

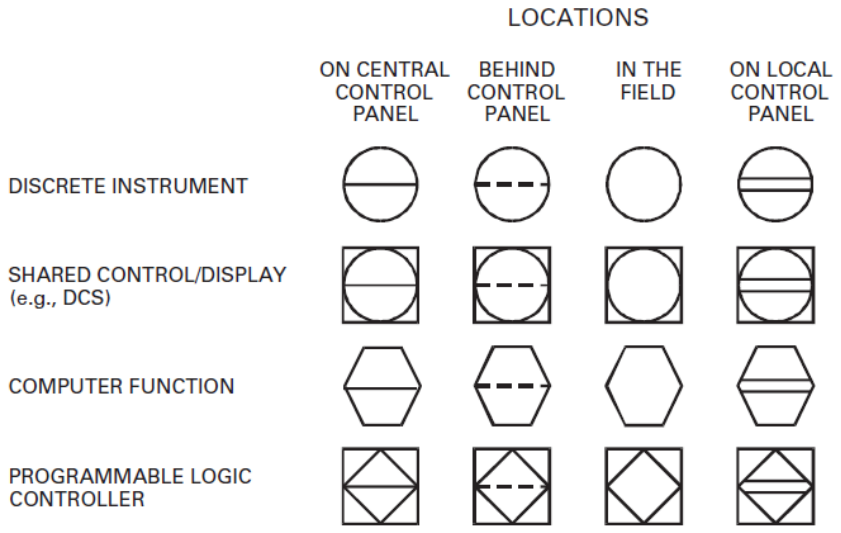

Figure 8: General Instrument and Function Symbols (Meier, 2011)

As shown in Figure 8, all the graphical shapes, such as circles, squares, hexagons, and diamonds, possess specific denotation. A circle indicates a device is located in the field area of a plant. A circle with an external square represents devices or functions which belong to a shared display and control system, e.g., a DCS system. A hexagon represents a computer function. A diamond with an external square defines functions within a programmable logic controller. The symbol with one line inside means the device is located in the central control room, whilst the one with two lines indicates the device is located in a local panel. A circle with a dotted line in the center means the device is installed behind the panel and inaccessible to the operator (Meier, 2011). The ISA-5.1 clarifies meanings of the identification letters for the instrument, and the function system in a tabular form as shown in Table 2.

Table 2: Instrumentation identification letters (ISA, 2009)

	First Letter		Succeeding Letters		
	Measured or Initiating Variable	Modifier	Readout or Passive Function	Output Function	Modifier
A	Analysis		Alarm		
C				Controller	
D		Differential			
E	Voltage			Sensing Element	
F	Flowrate	Ratio (Fraction)			
G			Sight glass		
H	Hand				High
I	Current		Indicator		
K		Rate of Change			
L	Level		Light		Low
M		Momentary			Middle
P	Pressure				
Q	Quantity	Integrate, Totalize	Point (Test) Connection		
R	Radiation		Recorder		
S	Speed	Safety		Switch	
T	Temperature				
V	Vibration			Valve, Damper	
Z	Position			Actuator	

This table is classified into five columns which consist of two parts, describing process variables, and the type of device respectively. The first part includes the first two columns, representing process variables the instrument is intended to control, and the further description (modifier) about the process variables, respectively. The most common process variables involve: flow (F), level (L), pressure (P), and temperature (T) (Meier, 2011). The next three columns define a device. The function, readout (e.g. record) or output (e.g. valve), of the device are defined by the third and fourth column respectively. The last column defines the output functionality.

The instrumentation within the same loop should carry the corresponding loop number. In other words, all devices combined to conduct a single specific action should be tagged with the same identifier based on the loop. This number combined with the identification letters uniquely identifies each device. For instance, FT-002 is a flow transmitter in the 2nd loop.

In addition, a prefix in the form of the area-unit-plant can be combined with the instrument number to distinguish the instrument location, when the project is implemented in several areas, units and plants; thus, 234-PT-102 is a pressure transmitter in the loop 102, which is located in the area 2, the unit 3 and the plant 4. When a particular area involves several P&IDs, the variation of these diagrams can be reflected with the first digit of the instrument number. For example, FT-1230 means the device in the 30th loop of the 12th P&ID (Meier, 2011).

The instruments can be uniquely identified when the identification letters, instrument numbers and symbols are combined in a specific form, namely ‘Instrument Symbol Tag Identification’ (Cook, 2010). The “Instrument Symbol Tag Identification” in a control symbol contains two lines inside it: an abbreviation for the instrument and function system on the top line, and a loop number at the bottom. Figure 9 is an example representing a discrete flow element in the 150th loop and it is field mounted.

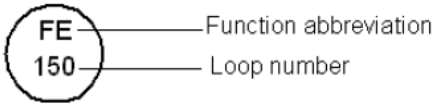

Figure 9: An example of the 'Instrument Symbol Tag Identification' (Cook, 2010)

3.4 Intelligent P&ID Applications

The P&IDs can be generated in an electronic form by the computer-aided design (CAD) programs. These programs are beneficial to produce the clean and neat P&IDs that can be stored and viewed electronically.

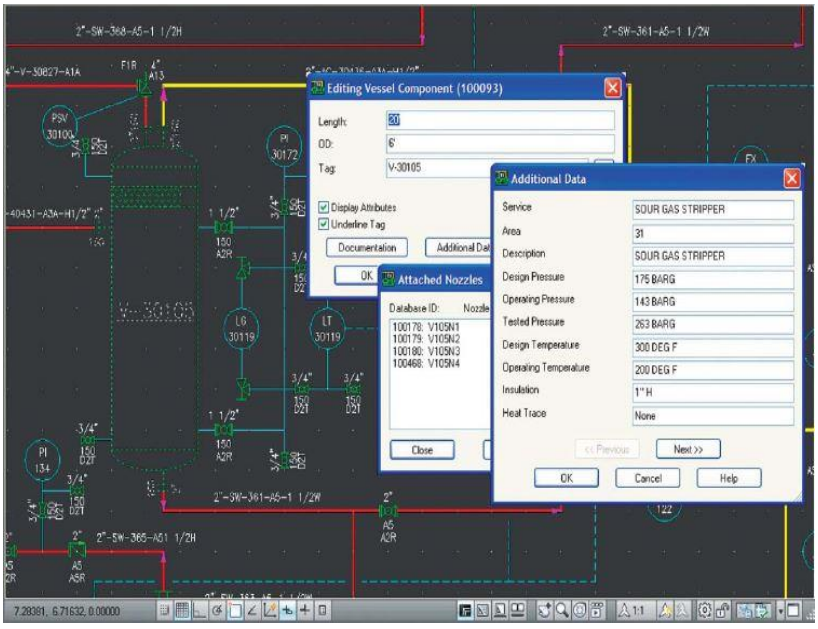

Figure 10: Electronic P&ID and its database (Walker, 2009)

The electronic or intelligent P&IDs are more efficiently generated than the printed ones. Firstly, there is usually a complete symbol library behind the CAD tools. This provides users convenience to perform drag-and–drop operations and reduces the repetitive works. Moreover, the symbols presented in the P&ID are more consistent since all of them are from the same source. Secondly, electronic drawing is more intelligent which is characterized by the following aspects: the lines are automatically broken when they cross; a line is automatically broken

when an inline item is inserted; the size of an inline item is automatically adjusted so as to match the line; and process items can be changed based on the original ones without redrawing. These advantages allow the electronic P&ID much easier to update and maintain than the printed P&IDs (Walker, 2009).

Another dramatic merit of an electronic P&ID is that its components carry extra information, which is not found in the printed P&IDs. Instead of a 'picture', the electronic P&ID can also be considered as a database which stores all the information related to the drawing. For instance, a piping on an electronic P&ID possesses a database which stores all the relevant information in the form of texts, such as connectivity, piping size, tag, material, and even vendor names. Further, this information can be exported and exchanged by other applications. Presently, the most common CAD programs for P&ID drawing include AutoCAD P&ID, Intergraph SmartPlant P&ID, and AVEVA P&ID.

3.4.1 AutoCAD P&ID, AVEVA P&ID and Intergraph SmartPlant P&ID

AutoCAD P&ID is a professional P&ID drafting application which has been developed based on the Autodesk AutoCAD software. Hence, it is readily to be mastered by many designers and engineers. The AutoCAD P&ID consists of the comprehensive P&ID symbol libraries which cover a wide range of standards, i.e., PIP, ISA, ISO, and DIN.

The humanistic tool palettes allow users to readily utilize components and lines to design the P&ID drawings. Furthermore, with the Data Manager, users can conveniently generate and obtain a variety of reports, including Instrument Lists, Line Lists, Equipment Lists, and Valve Lists, for all drawings in a project (AutoCAD, 2011).

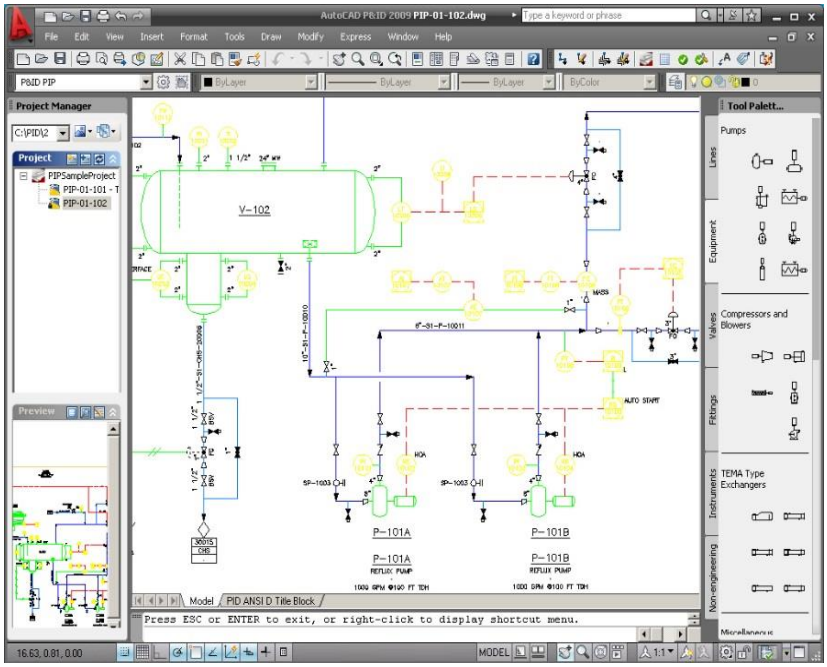

Figure 11: AutoCAD P&ID user interface (AutoCAD, 2011)

AVEVA P&ID is a P&ID drawing application which originates from the AutoCAD. It provides a symbol library which only supports the ISA standard. The P&ID sketch can be intelligently drawn by AVEVA which is characterized by the fact that the process items and the connectivity between them can be perceptively identified when symbols and flow lines are introduced into a drawing. Engineering tag information for the equipment, pipeline and instrument can be added as the items to extend the application scope of the P&ID drawings.

The project explorer in the Graphical User Interface (GUI) presents a list of process items on a drawing and symbol libraries, which enable the edition process conveniently. Furthermore, the users can add tags for process items in properties dialog boxes, which can integrate seamlessly with the AutoCAD software (AVEVA, 2010).

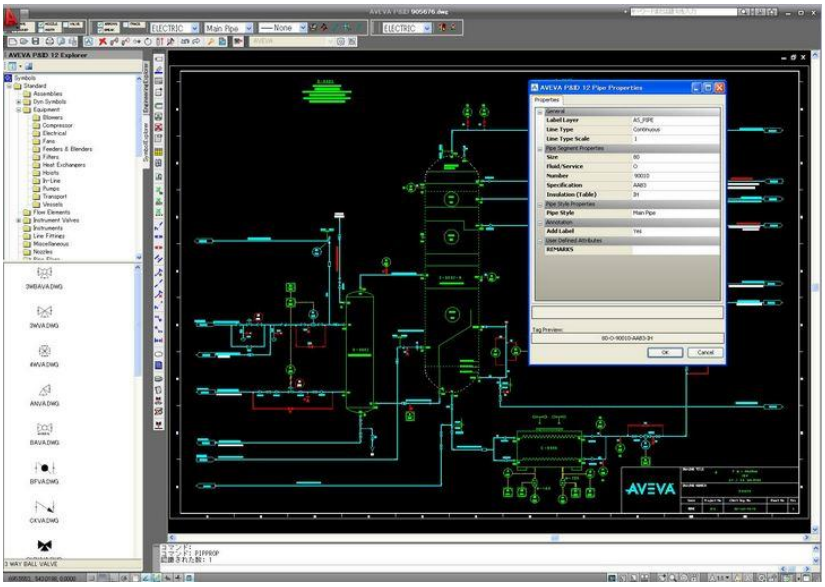

Figure 12: AVEVA P&ID user interface (AVEVA, 2010)

The SmartPlant P&ID is a P&ID application which is based on drawing data. Similar to the AutoCAD P&ID and AVEVA P&ID, the SmartPlant P&ID also includes two parts, a graphical drawing function and a drawing database, which are managed by the SmartPlant P&ID Drawing Manager and the SmartPlant P&ID Engineering Manager, respectively. This software provides the P&ID symbols conforming to the ISO and ISA standards (Intergraph, 2007).

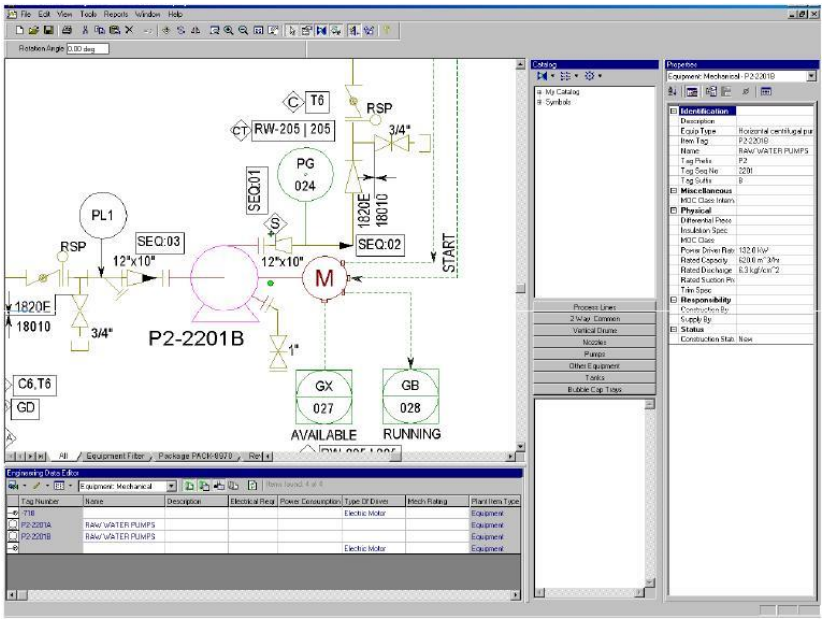

Figure 13: SmartPlant P&ID user interface (Intergraph, 2007)

4 XML REPRESENTATION OF THE P&IDS

In the modern industry, design data always needs to be exchanged among diverse CAD systems in order to complete a whole design process. However, different CAD systems always possess an individual data format, which seriously limits the data exchange.

Typically, a pictorial representation of the plant topology, such as a P&ID drawing, is of limited use to exchange data with computer programming tools. Thus, the definition of a generic text format is essential to ensure data consistency in different tools (IEC, 2005). As a commonly accepted data sharing format, XML is vendor independent and can be used to represent the plant topology, such as process components and their attributes, and the interconnections between them. As two accepted schemas, Computer Aided Engineering Exchange (CAEX) and XMpLant define the XML syntax when using XML files to represent the plant topology (Thambirajah, 2009). These schemas are developed based on a series of data exchange standards, e.g., ISO 10303, IEC/PAS 62424 and ISO 15926 (Alabi, 2010).

Nowadays, more and more CAD tools for P&ID design are beginning to support exporting P&ID drawings in the form of XML, for instance, Comos P&ID from Siemens, SmartPlant P&ID from Intergraph, and AVEVA P&ID (Thambirajah, 2009). In addition, for the P&ID design software which cannot export XML files, e.g., AutoCAD, it is possible to create XML files by means of programming languages, such as C++ and C#, in a self-defined format.

4.1 Engineering Data Exchange Standards

The requirement for standards that support data exchange results from the incompatibilities between computer systems (Fowler, 1995). There is no problem arising when one application separately operates. Nevertheless, the incompatibilities of data formats used by different applications restrict the cooperation between two or more different applications. Hence, a neutral format is

required when several computer systems communicate. This is the driving force behind a series of data exchange standards for the process plant industry (B2MML, 2009). Figure 14 shows the communication process based on the data exchange standards.

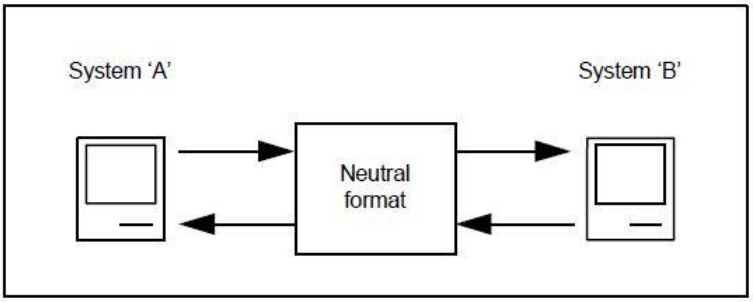

Figure 14: Neutral format data exchange (Fowler, 1995)

Engineering data exchange standards used in the process industries comprise ISO 10303(STEP) -221 and ISO15926.

4.1.1 ISO 10303(STEP) -221

The ISO 10303, also known as 'STEP' (Standard for the Exchange of Product Model Data), is a complete standard that depicts how to express and exchange digital manufacturing data (STEP Tools , 2013). It can be applied by a variety of disciplines in industry, e.g., automotive, aerospace, and chemical industries (Wiesner, 2011).

Application Protocols (APs), i.e., the implementable parts of the ISO 10303, define a series of models data exchange can be based on. The data structures in different engineering disciplines are specified by different APs. The AP applied in the process plant is developed by the European EPISTLE consortium and numbered as AP 221 "Functional data for process plant and their schematic representation". This standard involves the most common process schematics, e.g., P&IDs and PFDs, and the engineering facts which these schematics represent (Leal, 2005).

The AP221 can be described as an artificial language that computers can communicate with each other. Such a language contains two elements: the objects and the relationships between the objects. Therefore, the AP221 language consists of two main sections: the dictionary and the grammar, which define the objects and the rules for relationships between these objects, respectively.

The AP221 grammar, also called the AP221 Data Model, defines a standard sentence structure, such as '… is a part of a …' and '… has property …'. These sentence structures can be used to express the associations between two objects. For example, 'a valve is a part of a pipe segment'. The element of the expression between the two objects is called the "association type". The AP221 grammar consists of 60 such association types. The sentence structures can also be used to describe the events, activities, and behavior of objects in relation to each other. At the vacancies on both sides of the 'association types', the terms which represent equipment and plants, or their design and operation can be filled in.

In several cases, the terms filled in these places should be made from the AP221 Dictionary, also called STEPlib, which contains many thousands of terms. These terms include not only the types of plants and their properties, but also the process materials, design, operation and maintenance activities, and the roles of people and organizations involved.

The dictionary terms in the AP221 language are mainly used to express what things are, i.e., how they are classified or how their roles are classified. Thus, every term in the dictionary is a name of a class of the object, which is either a class of the physical object, a class of the events, a class of the role, a class of the property. Therefore, by using the association types, the sentence can be written as: '… is classified as … (class of the object)' or '… has a role as … (class of the role) in activity …'. For instance: V-200 is classified as a valve and V-200 has a role as a performer in an activity 'control fluid'.

4.1.2 ISO 15926

ISO 15926, also known as 'Life cycle data for process plant', is a standard for information integration, distribution, and exchange between different computer systems. It is developed from the AP 221 of the STEP and can record not only the instant state of the process plant, but also how the process plant changes (Leal, 2005). It aims at involving all engineering data in the whole life cycle of a chemical plant. Therefore, it can improve the data exchange between all engineering procedures starting from design to construction and operation (Wiesner, 2011). Leal (2005) summarized the contents that the standard involves: all physical items within a plant, the identifiers, properties and classifications of the physical items. In addition, the standard also defines how these process items are assembled and connected.

The ISO 15926 consists of 11 parts (Topping, 2011). The core of the ISO 15926 is the data model (Part 2) and the Reference Data Library (RDL) (Part 4). These two parts define how the data can be understood and the rest of the parts define how it is transferred.

Part 2 and Part 4 define the basic data template for communications between different applications. Such a template imitates the characteristic of the natural language, which includes the words and grammars. Particularly, if two people know the meaning of the words and how they are organized together (grammar), they can communicate seamlessly. Similarly, when two applications have a common dictionary which defines a series of words, and uses a common data model which defines the grammar, they can communicate seamlessly. Thus, the Part 4 (the dictionary) and the Part 2 (the data model) are the two most important parts of the ISO 15926. When two computer applications use the same terminology, i.e., the same RDL, and organize their information by same means, i.e., use the same data model, they can communicate freely.

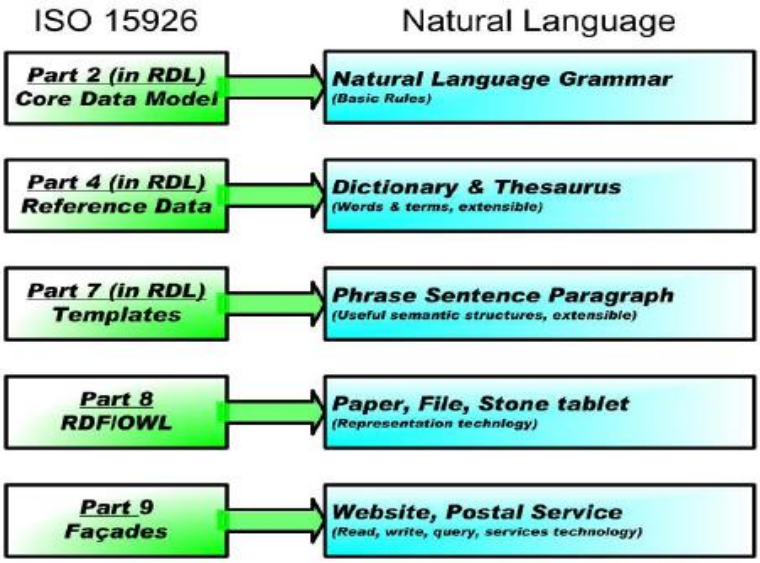

Figure 15：ISO 15926 Metaphor (Topping, 2011)

The following pyramid figure shows the structure of the ISO 15926, which is organized from generic classes to the specific objects from the top towards the bottom.

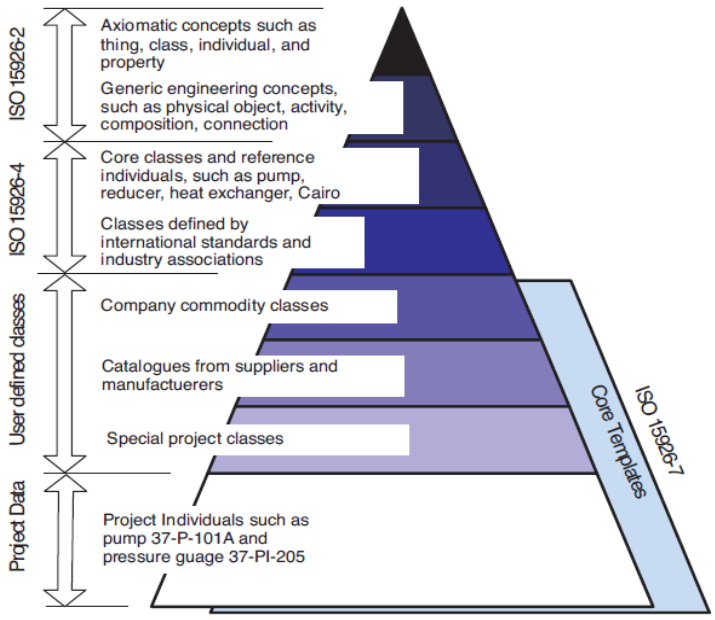

Figure 16: ISO 15926 pyramid (Leal, 2005)

Specifically, the Part 2 defines generic concepts of things, classes, and their relationships such as connection, composition, containment. The means by which the objects change with time are also defined. The Part 4 defines the core RDL for the usage of the ISO 15926 Part 2. The core RDL contains the core classes and reference individuals, which are arranged in an ontology of subtypes of the classes in the Part 2. Currently there are almost 20,000 classes in the Part 4 and the library is still extensible. Part 7, the Template Methodology, specifies a series of templates which are predefined expressions organized based on the generic formats defined in the Part 2. This means that it is possible for users to self-define and develop the grammar rules following the ISO 15926 protocols. It also allows users to implement the Part 2 data model in a convenient way without understanding details in the Part 2.

4.1.3 Comparisons between the AP 221 and the ISO 15926

As introduced in the 4.1.1 and 4.1.2, the AP 221 and ISO 15926 possess the similar structures, both of which define a general data model and reference data libraries. Figure 17 shows a P&ID case which is recorded by data exchange standards.

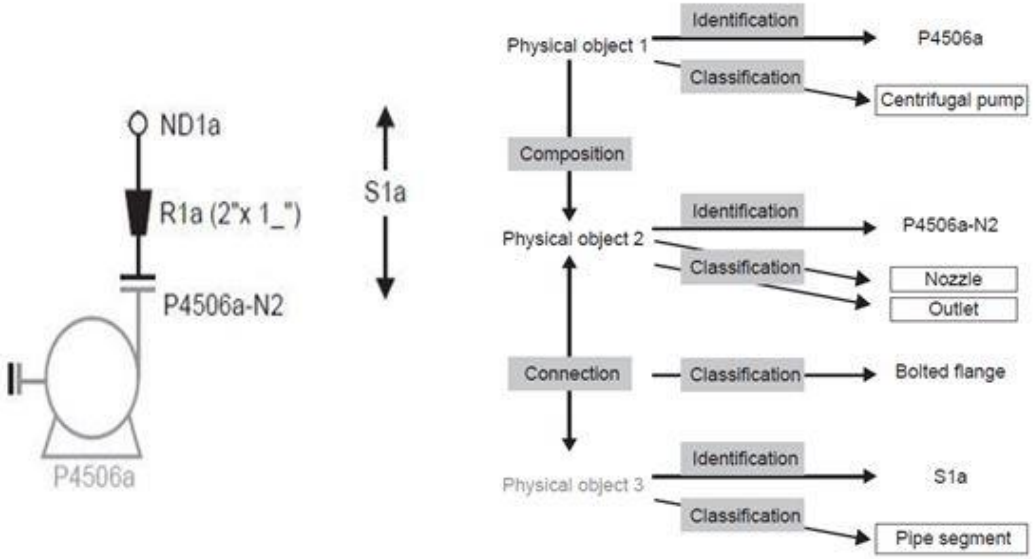

Figure 17: Records of the P&ID with the AP 221 and the ISO 15926 standards (Leal, 2005)

In this example, the P&ID shown on the left side describes the representations and interconnections of the several process items with the graphical symbols and annotations. There is a centrifugal pump which has an outlet nozzle p4506a-N2. The nozzle is further connected to the pipe segment S1a. Such information is recorded by the data exchange standards in the form of the structural texts on the right side of Figure 17 (Leal, 2005). The relationships such as identification, classification, composition, and connection are marked with shadow frames and they are defined within the ISO 15926-2 or the Grammar of the AP 221. The class names such as centrifugal pump, nozzle, outlet, and pipe segment are marked with blank frames and they are defined within the ISO 15926-4 or the Dictionary of the AP 221.

As shown in Figure 18, even if some overlaps, such as identification and connection of the physical objects existing in both the ISO 15926 and the AP 221 standards, there remain two differences between them. Leal (2005) referred that the AP 221 defines the detailed grammar rules for the relationships between objects in a P&ID, while it is not directly defined in the ISO 15926-2. Moreover, the ISO 15926 can record the process components in both temporal and spatial dimensions. By contrast, the AP 221 can only preserve information in spatial dimension, while hardly represent the varieties of a process over time.

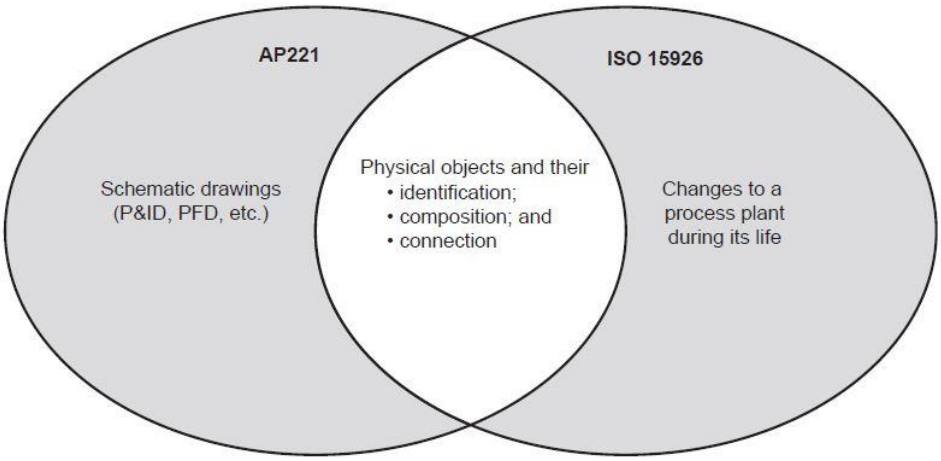

Figure 18: Relationships between the AP 221 and the ISO 15926 (Leal, 2005)

4.2 XML Representation for the P&IDs

4.2.1 Introduction to XML

Extensible Markup Language, abbreviated XML, was developed by the XML Working Group established by the World Wide Web Consortium (W3C) in 1996 (W3C, 2013). It is designed for the exchange of various kinds of information in the Web development, especially to structure, store and transport data or information.

An entire XML program comprises several single elements which can be classified as root elements (parent nodes) and their sub-elements (child nodes). All elements serve as a tree structure that starts at the root elements and extends to the branches (sub-elements) of the tree. XML can be simply considered as pure information wrapped in tags. The tags are enclosed in brackets (< >) and they define XML data structures (Alabi, 2010). Any element should have a start and an end tags in order to form an effective XML. It can also contain attributes that provide extra information about the elements (Bray, 1997). A typical XML structural representation can be summarized in Figure 19.

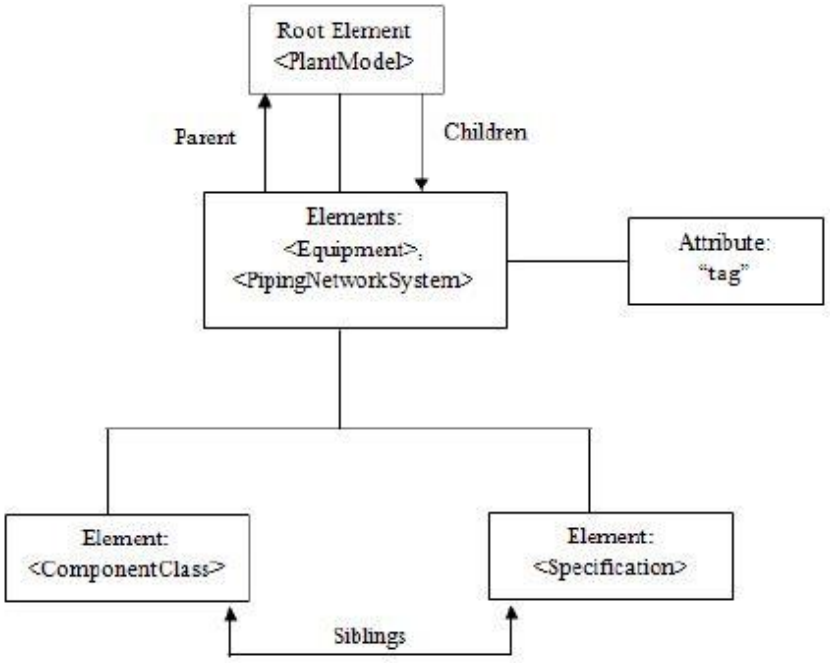

Figure 19: Structural representation of XML (Alabi, 2010)

4.2.2 XML Schemas for the P&IDs

The plant topology should be represented by the specific XML syntax, which is defined by the XML schemas. As the most common schema, XMpLant is developed based on the ISO 15926 standard and has been employed in increasing P&ID engineering applications.

4.2.2.1 XMpLant Schema

XMpLant is an XML standard developed by Noumenon and it is based on the ISO 15926. The aim is to establish a consistent, non-proprietary XML scheme for the storage and exchange of data (Noumenon, 2008). The XMpLant can be used to map data in a specific proprietary software to a format of the ISO 15926 and then transfer it to any other desirable proprietary system (Siemens, 2011).

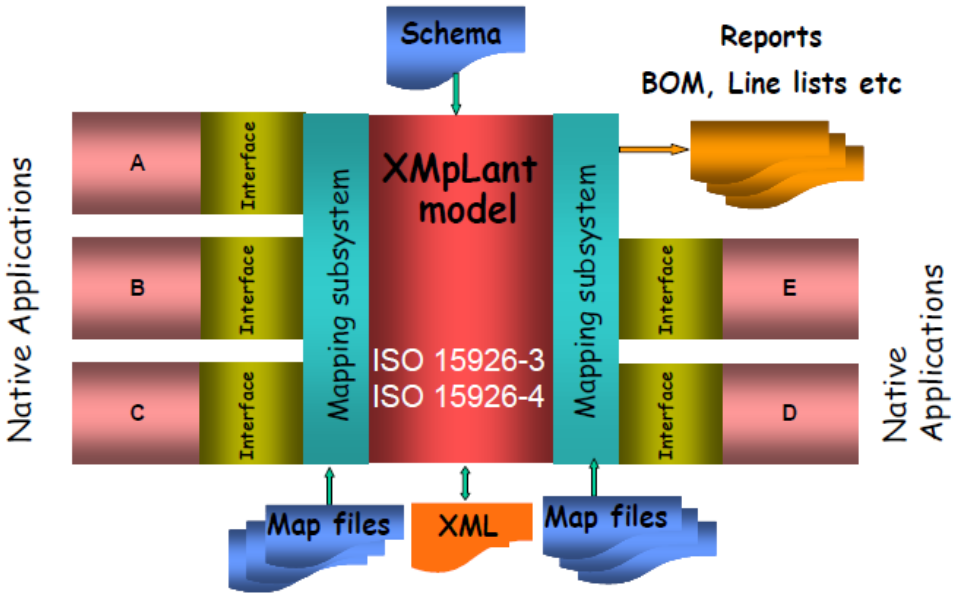

Figure 20: XMpLant conversion (Noumenon, 2008)

Figure 20 shows the data exchange process between different applications with the XMpLant. Data created in an engineering application is imported to the mapping subsystem, which is defined by the XML mapping files. These files provide relationships between the external information and classes defined in the ISO 15926. With such files, the data from native applications is converted into a

neutral XMpLant model which is a dictionary compliant file based on the XMpLant schema and independent of the original application and format. Similarly, the data is exported from the neutral model to the application based on the XML mapping files as well (Noumenon, 2008).

Based on the classes of the ISO 15926-3 (geometry) and the ISO 15926-4 (plant item), the XMpLant Schema defines a specific XML structure which is intended to support the whole process engineering information, including process objects, topology, and geometry. The XMpLant schema is organized as the structure shown in Figure 21.

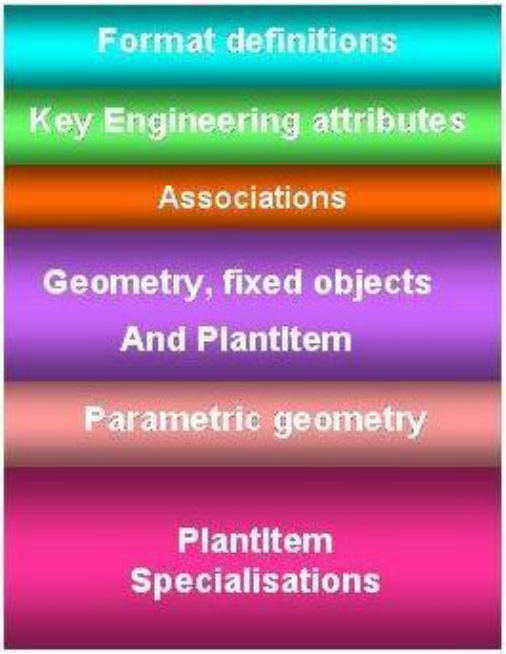

Figure 21: Structure of the XMpLant schema (Noumenon, 2008)

At the top of the XMpLant schema, the formats of attributes which are used by the plant item classes are defined, including integer, double and string. The second layer clarifies the formats of the key engineering attributes, the name of which is provided by the RDL of the ISO 15926-4. The fixed object classes for geometry and PlantItem are clarified in the following layer. The PlantItem class is the universal abstract object of all the specific plant items and it specifies their generic

attributes. At the bottom of the schema, the specific plant items are presented by adding extra key attributes to the PlantItem class (Noumenon, 2008).

4.2.3 A P&ID Model Conforming to the XMpLant Schema

POSC Caesar Association (PCA) and Fiatech presented a detailed information model for P&IDs based on the XMpLant schema in 2008. Nowadays, the XMpLant-compliant P&ID model has been employed into process design applications by the major system vendors.

This model describes the XML exchange format for P&IDs using the classes of the ISO 15926-4 Reference Data Library. The elements in a P&ID can be classified into component objects and connectivity objects according to the defined model. The model comprises two kinds of component objects: PlantItem and AnnotationItem. PlantItem refers to an abstract super-type for all physical assets e.g. equipment, piping components, etc. Each of item has eight attributes: ID, TagName, Specification, ComponentClass, ComponentName, ComponentType, Revision, and Status. All attributes are optional except ID.

An AnnotationItem is an abstract super-type for objects that are referenced in the P&ID but that does not represent a physical asset. The typical AnnotationItem includes drawing borders, tables, and notes, etc. AnnotationItem has six attributes: ID, ComponentClass, ComponentName, ComponentType, Revision, and Status.

Connectivity objects in the XMpLant model consists of Connection and ConnectionPoints. Connection has four attributes: FromID, FromNode, ToID, and ToNode. ConnectionPoints possesses two attributes: FlowIn and FlowOut.

The selection of the Connectivity objects needs to be considered according to the different cases. The internal connectivity within a PipingSegment is defined by the sequence of the components in it. The Connection Element can be used as an identifier of the connectivity between PipingSegments and other PlantItems. The

connectivity within a PipingComponenent, InstrumentComponent, or PipeTube can be identified with the ConnectionPoints Element (Noumenon, 2008).

The XML representation for a P&ID should be divided into fragments based on PipingSegment, where the engineering parameters are constant. In other words, a PipingSegment should start and end at a place where a key engineering parameter changes or the flow splits. Nozzles, reducers, and tees are typical components which indicate the start and end of the PipingSegments.

Within the XML of a single PipingSegment, the IDs of the start and end points should be identified in the initial line. The following lines introduce the detailed information, such as IDs, Tags, and classes, of all components included in the segment in a sequential order. The junction where a process instrument is connected to a PipingSegment should be also reflected. Figure 23 illustrates an example of the XML representation for a P&ID fragment shown in Figure 22.

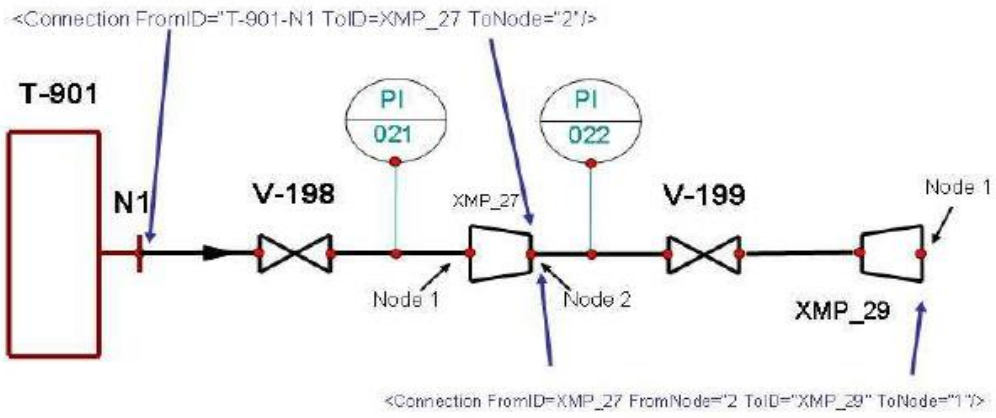

Figure 22: A P&ID fragment with two PipingSegments (Adrian, 2009)

```
<PipingNetworkSystem>
    <PipingNetworkSegment  ID=”XMP12” Tag=”200-CC110-01234-B1”>
          <Connection FromID=”T-901-N1” ToID=”XMP_27” ToNode=”2”/>
          <CenterLine …/>
          <PipingComponent ID=”XMP_15” Tag=”V-198” ComponentClass=”Valve” …/>
          <CenterLine …/>
          <InstrumentConnection ID=”XMP_23”  …/>
          <PipingComponent ID=”XMP_27” ComponentClass=”Reducer” …/>
    </ PipingNetworkSegment>
     <PipingNetworkSegment  ID=”XMP_13” Tag=”200-CC110-01234-B2”>
          <Connection FromID=”XMP_27” FromNode=”2” ToID=”XMP_29” ToNode=”1”/>
          <CenterLine …/>
          <InstrumentConnection ID=”XMP_35”  …/>
          <PipingComponent ID=”XMP_36” Tag=”V-199” ComponentClass=”Valve” …/>
          <CenterLine …/>
          <PipingComponent ID=”XMP_29” ComponentClass=”Reducer” …/>
    </ PipingNetworkSegment>
</PipingNetworkSystem>
```

Figure 23: XML texts for Figure 22 (Adrian, 2009)

4.3 Intelligent P&ID Applications Supporting the XML Representation

For the aim of the convenient P&ID data sharing, more and more P&ID software manufactures are integrating the XML export module into their applications. The most well-known ones are AVEVA P&ID Tool, Comos P&ID, SmartPlant P&ID, and AutoCAD P&ID.

4.3.1 Comos P&ID

The COMOS P&ID module implements an XMpLant interface, with which a P&ID can be exported to an XMpLant-compliant XML file which includes the following data (Siemens, 2011):

1. P&ID objects include Equipment, Instrumentation, Functions and their positions, Pipes, pipe branches, and pipe segments. These objects are exported as PlantItems. Each object can contain the following data: "Label" property, "SystemFullName" property, attributes which are located on the subtabs of the "Attributes" tab and whose "Value" is set, and P&ID coordinates of the object.

2. Data lines and effect lines are exported as PlantItems of the ‘SignalLine’ type and P&ID coordinates are included.

3. Purely graphical elements of the P&ID include Texts, Lines, Circles, and Elbows. These elements are exported as ShapeItems and P&ID coordinates and Graphics or text are included.

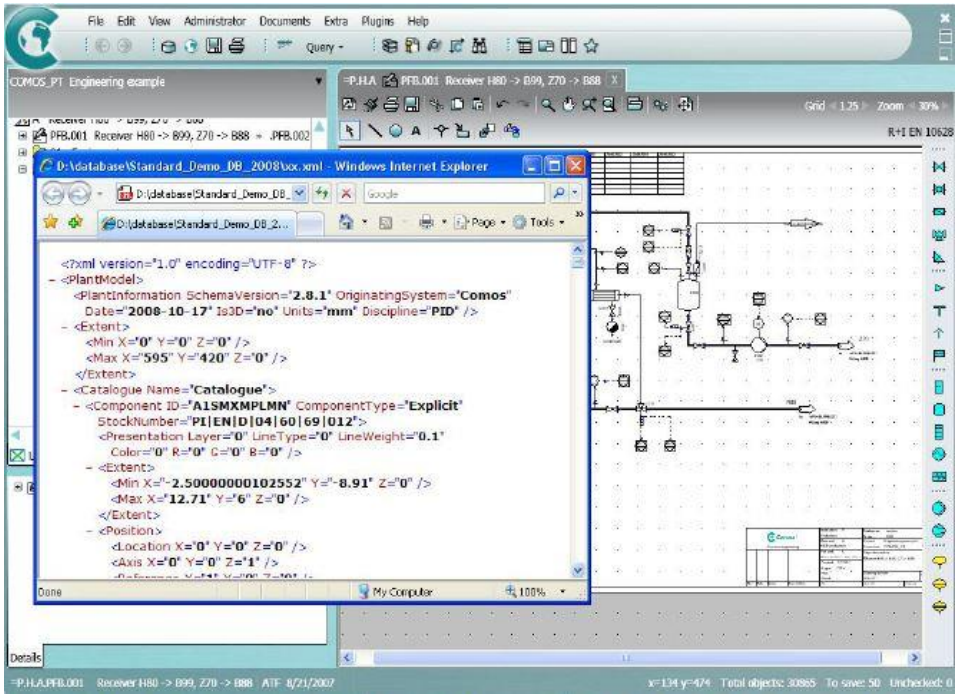

Figure 24: XMpLant output from the Comos tool (Siemens, 2011)

4.3.2 AVEVA P&ID

AVEVA P&ID is a P&ID design application which saves intelligent engineering data involving tagged items, quantities, and connectivity data. The tool can also create a thorough report of the plant from the P&ID drawing which is in accordance with the ISO 15926 and it consists of all the information about a plant throughout its life cycle.

Figure 25 shows an example of the XMpLant output displayed in the viewer of the AVEVA P&ID. The detailed information about any process item, such as equipment, instrument, or pipe, can be read by clicking it on the Plant Items tree

window. The information covers tags, geometry, coordinates, and other information about the plant as specified in the ISO 15926 (Alabi, 2010).

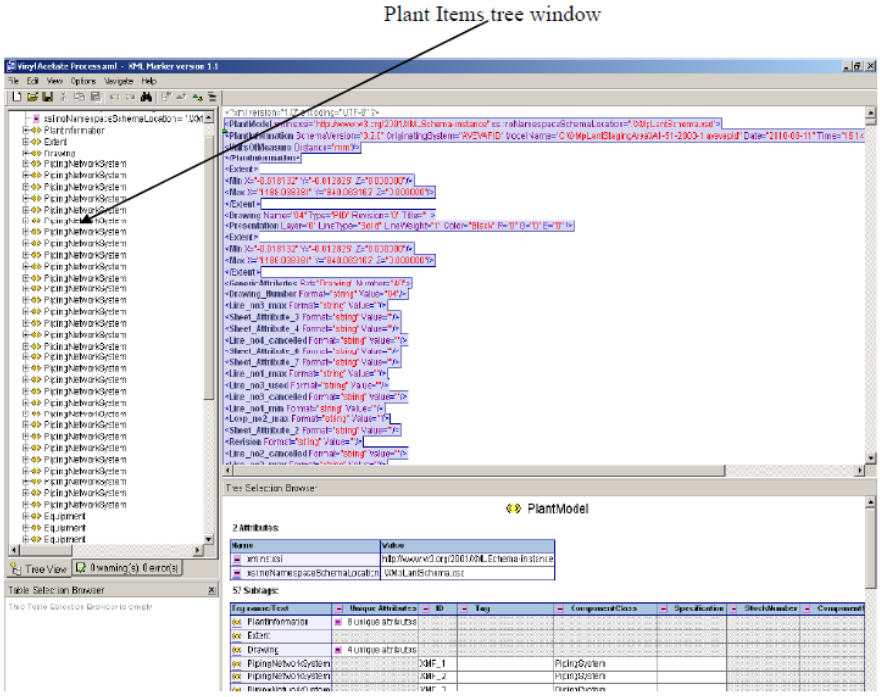

Figure 25: XMpLant output from the AVEVA P&ID tool (Alabi, 2010)

4.3.3 SmartPlant P&ID

XML data exchanges in the SmartPlant P&ID is completed through the XMpLant interface, which supports the bi-directional conversions between the P&IDs and ISO 15926 XML files.

The XMpLant read interface imports the P&ID files with the SmartSketch API and obtains the related engineering data from the ORACLE relational database management system (RDBMS) tables. The ISO 15926 XML files which are created by the interface conform to the XMpLant schema and store the complete plant topology. The graphical symbols in the P&ID is preserved in the ShapeCatalogue.

The XMpLant write interface creates P&ID files from the ISO 15926 files with the SmartPlant P&ID Automation layer, which generates physical symbols for

new P&ID files by matching symbol names in ShapeCatalogue to those in the SmartPlant P&ID library, and generates physical connections based on 'PipeRuns' and 'SignalRuns' properties. Identified tags are also added to the corresponding symbols by mapping the attributes shown in the XML files (Adrian, 2008).

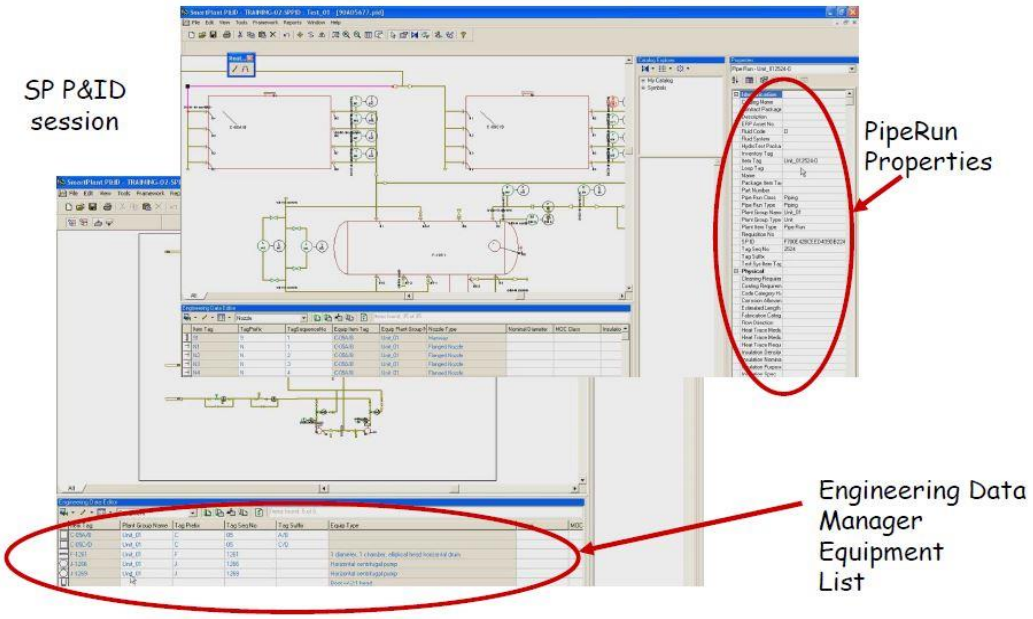

Figure 26: Relationships between P&ID files and ISO 15926 files in SmartPlant P&ID (Adrian, 2008)

EXPERIMENTAL PART

5 AIM OF THE EXPERIMENTAL PART

Some of the FDD methods, e.g., process history-based and qualitative model-based methods, can generate spurious solutions for the root disturbance. Such a problem can be alleviated when process topology information is considered (Thomhii, 2006).

The process topology information such as the connections between process items can be recognized from a process drawing, for instance, a P&ID drawing (Di Geronimo Gil, 2011). However, this type of drawing is usually designed for construction, and it is complicated and contains a large amount of information unrelated to the FDD research, which only requires the cause-effect relationships between process components without their geometric shape and size. This provides the motivation of the experimental part. That is, developing topology-based causal models which express process schematics in a brief way.

The topology-based causal model can be typically represented as a digraph, which uses nodes and directional arcs to represent the positional information about process items and their connections. The connectivity matrix, the other form of the causal model, is a matrix which represents the relationships between components with binary numbers. An element in the matrix is ‘1’ if the process component represented by the row header connects to another represented by the column header; otherwise, the value of the element is ‘0’.

The experimental part explains the development of these two causal models based on a drawing application, AutoCAD P&ID and a programming language, MATLAB OOP. This part starts by describing the tools and methods used to generate process topology-based causal models. Then, a case of the drying section of a board machine is introduced to clarify how the proposed methods are applied

to a practical scenario, and the detailed implementation of the methods is also presented. The experimental part concludes with presenting the experimental results of the proposed case.

6 DEVELOPMENT OF THE PROCESS TOPOLOGY-BASED CAUSAL MODELS

The process topology-based causal model refers to a brief representation of the connections between the process items as shown in a process schematic, such as a P&ID drawing. It is manifested in the form of causal digraphs or connectivity matrices. The topology-based causal model plays an accessorial role in the FDD research since it expresses the relationships of the process components in a brief and readable way, thus assisting the conventional FDD methods to precisely locate the most probable root cause (Benabbas, 2009). This chapter describes the thorough procedures to develop the topology-based causal model with the AutoCAD P&ID and the MATLAB OOP. A case study of the drying section of a board machine is further used to specify the application of the proposed method.

6.1 Tools and Methods Used to Generate Process Topology-based Causal Models

The topology-based causal models are generated through a procedure consisting of three steps, as indicated in Figure 27. The first step is completed by the P&ID drawing software, and the causal models are further developed with the Object – Oriented Programming (OOP) which is performed in the second and the third steps.

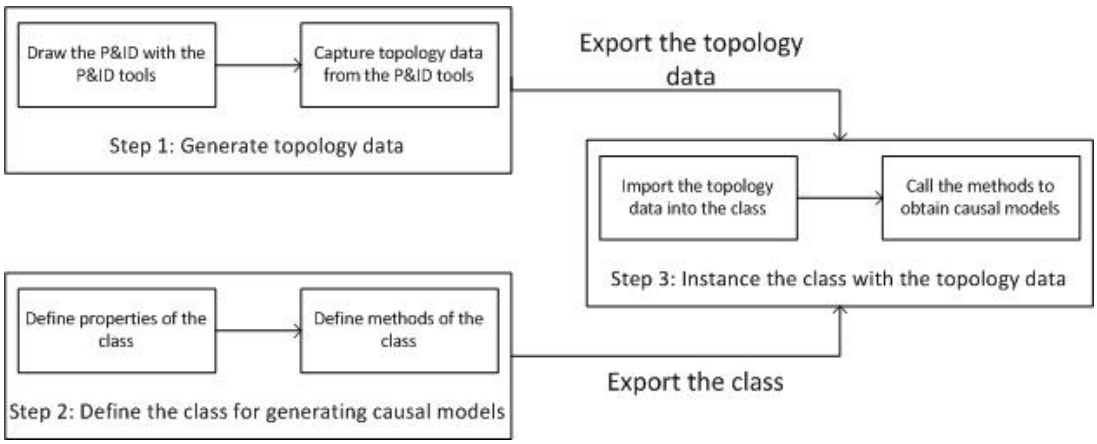

Figure 27: Schematic of generating topology-based causal models

Section 6.1 is divided into three parts. The first part (subsection 6.1.1) describes the definition of the process topology-based causal models and the motivation for using these models. To describe the three steps to create causal models, the second part introduces the tools and methods of acquiring topology data, and the last part presents the approach to develop causal models using OOP combining with the topology data.

6.1.1 Definition of the Topology-based Causal Models

Process topology information can improve diagnosis of the root cause of disturbances, together with the outcome of the traditional FDD methods (Thomhii, 2006). Generally, the process topology information, for instance, the connections between the process equipment can be identified from a process drawing, such as a P&ID (Di Geronimo Gil, 2011). However, this type of drawing is always designed for engineering applications, e.g. construction and maintenance. It is, therefore, complicated and contains a large amount of information unrelated to the FDD research, which only requires the connecting information about the process components without their geometric shape and size. This provides the motivation to simplify the P&ID drawing and to create a brief and readable topology-based model for the FDD research. There are two types of the topology-based causal models including the topology-based causal digraph and the connectivity matrix, which can be considered as a graphical representation and a numerical representation of the process schematics, respectively.

The process topology-based causal digraph is a directed graph reflecting positional information about the process items and their connections. The digraph is composed of a number of nodes and directional edges between them. The nodes represent the equipment and instruments in a process, while the edge reflects the physical flow or the signal flow from one item to another. Moreover, the positions of the nodes in a digraph should be according to the actual layout of the components they represent. Thus, it can be seen that the digraph shows interactions between the variables in different components, which have resulted from the physical or signal flows along the components in a system. Figure 28

displays a P&ID case of the level control loop of a tank and its causal digraph. As shown in the picture, the digraph only saves the relationship resulting from the physical and signal flows between different components, while ignoring the irrelevant information, such as the specific geometrical shapes of process items.

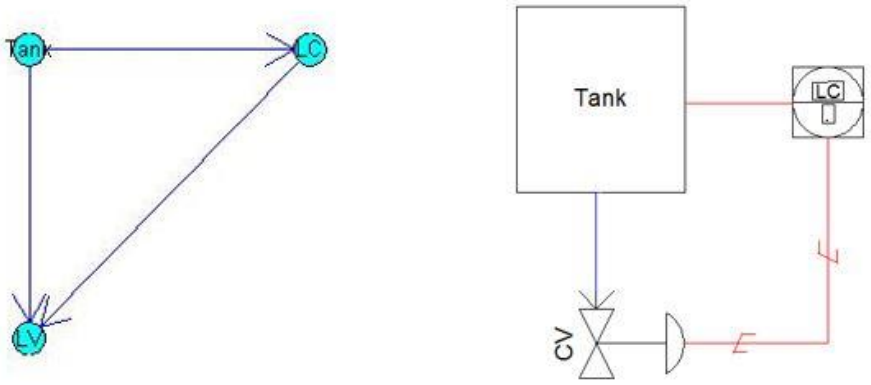

Figure 28: Comparison between a P&ID drawing and its causal digraph

Similar to the digraph, the connectivity matrix indicates the relationship in the form of the binary matrix with N-dimension, where N is the number of the elements. The row and column headers separately represent the start and ending points of each edge. Elements in the matrix can be either '1' or '0' according to the existence of a directional connection from the row header to the column header, which represents a specific process component (Benabbas, 2009). Table 3 reveals the connectivity matrix of the example above. The directional connections can be obviously identified through binary numbers. For instance, the 1 in the intersection of the second row and third column means there is a signal flow from the tank to the level controller (LC).

Table 3: An example of the connectivity matrix

	Tank	LC	LV
Tank	0	1	1
LC	0	0	1
LV	0	0	0

6.1.2 Methods for Capturing Topology Information from the AutoCAD P&ID

As essential information for generating causal models, topology data is a standard semantic expression of the process schematic in the XML or XLS/XLSX format. This type of data depicts the properties of the process items and the relationship between them. Specifically, as shown in Figure 29, the topology data used in causal models can be divided into three aspects: the name of the process items, the coordinates of the process items, and the connections between them. The topology data improves the exchange of the graphical information among different systems and allows the drawing to be conveniently reused by downstream engineering and design activities, therefore extends the application scope of the original P&IDs.

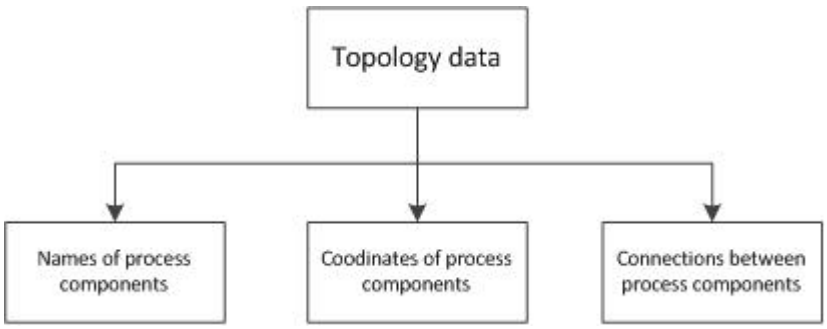

Figure 29: Classification of the topology data

Topology data is derived from the electronic P&ID which is drawn by the specialized P&ID drafting applications. These type of software can not only perform the normal P&ID drawing, but also possesses the database which stores and manages the topology data. The most popular CAD programs used in P&ID drawings include AutoCAD P&ID, Intergraph SmartPlant P&ID, AVEVA P&ID, and COMOS P&ID, etc. Topology data exported from the AutoCAD P&ID is in the format of XLS/XLSX, while the other software mainly supports the schematic information defined by the ISO 15926-compliant XML scheme.

The AutoCAD P&ID is used as an example to explicate the method for extracting topology data as it is the primary tool applied in the experimental part. The

generation of the topology data is performed in two steps: design a P&ID drawing, and then extract topology data from the P&ID drawing.

6.1.2.1 Design a P&ID Drawing

The alteration of the topology data always depends on the modification of the schematic drawing since the AutoCAD P&ID provides abundant process component and line symbols, each of which comprises data linking to the Data Manager from which the topology data is extracted. Thus, the most important steps of designing a P&ID drawing are placing, tagging, and connecting process components, which correspond to the three aspects of the topology data respectively. Figure 30 shows the correspondence between the three phases of drawing a P&ID and the matching topology data they affect.

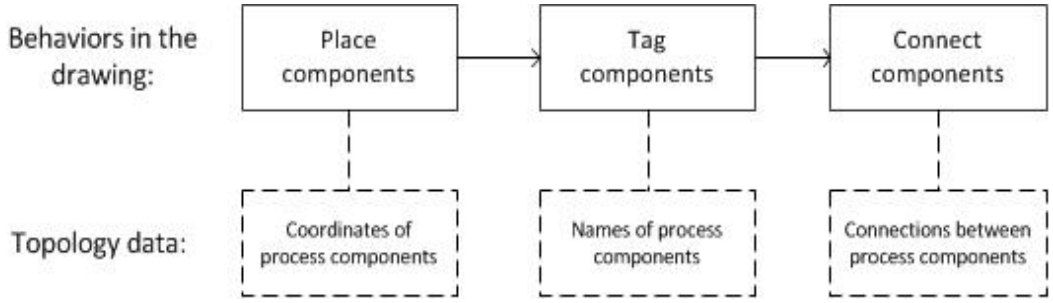

Figure 30：Procedures of designing a P&ID drawing

The first step of designing a P&ID drawing is to add components to a blank P&ID template. The P&ID components in the P&ID tool palette include equipment (such as, pumps and tanks), instruments (such as, control valves and instrument bubbles), and inline components (such as valves). The position of the component is automatically determined when it is chosen in the P&ID tool palette and placed in a specific drawing area. The location of each component is specified and stored as absolute cartesian coordinates which identify the distance of an item from the point of origin.

After the components are placed on a drawing, tags are then assigned to these items by entering the required data in the Assign Tag dialog box. The tag is an

identifier which uniquely distinguishes components or lines in a project. Tag formats can be self-defined by combining different properties such as area property, type property, and number.

The last step is to add pipe lines and signal lines between all the components that need to be connected. A significant aspect of the topology data are the physical connections, in which the physical material or signals flow between different components. Different from the AutoCAD lines, the P&ID schematic lines include additional data, e.g. the moving path and direction of gas, liquid or signal flow along the process, in addition to the physical connecting information. Hence, the schematic lines imply the internal connections between the components.

The schematic lines are put on the basis of whether there is an internal connection such as material or signal flow between the components. In other words, a new directional line is added whenever there is a material or signal flow between two items. The arrow at the end of each line indicates the flow direction. Whenever a line segment is built in the P&ID drawing, the tags of start and end components of the line are synchronously created and stored in the Data Manager. Similarly, as the line segments are moved or connected components are changed, the 'To' and 'From' information of this line is correspondingly updated.

6.1.2.2 Extract Topology Data from the P&ID Drawing

One of the most important features of the AutoCAD P&ID is that it can intelligently manage the drawing data by the Data Manager module, which is used to store, view, edit, and manipulate data for P&ID objects in a drawing (P&ID, 2013).

The data extracted from the Data Manager for generating the causal models involves the tags of the initial component and the terminal component of every line segment. Such information is stored as 'From' and 'To' properties in the Line Segments Report which lists the data of the entire lines in the drawing. The Line Segments Report can be reconfigured by reserving the required properties, such as

‘From’ and ‘To’ properties, and removing the extra ones based on the default report template, which contains several properties relevant to the line segments.

The Line Segments Report involving the start and terminal points of each line is then exported in the form of the Microsoft Excel spreadsheet (XLS/XLSX). Furthermore, this file is handled by the MATLAB programs to generate the topology information about the connections between process components

In contrast to the connecting information directly acquired from the Data Manager of the AutoCAD P&ID, the names and position data are attained by entering a self-defined command in the command window. The command is developed by using C# programs to manipulate the database of drawing files through the AutoCAD .NET application programming interface (API), which is a collection of the DLL (Dynamic-link library) files that comprise a variety of classes. With these classes, the database in an AutoCAD drawing file can be accessed.

The database object invoked by the AutoCAD .NET API includes both graphical and non-graphical information related to a P&ID drawing. Figure 31 illustrates the structure of the Database object. Typically, as an important part of the database, BlockTables includes two types of the BlockTableRecords, namely ‘Paper_Space’ and ‘Model_Space’, where all graphical entities (lines and components) are stored.

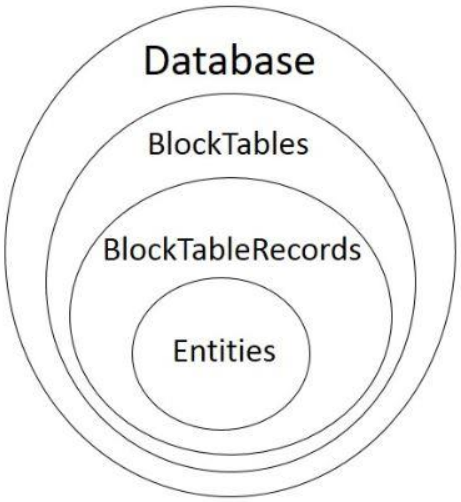

Figure 31: Hierarchical structure of the Database object

The names and coordinates of the P&ID components are captured with a self-defined command, which is developed based on an iteration statement traversing all entities recorded in the 'Model_Space'. The name and coordinate of an entity are read and saved in a user-defined XML template if it is identified as an 'asset' (process component) instead of 'lineSegment'. It should be noted that the structure of the XML template can be defined as any schema, for instance, XMpLant. In this way, the AutoCAD P&ID will support the files exported in the multiple XML schemas, thus enhancing the data exchange of the software.

Eventually, the XML report containing the names and coordinates of all components are exported from the AutoCAD P&ID by quoting the defined command. This data is further captured by the MATLAB program and converted into the topology information about 'names of process components' and 'coordinates of process components'.

6.1.3 Methods for Generating Causal Models with the MATLAB OOP

The generation of causal models is performed by the MATLAB OOP, which considers the task as a class and defines the variables about the topology data as static characteristics (called Properties) and the steps of developing causal models as dynamic characteristics (called Methods). After this, the causal models are obtained when the specific values are assigned to the Properties and a series of Methods are invoked and implemented. This section introduces the concepts of the MATLAB OOP and its applications in the development of causal models combining with the topology data.

6.1.3.1 Introduction to the MATLAB OOP

Object-oriented programming, as its name implies, is a programming paradigm which is based on objects. Different from traditional procedural programming languages, such as C and Pascal, with top-to-down structures, the object-oriented programming is organized in the form of several blocks shown as individual objects. Since the late 1960s, when the first object-oriented programming

language Simula was published, a large number of languages based on OOP have been launched and been extensively applied.

MATLAB has started to support OOP since the version R2008a when MATLAB introduced a new syntax for defining classes (MathWorks, 2012). Similar to the common OOP languages, MATLAB possesses the typical patterns of OOP, including class, object, property, and method. It also possesses basic characteristics of OOP, such as inheritance, encapsulation, and Polymorphism.

The basic idea of object-oriented programming originates from problem decomposition (Urban, 2012). Figure 32 indicates the procedures for solving a problem with MATLAB OOP. The solution is always implemented with three phases: classification of a problem, definition of a class, and instantiation of the class. These three steps can also be treated as a process: 1) from concrete to 2) abstract, and finally to 3) concrete.

Typically, one problem tends to be classified into several groups, each of which has several objects with common characteristics. Furthermore, a group of objects is generalized to a class. As the structure of objects, the class describes these common features named properties and methods, also known as static data member descriptions and dynamic behaviors separately. Properties expressed by variables reflect which states the objects maintain, while methods shown as a set of functions clarify which behaviors can be performed to the objects. Classes are further instantiated to the objects by assigning specific values to the properties. The problem is finally solved by invoking different methods to access and manipulate the objects.

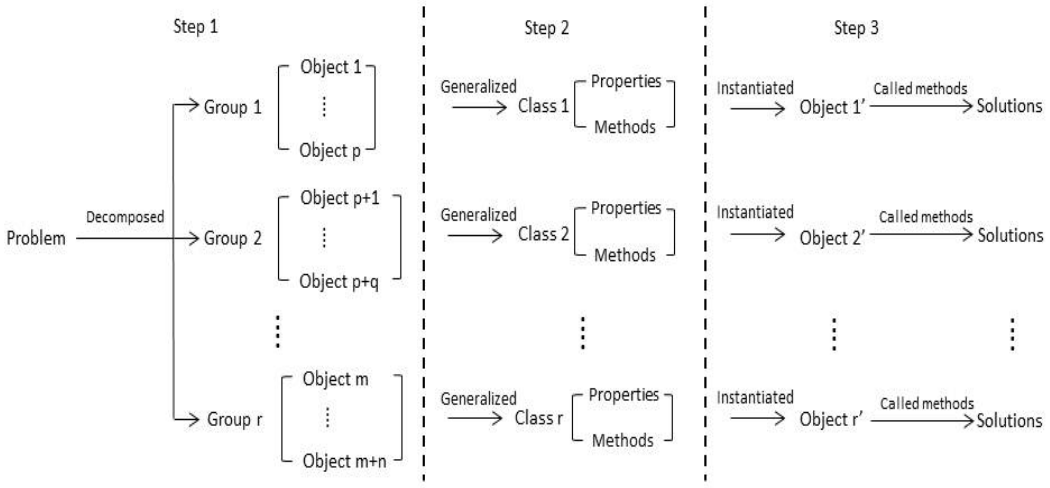

Figure 32：Scheme of MATLAB OOP. Step 1: classification of a problem (concrete). Step 2: definition of a class (abstract). Step 3: instantiation of the class (concrete).

MATLAB OOP has several merits over conventional procedural programming. Firstly, OOP can be treated as a precise classification of procedural codes; that is, object-oriented codes encapsulate data and behaviors in individual objects that interact with each other through the object's interface. Such an encapsulation, on the one hand, optimizes the structure of codes and makes them more convenient to be used. Objects afford interfaces that hide implementation details. Codes therefore can be easily implemented by invoking methods without knowing the internal states. On the other hand, it allows an object to be modified independently without affecting others. Moreover, the information hiding can ensure the security of codes and avoid the malicious access. Secondly, OOP is good at managing the data transmission between functions. Hence, it is suitable for the cases which contain a large number of functions. Furthermore, codes for each responsibility are packed into individual functions which can be conveniently organized and called according to requirements. Lastly, inheritance allows the class to be easily extended without redundant coding. Due to these advantages, OOP has more advantages when developing complicated and large-scale applications.

6.1.3.2 Procedures for Generating Causal Models with the MATLAB OOP

The approach to develop casual models is established according to the procedures shown in Figure 32. The target of the task is to generate causal models including the connectivity matrix and the causal digraph. Since both of the causal models can be obtained based on the same kinds of topology data shown in Figure 29, generations of the two models are classified into one group. Hence, only one object, i.e. generation of causal models, is considered in this case.

The second step focuses on the establishment of a class which defines the basic factors (properties) and manners (methods) required to solve a problem. Specifically, static and dynamic characteristics of the object are explored and generalized to a class. In this case, the variables individually representing the three types of topology data are defined as static features (properties), since the causal models are derived from these data.

The methods, known as dynamic characteristics of the class, define three kinds of functions to develop the causal models. The first type of functions named property functions is used to obtain the specific values of three variables defined in the properties. These functions describe the detailed process to generate the properties which are the return values, whereas the arguments of such functions are the original drawing data from P&ID tools.

The second type of functions aims to create causal models. They present the procedures to achieve the connectivity matrix and the causal digraph, respectively. These functions are implemented with the inputs of property values returned from property functions.

The last type of functions, namely operational functions, is defined for modifying generated causal models to satisfy the research requirements. These functions simulate what actually happens when modifying the process topology by increasing or decreasing connections, increasing or decreasing nodes to causal models. Such functions act based on modifications to the three properties of the

class. The causal models then vary with the alteration of properties since both matrix and digraph functions are constructed in terms of these properties. Figure 33 shows the relationship between the three functions and clarifies the realization process of the methods.

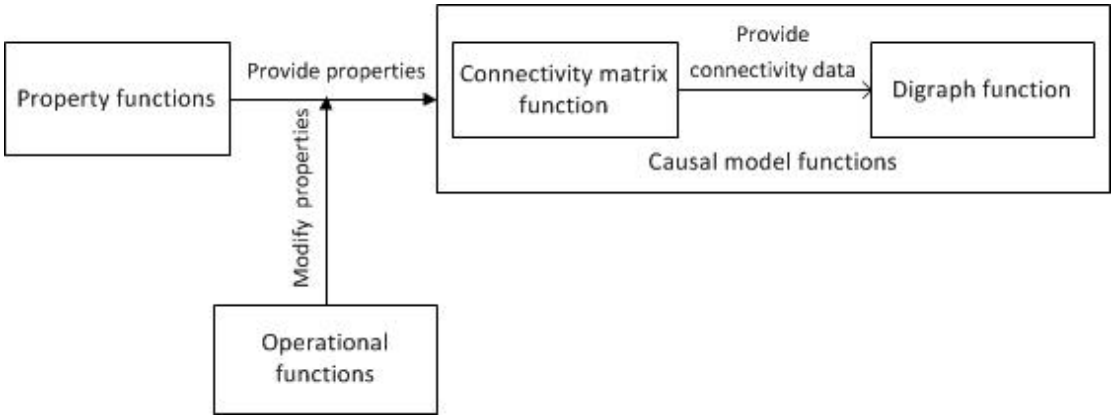

Figure 33: The implementation flow of the methods for generating causal models

Finally, in Step 3, the class is instantiated to the specific object by assigning values to the properties. This process is implemented by calling property functions which use the drawing data from the P&ID tool as arguments. Furthermore, the connectivity matrix and digraph are obtained by invoking corresponding functions. The established models can be also readily adjusted by calling the operational functions according to requirements.

6.2 Case Study for the Drying Section of a Board Machine

This section aims at describing how the methodology for generating topology-based causal models proposed in Section 6.1 is applied in the practice, and presenting the detailed implementation for the methods. The drying section of a board machine is used as the case study. This section first describes the process of the drying section after giving a brief introduction to the production process of the whole board machine. The following parts specify the thorough procedures of generating the causal models for the drying section, which include extracting drawing data from the AutoCAD P&ID and developing causal models with

MATLAB OOP. Section 6.2 concludes with the exhibition and analysis of the results.

6.2.1 Description of the Drying Section of the Board Machine 4

This part describes the process structure of the drying section of the board machine 4 (BM4). In order to generate causal models, a P&ID drawing of the drying section is used as the case. As the facility of Stora Enso Imatra Mills, the BM4 produces three-layer liquid packaging boards. As shown in Figure 34, the production process comprises a sequence of five sections: (1) three short circulation sections, (2) a wire section, (3) a press section, (4) a drying section, and (5) a calendering and reeling section (Kuuluvainen, 2012).

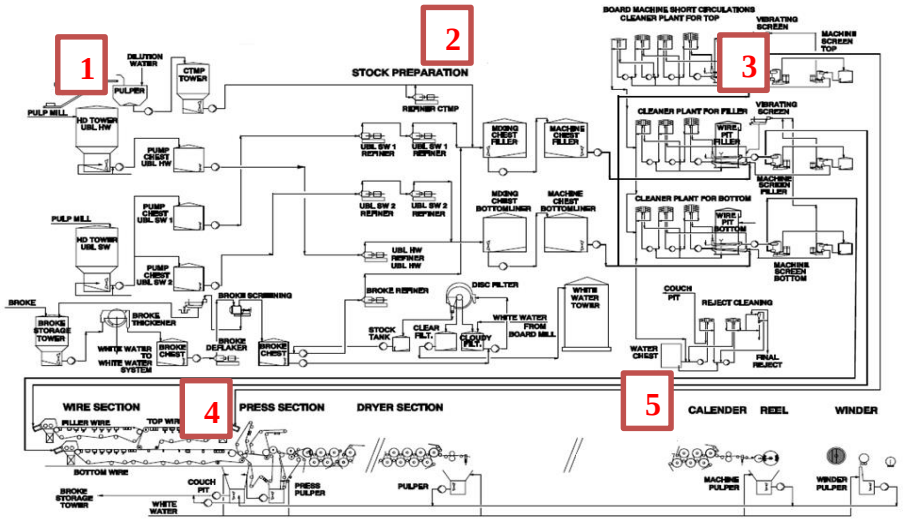

Figure 34: BM4 production flow (Kuuluvainen, 2012)

The boards are produced from the raw materials to the final end products by the following steps. Firstly, the stock from the machine chest is diluted, cleaned and further mixed with additives in the short circulations sections (1). Furthermore, the flow without debris and dirt is delivered to the headbox where the stock is evenly spread on the wire. In the wire section (2), the water in the stock is dried through the wire while the fibers and other solid materials remain to form the web. The webs from three layers are in combination with chemical bonds at the end so

as to form the final three-layer board. Then, in the press section (3), the water is removed from the web with the help of mechanical pressure. Moreover, a balance press is used to adjust the thickness and the surface properties of the board. Next, the moisture of the board is precisely controlled by the evaporation process in the drying section (4). The process of production is ended in the calendering and reeling section (5), which adjusts the thickness of the board and rolls it into reels for next procedures, such as winding and coating.

The case study focuses on the drying section which is in charge of controlling the moisture of the board. The drying section can be divided into six similar parts, shown in Figure 35. Each part consists of a condensate tank and a steam group (SG) comprising a series of drying cylinders. The steam is fed into the cylinders and releases its heat through the tube wall to evaporate the water of the board web. The mixture of condensate and steam is then collected into the condensate tank where they are separated. Steam is transported back for reuse, while the condensates are collected and delivered to the power plant.

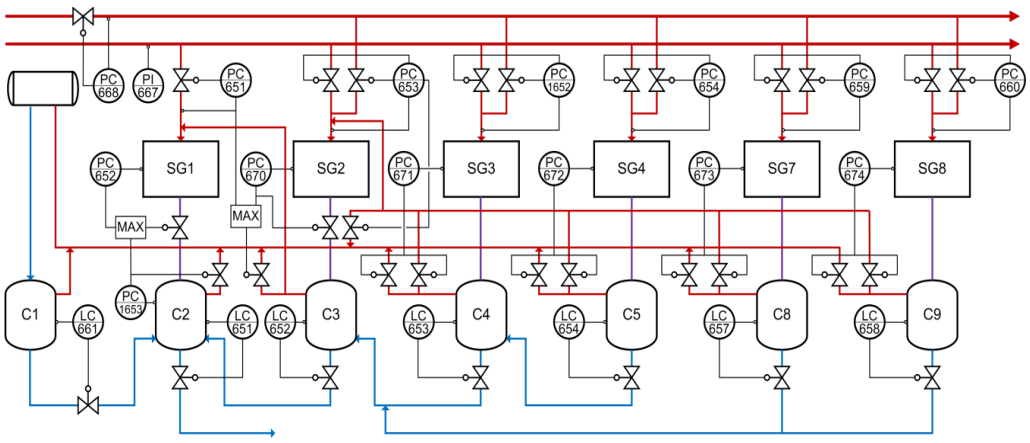

Figure 35: Steam groups of the drying section of BM4

Each part of the drying section performs the similar control schemes which include three control systems. As shown in Figure 36, there are three control loops with their own controllers, namely steam pressure controller (PC), pressure difference controller (PDC), and level controller (LC), which are responsible for

controlling the steam pressure, the steam pressure difference, and the level of condensate tank separately.

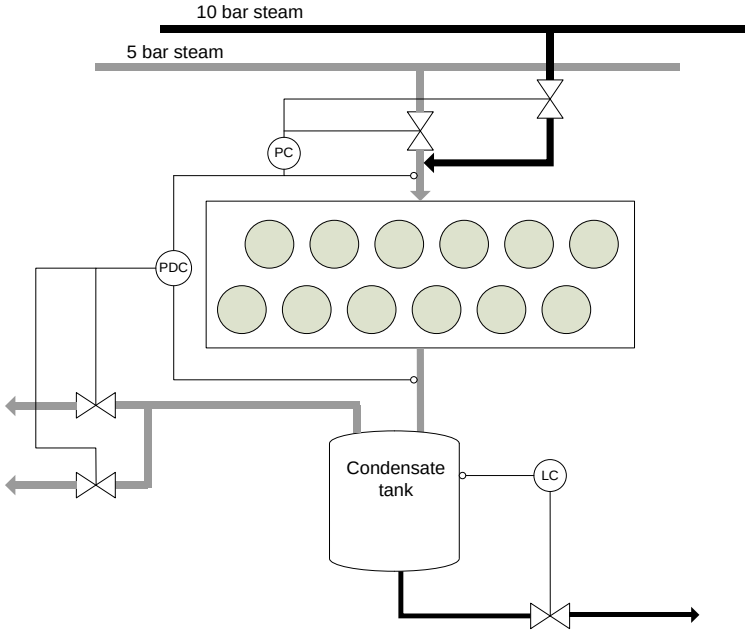

Figure 36: Control scheme of the single part: steam pressure controller (PC), pressure difference controller (PDC), and level controller (LC)

Specifically, the steam source provides the steam groups with 5-bar and 10-bar headers. The pressure controller adjusts two control valves connected to the two headers to obtain the required steam pressure. That is, only one valve is applied when the pressure demand is low, otherwise both valves are opened. The setpoints of SGs 1 to 4 are set by operators while the SG 8 gains the setpoint from the quality control system (QCS) in the top control level. SG 7 achieves the steam control with the target proportional to the SG 8.

The steam pressure difference between the steam and condensate headers should be maintained within a reasonable range. Therefore, the controller must present a moderate output, which guarantees the pressure difference both in order to ensure that the steam is fully condensated in the cylinder and the condensate is discharged from the cylinder. This control is accomplished by regulating two

control valves in the steam exit of the condensate tank. Only one valve works when lower pressure difference is required and vice versa.

For each steam group, there is a condensate tank installed below the cylinder to collect the condensate. The level of the condensate tank is adjusted by the outlet valve which acts according to the signal from the level controller.

6.2.2 Acquisition of Topology Data for the Drying Section of the BM4

Since the drying section comprises six parts with similar structures, one single part is therefore used as the case to describe the process of extracting topology data. The described method can be generalized to the whole drying section.

According to the methods proposed in Section 6.1.2, the topology data is generated starting at drawing a P&ID drawing. Firstly, a project named ‘drying section’ is configured with the Project Setup wizard where the ISO-based P&ID symbology standard is chosen. Additionally, the tag formats of the components including Equipment, Valves, and Instrumentation are defined as ‘Type-Number’. ‘Type’ reflects the class of the component while ‘Number’ distinguishes the components in the same class from each other.

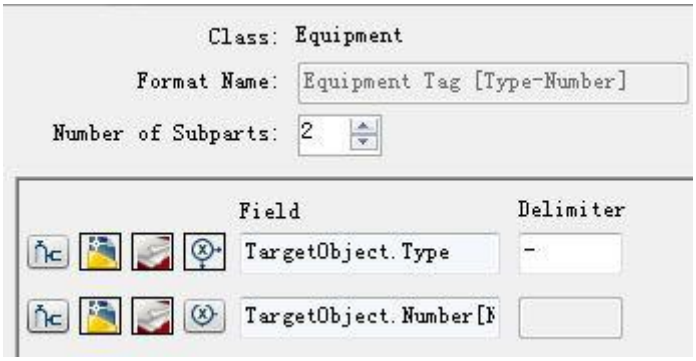

Figure 37: Tag format setup

Once the project is set up, a new drawing namely ‘the third part’ is built based on the existing AutoCAD drawing which does not include data information. There are two ways for formulating a P&ID drawing from an AutoCAD schema. The

first one is to import the AutoCAD drawing as an external reference, which is the template for designing a new P&ID drawing. Attached references are a link of the external drawing instead of the actual one, thus disassociating them from the present project. The other is to convert blocks or groups in the AutoCAD one by one to the specific P&ID components or lines; for instance, a group of the AutoCAD lines can be converted to a single component of the 'tank' class. The converted objects possess the same characters as the AutoCAD P&ID components and they are also referenced in the Data Manager.

In order to shorten the drawing period, the first method is employed. The AutoCAD drawing with the DWG format is attached to the current blank drawing as a reference, which is placed under the current layer. The visibility of the referenced layer is adjusted to an appropriate level in order that the external drawing can be well referred while not interfering with the ongoing drawing.

The third part of the drying section consists of three types of components such as valves, tanks, and instruments, which are selected from the P&ID tool palette and placed in the drawing area where their counterparts are located in the reference. When all the components are placed in the drawing, tag information is then entered for each item in the Assign Tag dialog box based on the format set up in the project configuration.

Finally, the pipe and signal schematic lines are added between components referring to the physical connections shown in the AutoCAD reference. However, different from the AutoCAD lines which reflects the physical connections, the P&ID schematic lines also need to depict the internal flows. Therefore, a new directional line is added whenever there is a material or signal flow between two items. Figure 38 shows the P&ID drawing of the third part of the drying section finished in the AutoCAD P&ID environment. Blue and red connections represent the pipe and signal lines, respectively.

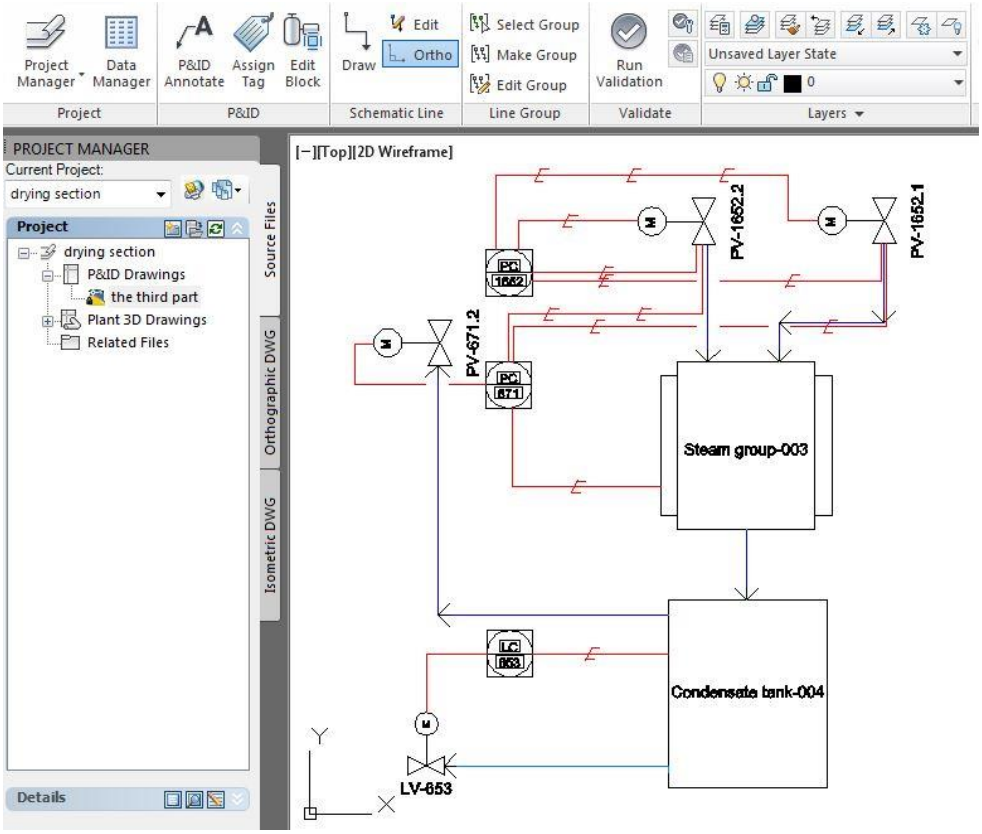

Figure 38: P&ID drawing of the third part of the drying section

Once the P&ID drawing is finished, the reports with drawing information are synchronously generated in the Data Manager. The most important reports needed to export are the reports of the Line Segments which include the required topology data. The structure of the reports is first configured before they are exported. In the Report Setting pane, the properties ‘From’ and ’to’ of the Line Segments are selected as the items of the reports. Subsequently, the Line reports in the self-defined form can be queried in the Data Manager which classifies the reports into the Pipe Line Segments and Signal Line Segments, as shown in Figure 39 and Figure 40, respectively.

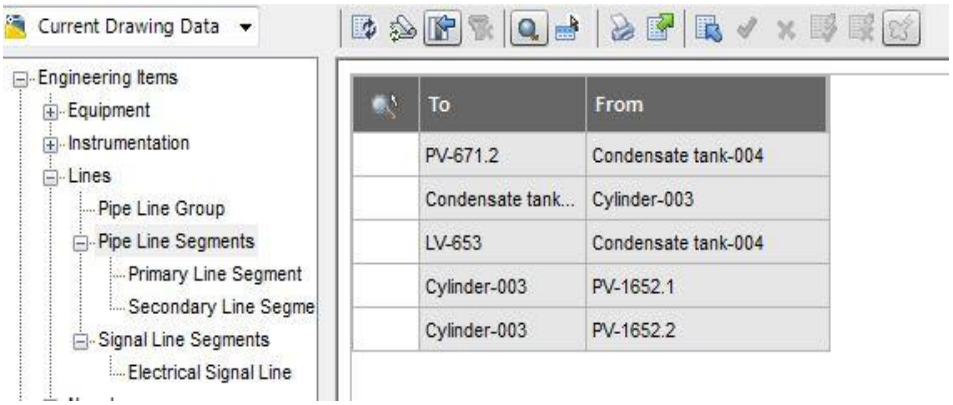

Figure 39: Report of Pipe Line Segments

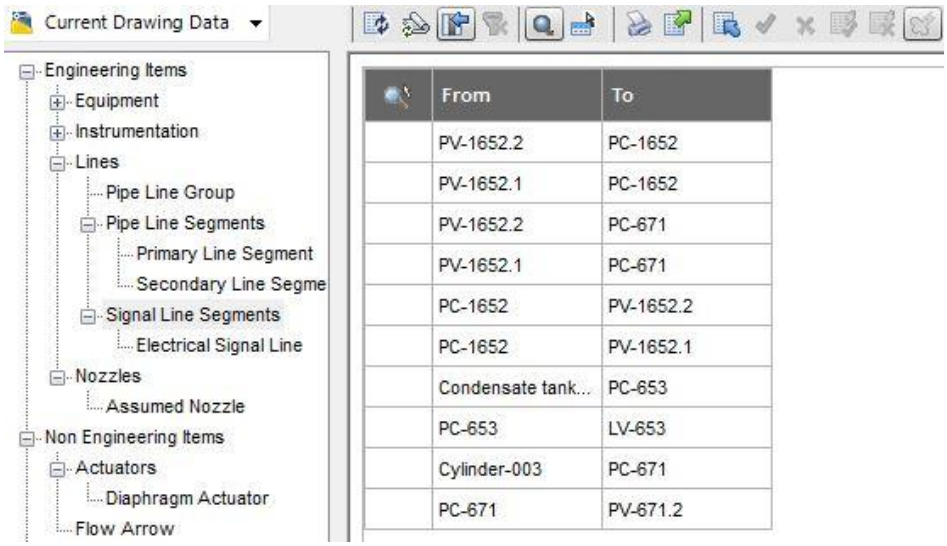

Figure 40: Report of Signal Line Segments

The reports of the Line segments are then exported to the Microsoft Excel spreadsheets with the names 'the third part-Pipe Line Segments.xls' and 'the third part-Signal Line Segments.xls'. These Excel files include all the columns and rows displayed in the Data Manager.

The name and coordinate information of the components is acquired with an AutoCAD command which is developed using C# programs to access the database of the drawing file through the API. In fact, this command can be considered as a self-defined method defined by the C#.

The process of building the command method begins with assigning a name ‘GetComponents’ to the method under which a series of procedures applied to capture the components’ data are created. More specifically, the database of the current drawing is first obtained by the database property of the document object. Furthermore, before the entities are accessed, the ‘TransactionManager’ property of the current database is quoted to start a transaction which can integrate multiple operations on several objects into a single operation (AutoCAD, 2011). After this, the BlockTableRecord ‘Model_Space’ is opened with the ‘GetObject’ method. The ‘GetEnumerator’ and ‘MoveNext’ methods are then applied to navigate the ‘Model_Space’ from line to line distinguishing the ‘Components’ entities from the ‘Linesegments’ entities. For each identified component, the ‘Position’ and ‘TagValue’ properties are captured and inserted into a textual template with the self-defined XML schema, which is expressed as ‘<coordinate=’ Position’ tagname=’ TagValue ‘/>’.

Finally, the XML report including coordinates and names of all components is generated when entering the ‘GetComponents’ command in the command window of the AutoCAD P&ID.

6.2.3 Generation of Causal Models for the Drying Section of the BM4

In the light of the methodology specified in Section 6.1.3.2, the causal models of the drying section are developed in three phases: (1) classification of the problem, (2) definition of a class, and (3) instantiation of the class.

6.2.3.1 Phase 1: Classification of the Problem

In the first phase, the problem is classified. The problem contains two tasks: creating the connectivity matrix and the causal digraph. These two models possess the common characters since both of them are obtained from the same topology data. Moreover, a relationship exists between the two models since the digraph is built based on the matrix. Thus, the two tasks can be consolidated into one group

which is treated as an object named ‘Generation of causal models for the drying section’.

6.2.3.2 Phase 2: Definition of a Class

In the second phase, i.e., the definition of a class, a class with the name ‘generation of causal models’ is constructed, and it extracts the features of the object confirmed in the first phase. The static characteristics (properties) including the names of components, the coordinates of components and directional connections between them are defined as three array variables, namely ‘cmNames’, ‘cmPos’, and ‘cmLines’. The default values of all properties remain empty and they will be assigned by calling the functions in the methods block.

In the methods block, eight functions are defined which can be classified into three types. The 'getLines' function and 'getPositions' function define the algorithms to gain the property values. More specifically, the 'getLines' function respectively reads the Excel files of the pipe line and signal line segments and extracts the start and end points of all connections, which are further stored as an array in the property ‘cmLines’. Similarly, the 'getPositions' function reads the XML file of the coordinates and captures the implicit topology data such as names and coordinates of all components and reserves them into ‘cmNames’ and ‘cmPos’ properties separately.

The most critical tasks, the creation of the connectivity matrix and causal digraph, are conducted by the 'getMatrix' function and the ‘digraph’ function. The 'getMatrix' function first defines the initial state for the connectivity matrix state as a null matrix with N-dimension, N is the number of components. The row and column headers of the matrix are the component names from the ‘cmNames’ property. The value of the entry where a column and a row intersects is set to ‘1’, when the process component represented by the header of the row directly connects to that represented by the column header. The position of the intersection is determined by matching each row in the ‘cmLines’ property with the row and column headers of the connectivity matrix. That is, the row number of the cross

cell is determined when a ‘From’ point in the ‘cmLines’ property matches a certain element in the row header of the connectivity matrix, and the same way is applied for confirming the column number. Figure 41 shows the realization of the proposed method using three connected components as a case. The connection from ‘PV-1652.2’ to ‘steam group-003’ is identified by ‘1’ value in the intersection of the second row and the third column, since the components in the second row of the ‘cmLines’ property are in accordance with the headers of the second row and the third column of the connectivity matrix, respectively.

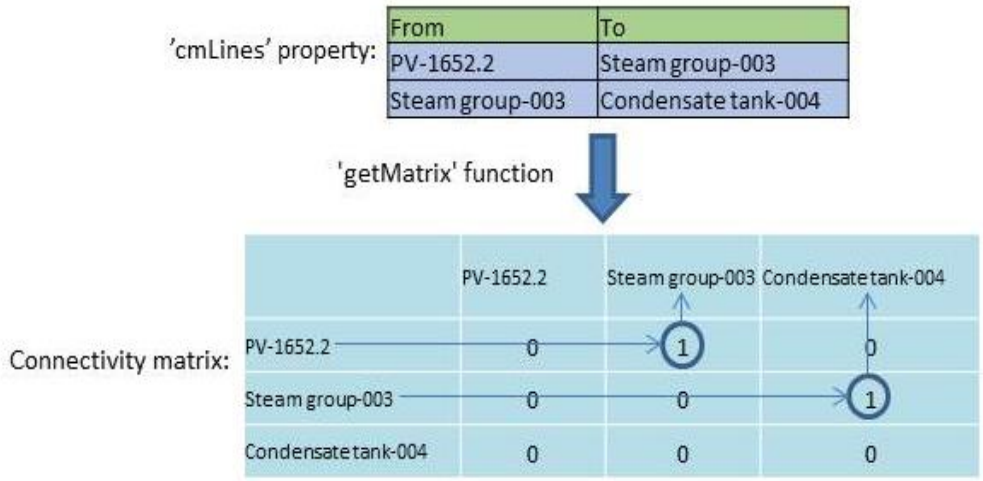

Figure 41: Scheme for generating the connectivity matrix

The ‘digraph’ function drafts the digraph based on the ‘cmPos’ property, ‘cmNames’ property, and the established connectivity matrix. A set of nodes representing all components are drawn in the plane using their coordinates information from the ‘cmPos’ property as the center of circles. The radius of the nodes can be self-defined. Meanwhile, the components’ names from ‘cmNames’ property are also marked on these nodes. Furthermore, the directional edges between nodes are determined by the link information from the connectivity matrix. That is, a ‘for loop’ is executed to traverse every entry of the connectivity matrix and a connecting line with an arrow is drawn when the ‘1’ value is detected.

The directional edge between two nodes can be developed with three steps. Firstly,

the start and end points of the edge (shown as B and C in Figure 42) are confirmed from the intersections of the connecting line of two circle centers (shown as A and D in Figure 42) and the circumferences of the circles. From the geometrical relationship shown in Figure 42, the coordinates of the two terminal points (B and C) are determined by the positions of two circle centers (the 'cmPos' property of the nodes), the included angle Q between the edge and the horizontal line, and the radius of the nodes. As shown in Eq. (1), the angle Q is derived from the coordinates of the circle centers. Eq. (2) to Eq. (5) present the generation of the angle coordinates of the start point (X_B , Y_B) and the end point (X_C , Y_C), which are further saved in the **X** and **Y** arrays.

$$Q = \arctan\left(\frac{Y_D - Y_A}{X_D - X_A}\right) \tag{1}$$

$$X_B = X_A + r \times \cos(Q) \tag{2}$$

$$Y_B = Y_A + r \times \sin(Q) \tag{3}$$

$$X_C = X_D + r \times \cos(Q + \pi) \tag{4}$$

$$Y_C = Y_D + r \times \sin(Q + \pi) \tag{5}$$

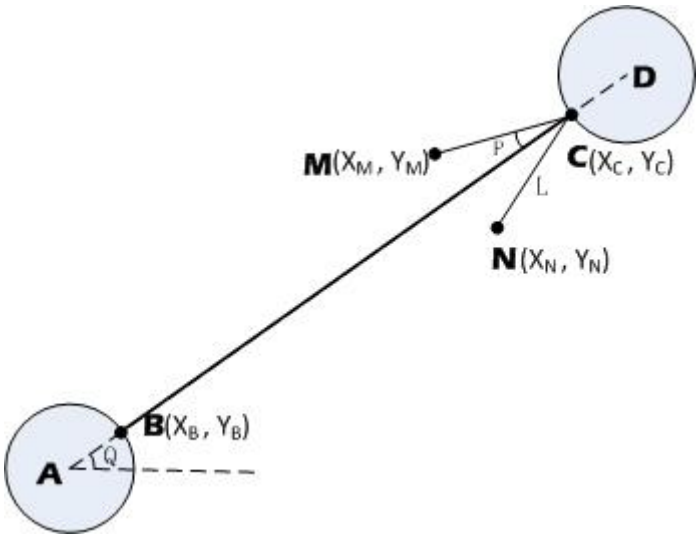

Figure 42: Generation of the edge between two nodes

Secondly, the arrowhead is constructed on the premise that the terminal points (M and N) are settled according to the positional relationship between the arrowhead

and the connecting line. Specifically, the coordinates of M and N are computed based on the angle Q, the coordinate of point C, the length of the arrowhead line MC and NC, and the included angle P. Eq. (6)-(9) show the calculation of the coordinates of arrowhead points M (XM, YM) and N (XN, YN), which are stored in the **Xa** and **Ya** arrays. The length of MC and the angle P are self-defined.

$$X_M = X_C + L \times cos(Q - P + \pi) \quad (6)$$

$$Y_M = Y_C + L \times sin(Q - P + \pi) \quad (7)$$

$$X_N = X_C + L \times cos(Q + P + \pi) \quad (8)$$

$$Y_N = Y_C + L \times sin(Q + P + \pi) \quad (9)$$

Finally, the 'Line' command is executed to connect the four end points B, C, M, and N, whose coordinates have been confirmed in the second step, to three intersectant lines, BC, MC, and NC, which constitute the directional edge connecting the two nodes.

The generated models are usually required to be modified to satisfy the research requirements. Four operational functions are therefore defined which can perform the 'addline', 'removeline', 'addnode', and 'removenode' operations to the created causal models. The 'addline' and 'removeline' functions create and remove a connection between any two given nodes by adding and removing a connecting record to and from the 'cmLines' property, respectively. Similarly, the function 'addnode' adds a new node to models by increasing the name and position data to the 'cmNames' and 'cmPos' properties, separately. The function 'removenode', however, removes the given node and the lines connected with it from models by deleting the node's name and coordinate information from the 'cmNames' and 'cmPos' properties, respectively. The causal models then change along with the properties as both matrix and digraph functions are constructed in terms of these properties.

6.2.3.3 Phase 3: Instantiation for the Created Class

In the third phase of the causal model development, the program of class

instantiation is compiled after the ‘generation of causal models’ class is established, and the topology information about the drying section is thereby imported into the defined class, which is instantiated to the specific ‘drying section’ object. The instantiation is started with assigning the object name ‘Drying section’ to the abstract class, and then the two Excel files namely 'drying section-Pipe Line Segments.xls' and 'drying section-Signal Line Segments.xls' are introduced into the ‘getLines’ function, which provides the specific value to the ‘cmLines’ property of the object. Next, the XML file 'coordinate.html' is imported into the ‘getPosition’ function in order to acquire the exact value of the ‘cmNames’ and ‘cmPos’ properties of the ‘drying section’ object. Furthermore, the connectivity matrix and digraph can be gained by typing ‘getMatrix’ and ‘digraph’ functions respectively in the command window. The established models can also be modified by calling the four operational functions to satisfy the actual requirements.

6.2.4 Results

This section uses the third part of the drying section as a case, which was applied in Section 6.2.2, to present the results of the experimental part due to the limitation of the textual space. The causal digraph of the whole drying section can be found in the appendix D.

After running the program of class instantiation, the causal models are displayed when the corresponding functions are entered in the command window. The connectivity matrix indicated in Table 4 appears when the ‘getMatrix’ function is implemented, and it presents the topology connections of the P&ID drawing in Figure 38 in a binary format. The 9- dimensional matrix indicates the relationship of all the nine components shown in the P&ID drawing through the binary numbers. The entry with the value ‘1’ denotes that a directional edge exists from its row header to its column header. Hence, there are in total of 15 entries which take ‘1’ values and they are consistent with the number of connecting lines in the P&ID shown in Figure 38.

Table 4: Connectivity matrix of the third part of the drying section

	PV-1652.2	PV-1652.1	Steam group-003	PC-1652	PC-671	PV-671.2	Condensate tank-004	LC-653	LV-653
PV-1652.2	0	0	1	1	1	0	0	0	0
PV-1652.1	0	0	1	1	1	0	0	0	0
Steam group-003	0	0	0	0	1	0	1	0	0
PC-1652	1	1	0	0	0	0	0	0	0
PC-671	0	0	0	0	0	1	0	0	0
PV-671.2	0	0	0	0	0	0	0	0	0
Condensate tank-004	0	0	0	0	0	1	0	1	1
LC-653	0	0	0	0	0	0	0	0	1
LV-653	0	0	0	0	0	0	0	0	0

The causal digraph shown in Figure 43 is obtained when the ‘digraph’ function is applied. It is clear that the nodes in the graph are arranged at the same positions as the process components in the P&ID shown in Figure 38. Meanwhile, the edges marked in the digraph clearly present the physical linkages between nodes, which are in accordance with the topology information about the original P&ID drawing. However, the digraph manifests the internal relationship between different components caused by material flows and signal flows in a clearer way, as it only reserves the information of relative locations and connections without showing the geometrical shape of components. Therefore, this kind of model can play an important role in the research associated with the fault tracking and diagnosis.

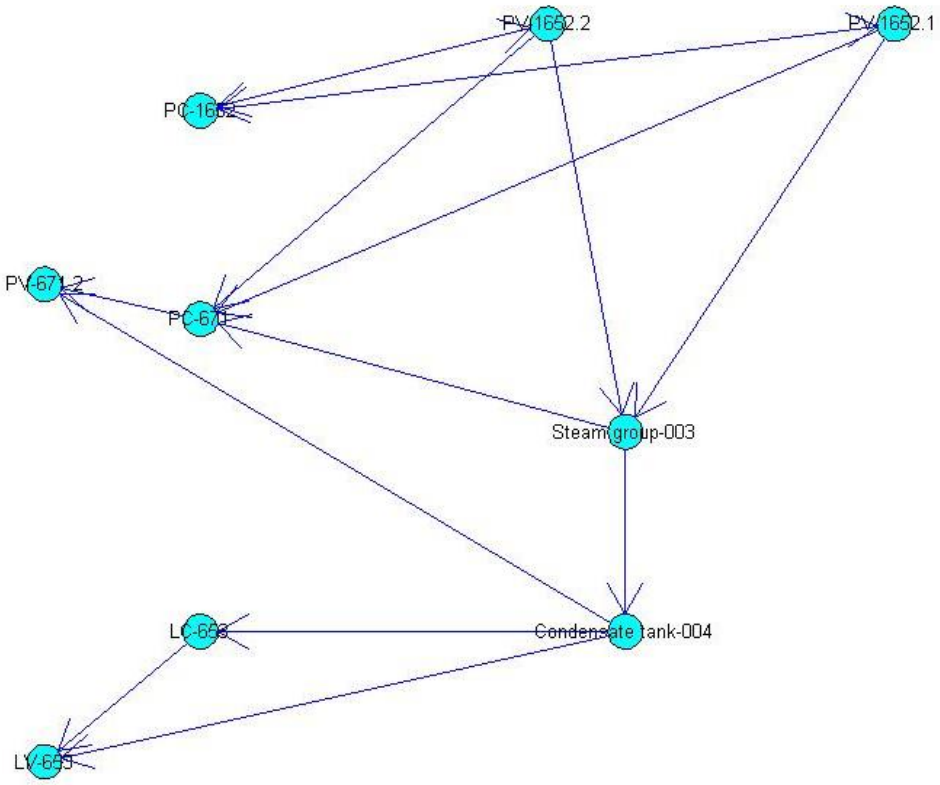

Figure 43: Causal digraph of the third part of the drying section

Operational functions can be invoked to flexibly modify the causal models so as to imitate the adjustment occurred in the actual process. Figure 44 presents how the operational functions are utilized to modify the causal digraph through a case, which simulates a series of changes to the process connections where a new valve is added between the steam group and the condensate tank, and the valve 'PV-1652.1' is removed from the process. The first step uses the function 'steamgroup.removeline ('Steam group-003','Condensate tank-004')' to remove the connection between the steam group and the condensate tank. The second phase applies the function 'steamgroup.addnode ('PV-671.1',529,120)' to add a new node called 'PV-671.1' at the given coordinate (529,120). The steam group and the condensate tank are connected to the new component with the functions 'steamgroup.addline ('Steam group-003','PV-671.1')' and 'steamgroup.addline ('PV-671.1','Condensate tank-004')'. Finally, the function 'steamgroup.deletenode('PV-1652.1')' is used to remove the node 'PV-1652.1' and the connecting lines associated with it. The results reveal the right changes of

the digraph following the expectant requests so as to verify the effectiveness of the operational functions proposed in Section 6.2.3.

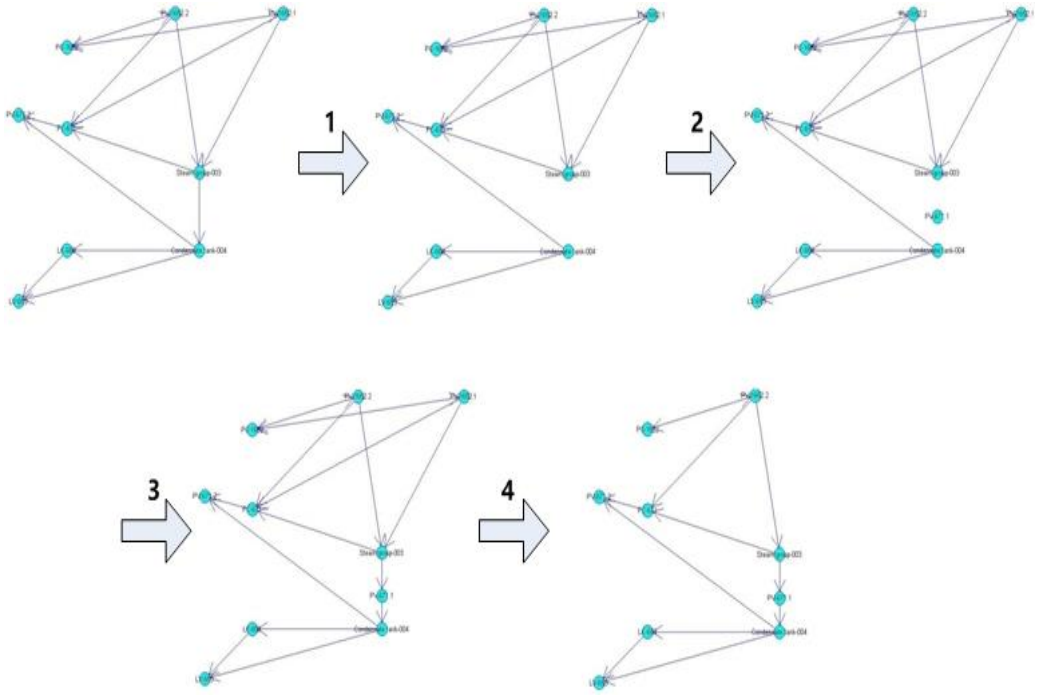

Figure 44: Modifications to the generated digraph. Step 1: remove the connecting line between ‘Steam group-003’and ‘Condensate tank-004’. Step 2: add the valve ‘PV-671.1’ between ‘Steam group-003’and ‘Condensate tank-004’. Step 3: add connecting lines between ‘Steam group-003’and ‘PV-671.1’and‘Condensate tank-004’. Step 4: remove the node ‘PV-1652.1’.

7 CONCLUSIONS

This thesis provides an easy and practicable method to generate the causal model reflecting the relationship of process equipment. The information sources used to build the model are readily obtained from the intelligent P&ID design tools, and the proposed algorithm based on the MATLAB OOP has several merits: (1) it completes a variety of tasks via calling corresponding functions, which is easy to apply even by those who are not familiar with programming, (2) the definition of a class provides a template to solve similar problems, i.e., it possesses the feature of universality. It can be applied in other similar situations without changing the codes but by defining a new instance to the class. The established models are extremely meaningful in the study of fault detection and diagnosis.

However, the proposed method still possesses limitations, since it was developed based on topology data in a specific format, i.e., Excel files extracted from AutoCAD P&ID. As a popular format for the data exchange, XML has been employed by increasing P&ID design applications. The proposed approach should be extended to be capable of handling the XML format in addition to the Excel files when building the causal models.

In addition, a topology-based model derived from a P&ID shows items of equipment and the directional connections between them, and it can only be used as an accessory tool to aid the FDD (Di Geronimo Gil, 2011). It is more valuable to link information about variables such as temperature, composition, pressure, and flow rate with connectivity models to enhance the cause-effect representation of the process. Maurya et.al. (2003) proposed a first principles structural model, which is derived from mathematical equations of the equipment and shows the variable relationship within one single equipment item. Thus, another development of topology-based causal models should concentrate on their combination with the first principles structural models.

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Appendix 1: MATLAB Codes for Class Generation

```
        %% define a class namely 'topology_based_causal_models'

classdef topology_based_causal_models

    properties
        cmLabels = [];%components' names
        cmPos    = [];%components' coordinates
        cmLines  = [];%start and end points of each connection
    end

    methods

        %% 'getLabel' function creats 'cmLines' property
        function obj = getLabel(obj, excelfile)
            [NUMERIC,X] = xlsread(excelfile); % convert the excel
into matrix, NUMERIC is the numeric array, X is the text array
            startCol = strmatch('From',X(1,:)); % the 'column
number' of the 'from' header
            endCol  = strmatch('To',X(1,:)); % the 'column number'
of the 'to' header
            startNodes = X(2:size(X,1),startCol);% obtain all
start points
            endNodes  = X(2:size(X,1),endCol); % obtain all end
points
            newLines = [startNodes endNodes];
            obj.cmLines  = [obj.cmLines; newLines]; % start and
end points of all connections
        end

        %% 'getPosition' function creats 'cmLabels' and 'cmPos'
properties
        function obj = getPositon(obj, excelfile)
            [NUMERIC,X] = xlsread(excelfile); % convert the excel
into matrix, NUMERIC is the numeric array, X is the text array
            obj.cmLabels = X(2:size(X,1),1); %capture names of all
components
            obj.cmPos = NUMERIC(:,1:2); %capture coordinates of
all components
        end

        %% 'getMatrix' function creats the connetivity matrix
         function connectMat = getMatrix(obj)
            connectMat=zeros(length(obj.cmLabels));
            for i=1:size(obj.cmLines,1)

r=strmatch(obj.cmLines{i,1},obj.cmLabels,'exact'); %the row number
of the start point of each line

c=strmatch(obj.cmLines{i,2},obj.cmLabels,'exact'); %the column
number of the end point of each line
                connectMat(r,c)=1; %the entry determined by the
row and column numbers should be 1
            end
         end
```

```
        %% 'getTable' function creats the connectivity table which
combines the matrix and text headers
        function connectTable = getTable(obj)
           connectTable=cell(size(obj.cmLabels,1)+1); %define a
cell matrix with the dimension of all components plus one
           connectTable(2:end,1)=obj.cmLabels;
           connectTable(1,2:end)=obj.cmLabels';

connectTable(2:end,2:end)=mat2cell(getMatrix(obj),ones(1,size(obj.
cmLabels,1)),ones(1,size(obj.cmLabels,1)));% convert matrix into
cell array
        end

        %% Build four basic operations for the digraph model
        %% 'addline' function adds a line between two nodes
        function obj = addline(obj,strFrom,strTo)
            if(isempty(strmatch(strFrom,obj.cmLabels)))
                str = sprintf('The equipment %s doesn''t
exist.',strFrom);
                disp(str)
                return;
            end
            if(isempty(strmatch(strTo,obj.cmLabels)))
                str = sprintf('The equipment %s  doesn''t
exist.',strTo);
                disp(str)
                return;
            end

            newLine = [{strFrom} {strTo}];
            obj.cmLines  = [obj.cmLines; newLine]; % add a new
line into the 'cmLines' property
        end

        %% 'deleteline' function removes the connection between
two nodes
        function obj = deleteline(obj,strFrom,strTo)
            if(isempty(strmatch(strFrom,obj.cmLabels)))
                str = sprintf('The equipment %s doesn''t
exist.',strFrom);
                disp(str)
                return;
            end
            if(isempty(strmatch(strTo,obj.cmLabels)))
                str = sprintf('The equipment %s  doesn''t
exist.',strTo);
                disp(str)
                return;
            end

            cmLinesTmp=[];
            for i=1:length(obj.cmLines)
                if(~(strcmp(obj.cmLines(i,1),strFrom) &&
strcmp(obj.cmLines(i,2),strTo)))
                    cmLinesTmp = [cmLinesTmp; obj.cmLines(i,:)];%
update 'cmlines' property without the given node
                end
```

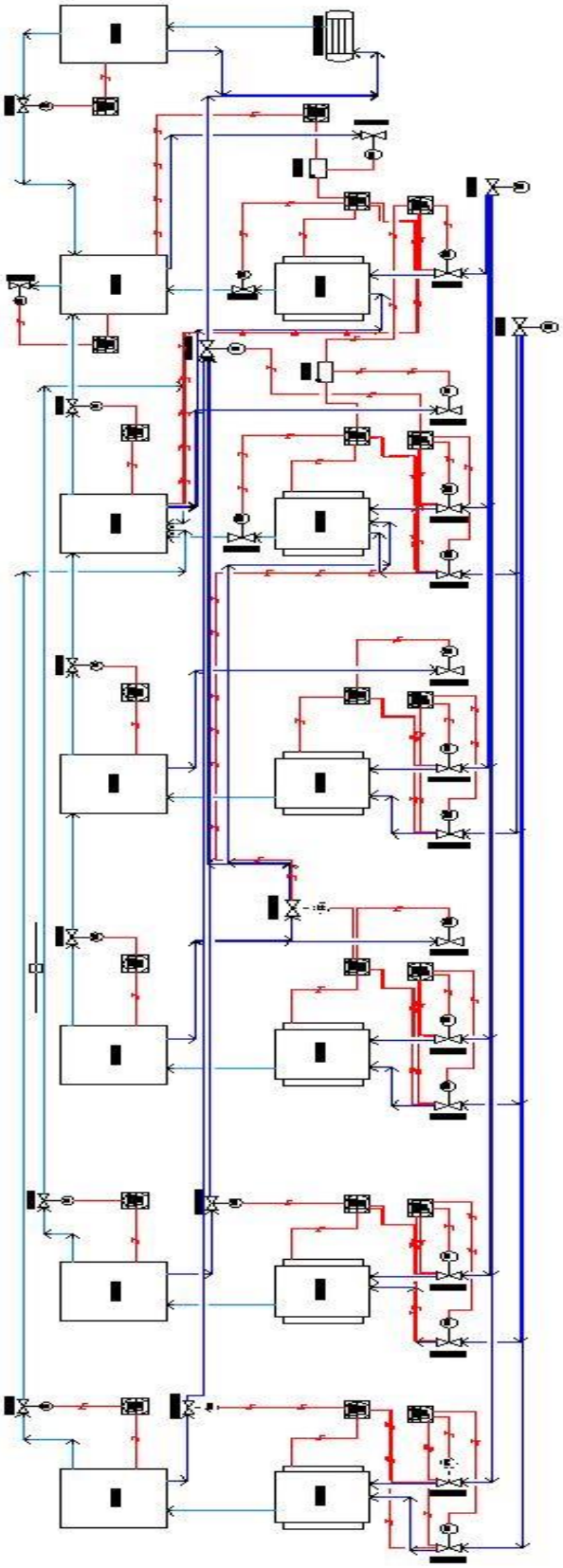
```
            end
            obj.cmLines = cmLinesTmp;
        end

        %% 'addnode' function adds a node into the digraph
        function obj = addnode(obj,strLabel,x,y)
            if(~isempty(strmatch(strLabel,obj.cmLabels)))
                str = sprintf('The equipment %s has
existed.',strLabel);
                disp(str)
                return;
            end
            obj.cmLabels = [obj.cmLabels;{strLabel}];
            obj.cmPos = [obj.cmPos;x y]; %add a new line to the
coordinate matrix
        end

        %% 'deletenode' function deletes the given node and its
connections
        function obj = deletenode(obj,strLabel)
            indexTemp = strmatch(strLabel,obj.cmLabels);
            if(isempty(indexTemp))
                str = sprintf('The equipment %s doesn''t
exist.',strLabel);
                disp(str)
                return;
            end
            labelTemp = obj.cmLabels(indexTemp);

            obj.cmLabels = obj.cmLabels([1:indexTemp-1
indexTemp+1:length(obj.cmLabels)]);
            obj.cmPos = obj.cmPos([1:indexTemp-1
indexTemp+1:length(obj.cmPos)],:);

            cmLinesTmp=[];
            for i=1:length(obj.cmLines)
                if(~(strcmp(obj.cmLines(i,1),labelTemp) ||
strcmp(obj.cmLines(i,2),labelTemp)))
                    cmLinesTmp = [cmLinesTmp; obj.cmLines(i,:)];
                end
            end
            obj.cmLines = cmLinesTmp;
        end

        %% function 'display' creates the digraph
        function digraph(obj)
            figure
            % draw the nodes
            r = 2;   % radius of each node
            t = linspace(0,2*pi,50);
            X = r*cos(t);
            Y = r*sin(t);
            n = length(obj.cmLabels);
            clf
            for i=1:n
                patch(obj.cmPos(i,1)+X,obj.cmPos(i,2)+Y,'c')

text(obj.cmPos(i,1),obj.cmPos(i,2),obj.cmLabels{i},'Horiz','center
```

```
','Vert','middle');
            end
            axis equal
            axis off

            connMatrix = getMatrix(obj);

            % draw connection lines
            L = 4;           % length of the arrows
            A = 30*pi/180;   % angle of the arrows
            for i=1:n
                for j=1:n
                    if connMatrix(i,j)
                        Q = atan2(obj.cmPos(j,2)-obj.cmPos(i,2),
obj.cmPos(j,1)-obj.cmPos(i,1));
                        X = [ obj.cmPos(i,1)+r*cos(Q)
obj.cmPos(j,1)+r*cos(Q+pi)];
                        Y = [ obj.cmPos(i,2)+r*sin(Q)
obj.cmPos(j,2)+r*sin(Q+pi)];
                        Xa = X(2) + [L*cos(-A+Q+pi) 0
L*cos(A+Q+pi)];
                        Ya = Y(2) + [L*sin(-A+Q+pi) 0
L*sin(A+Q+pi)];
                        line([X NaN Xa],[Y NaN Ya])
                    end
                end
            end
        end
    end
end
```

Appendix 2: MATLAB Codes for Class Instantiation

```
clear
clc

dryingsection = topology_based_causal_models; %instantiation of
the class,e.g., define an object 'dryingsection' as an instance of
the class

dryingsection =dryingsection.getLabel('steam group-Pipe Line
Segments.xls'); %load the excel file of pipe line segments and
return the 'cmLines' property

dryingsection =dryingsection.getLabel('steam group-Signal Line
Segments.xls'); %load the excel file of signal line segments and
update the 'cmLines' property

dryingsection =dryingsection.getPositon('coordinate.xls'); %load
the excel file of coordinates and return 'cmLabels' and 'cmPos'
properties
```

Appendix 3: P&ID Drawing of the Drying Section of the BM4



Appendix 4: Causal Digraph of the Drying Section of the BM4