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A hierarchical approach to construct Petri nets for modeling the fault propagation mechanisms in sequential operations

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Abstract

A systematic procedure has been proposed to construct Petri nets for modeling the fault propagation behaviors in batch processes. In this work, a complete system model is organized according to a hierarchy of four levels, i.e. (1) the controller/operator; (2) the valves; (3) the process units; and (4) the sensors. Every component in this system model consists of two distinct elements. One is used to characterize the equipment states and the other the input–output relations. For the purpose of reducing model construction effort, the general structure of object-oriented abbreviations is also developed to represent the PN in a user-friendly format. The effectiveness and correctness of this approach have been successfully demonstrated with a number of practical examples.

Keywords: Sequential operation; Petri net; Digraph; Hazard analysis; Fault propagation mechanism; Hierarchical approach

1. Introduction

In order to ensure operation safety, hazard analysis is one of the basic tasks that must be performed in designing or revamping any chemical process. Numerous techniques are available for this purpose, e.g. fault tree analysis (FTA), event tree analysis (ETA), failure modes and effects analysis (FMEA) and hazard and operability study (HAZOP), etc. In implementing these methods, there are always needs (1) to reason deductively for finding all combinations of basic events that could lead to an undesirable condition and/or (2) to predict all possible consequences of a given fault origin. However, if every fault propagation mechanism is to be identified manually, a rigorous hazard analysis is bound to be labor- and time-consuming and its results often error-prone. To alleviate these practical problems, there have been many attempts in the past to develop computer aids on the basis of various qualitative models.

In the last two decades, the research on automatic hazard analysis has advanced significantly. Many efficient tools have been adopted to develop the fault-tree synthesis algorithms, e.g. digraph (Lapp & Powers, 1977; Chang & Hwang, 1992), decision table (Kumamoto & Henley, 1979) and mini-fault tree (Kelly & Lees, 1986a,b). Several generic expert systems have also been constructed to produce comprehensive HAZOP reports (Vaidhyanathan & Venkatasubramanian, 1996a,b). The prerequisite for identifying the fault propagation mechanisms in implementing any of these methods is basically a qualitative system model. It can be observed from the literature that the digraph is by far the most popular choice (Allen & Rao, 1980; Andrews & Morgan, 1986; Chang & Hwang, 1994; Chang, Hsu & Hwang, 1994). Although the digraph-based approach has been proven to be useful, it is effective mostly in applications concerning the continuous processes. This is due to the fact that the digraph is inherently unsuitable for describing the dynamic causal relationships among time, discrete events, equipment states and system configurations in the *batch* or *semi-batch* processes.

In this work, the Petri net (PN) is used as a modeling tool to circumvent the above drawbacks. The *ordinary* Petri net (Petri, 1962) is well known for its capability in describing the discrete-event systems. However, it is also apparent that this original version of PN lacks the

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Nomenclature

I-H (II-H)	the fresh air to Bed-I (Bed-II) is heated
I-C (II-C)	the fresh air to Bed-I (Bed-II) is not heated
I-P (II-P)	the recycled air is directed to Bed-I (Bed-II)
I-E (II-E)	the outlet air from Bed-I (Bed-II) is discharged to stream 25
I-R (II-R)	the outlet air from Bed-I (Bed-II) is recycled to the proportionating valve
I-T (II-T)	the temperature of Bed-I (Bed-II)
I-M (II-M)	the water content in Bed-I (Bed-II)

capability of representing the relationships among continuous process variables. Consequently, the idea of automating *procedure* HAZOP on the basis of Petri net–digraph hybrid models was proposed in recent literature (Srinivasan & Venkatasubramanian, 1998a,b). From a critical review of these works, one can observe that this modeling approach is not suitable for depicting a number of important features in more complex batch (sequential) operations. Specifically,

1.1. Concurrent activities

Concurrent activities can be easily expressed in terms of Petri nets. Most batch chemical processes are designed with a certain degree of parallelism to ensure flexibility and efficiency in operation. This type of operation has not been considered in the published studies.

1.2. Cyclic operations

In a sense, all batch operations are repetitive or cyclic. It is thus necessary to investigate the possibilities of a current failure causing undesirable consequences in the later cycles. Therefore, in certain cases, it is not enough to build a recipe-based PN model representing the operation steps only in a single batch (or cycle).

1.3. Continuous transients

The batch operations are typically characterized by time-variant operating conditions and/or process variables. These quantities were discretized and expressed with digraphs in the hybrid models proposed by Srinivasan and Venkatasubramanian (1998a,b). However, since these transients can be better described with the continuous places, there is a strong incentive to model the batch systems in a unified format with PNs only.

1.4. Multi-purpose productions

It is a common practice to manufacture more than one product with the same facilities in a batch plant. Due to the need to share resources, it may be necessary to run some units under different operation modes at different times. As a result, the process configuration, i.e. the connections among units, may be changed accordingly. Since the conventional recipe-based PN models are built individually for a single product, they cannot be easily integrated to represent the overall orchestrated production activities efficiently.

It should be noted that a large number of enhancements have already been introduced since the original PN was proposed (Peterson, 1981; David & Alla, 1994; Alla & David, 1998). Two commonly used versions, i.e. *extensions* and *abbreviations*, can be found in the literature. The extensions are used to enrich the ordinary PN by incorporating additional functions and thereby allow a greater number of applications to be treated. For example, David (1997) developed the hybrid and continuous Petri nets to model a number of realistic engineering systems. On the other hand, the abbreviations are used to simplify the overcrowded graphical representations to ensure legibility. In this respect, Szücs, Gerzson and Hangos (1998) used the colored Petri net to concisely represent the transient behaviors of the states, inputs and outputs in batch processes for fault diagnosis purpose. Thus, by incorporating various additional features, it is possible to systematically construct a system model with the Petri nets for the sequential operations in batch processes.

The rest of this paper is organized as follows. In order to facilitate illustration of the component models, a listing of the PN extensions used in this study is first provided. The hierarchy in the system model and also the generalized component models adopted in each level of the hierarchy are then explained in detail. Additional PN-building techniques for incorporating the failure mechanisms into the component models are discussed in a following section. Next, a systematic procedure is presented to construct the system model by connecting the component models according to the proposed hierarchy. For the purpose of relieving the burden in model construction, the object-oriented abbreviations are adopted to organize the PN in a user-friendly format. The general object structure is also briefly described in this paper. Finally, the synthesis procedure of the PN model for an air-drying process and the results of a comprehensive hazard analysis are presented to demonstrate the effectiveness of the proposed approach.

2. The extensions of ordinary Petri net

A formal mathematical description of the ordinary Petri net can be found in Peterson (1981). For the sake of brevity, only a condensed version is provided here. As originally designed, the ordinary PN consists of only three types of elements, i.e. places, transitions and arcs. The state of a discrete-event system is basically reflected with a *marking*, i.e. a vector of the *token* numbers in all places of PN. Since only the discrete places are considered in the original Petri net, this vector contains only positive integers and/or zeros. The movements of tokens can be realized by *enabling* and then immediately *firing* the transitions. A transition is enabled if the token number in every input place is larger than or equal to the *weight* on the corresponding place-to-transition arc. After firing the transition, additional tokens are introduced into its output places and the increased token number in each place is the weight on the corresponding transition-to-place arc. Finally, it should be noted that the only allowed weight in an ordinary Petri net is 1 and all the transitions are without time delay.

In order to facilitate proper representation of sequential operations, several special extensions are adopted in this study (David & Alla, 1994; Drath, 1998b; Bowden, 2000). Following is a list of specific places and transitions used in the proposed PN models.

2.1. The discrete and continuous places

Both the discrete and continuous places are adopted in this work. A discrete place can be used to represent the Boolean state of a device, e.g. the open/close position of a valve or the on/off status of a power supply. On the other hand, since the token number in a continuous place is real, it is well suited for describing the variation of a state variable, such as the temperature, pressure or liquid level, associated with a process unit.

2.2. The timed and non-timed transitions

Both the timed and non-timed transitions are used in the proposed PN-based system model. It should be noted that various events can take place over a wide range of different time spans in sequential operations. The non-timed transitions are suitable for representing events occurring almost instantly. There are in general two alternative mechanisms for representing non-zero event times. They can be either associated with the places (P-timed) or with the transitions (T-timed). Since it is always possible to transform from a P-timed PN to the T-timed PN, and vice versa, the latter is chosen in this work.

In addition, three different types of place-to-transition arcs are utilized, i.e. the weighted arcs, the inhibitor arcs and the static test arcs. The transition enabling rules of these place-to-transition arcs are listed in Table 1. In this table, M denotes the number of tokens in input places and W denotes the weight of corresponding arc.

Note that a time-delayed transition cannot be fired right after the enabling condition is satisfied. Extra tokens will not be added in its output places until the designated firing duration has elapsed. Additional details concerning these arcs are summarized below.

2.3. The weighted arcs

A generalized version of the arcs in an ordinary PN is one in which the arc weight may not be one. A positive integer k can be used to label the outward arc of a discrete place. A k-weighted arc can be interpreted as a set of k parallel arcs. For the sake of simplicity, the unity weights are omitted in the Petri net. On the other hand, if an arc is attached to a continuous place, one can use a mathematical function of the token numbers in a set of selected places as the weight.

2.4. The inhibitor arcs

An inhibitor arc is usually represented by a directed arc with a small circle at its end. The token number in its input place remains unchanged even after firing the output transition. This type of arcs can be used in executing zero test or in modeling the failure mechanisms that inhibit certain normal events in operation.

2.5. The static test arcs

The static test arc is marked by a directed dash line. In general, it is often used to replace the self-looping structure in PN. In other words, a static test arc is equivalent to two equally-weighted arcs pointing in opposite directions. Notice that this arc also does not allow token flow, i.e. the token quantity of its input place cannot be reduced by firing the output transition.

Finally, it should be noted that all tranaition-to-place arcs are weighted arcs. If an arc is directed toward a continuous place and a mathematical function is used as

Table 1
The transition enabling rules

Arc type	Enabling condition	Token removal from input place
Normal arc	$M \geq W$	Yes
Static test arc	$M \geq W$	No
Inhibitor arc	$M < W$	No

its weight, the independent variables of this function should be the token numbers in selected places.

3. The hierarchy in a system model

A hierarchical approach has been taken in this work to construct Petri nets for modeling the *normal* operation steps in batch processes. The components in a complete system model can be classified into the four different levels shown in Table 2. Basically every item in the P&ID is described with a component model here. Each component consists of two distinct parts. One is used to characterize the equipment state and the other the input–output conditions. In the latter case, several different versions are needed if a change in the equipment state alters the relations among process conditions.

Following is a general description of these component models in every level.

3.1. Level 1

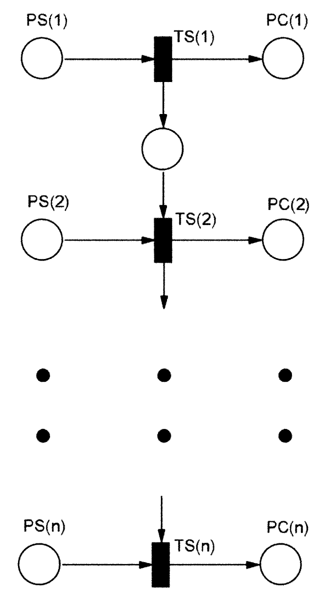
The operating steps specified in a recipe are executed sequentially by a first-level component. Notice first that it is not necessary to model its equipment state in this case since there is only one possibility during normal operation, i.e. the component is in service.

In general, each operation step can be characterized with two elementary actions: (1) confirmation of an initiation signal and (2) execution of an operation command. The operation command issued by the controller/operator is always concerned with a change in the equipment state of a second-level component. On the other hand, the initiation signal can be obtained either from a sensor in the fourth level or from an internal clock. In both cases, this signal is used to mark the beginning of an operation step for execution.

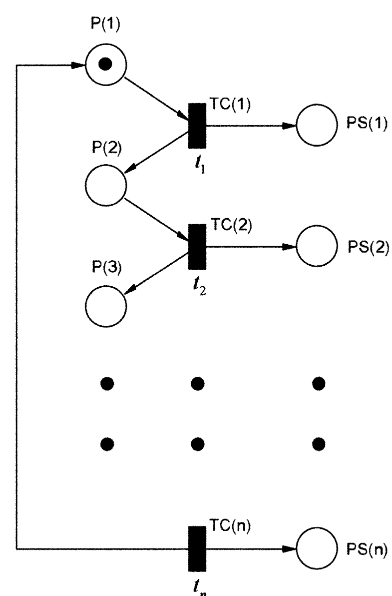
The generalized operator/controller model can be found in Fig. 1a. Notice that only discrete places are needed to represent its input and output conditions. The input place PS(i) and the non-timed transition TS(i) denote, respectively, the status and confirmation action of the ith initiation signal. The output place PC(i) is used to reflect the status of the ith operation command. Notice also that the order in which these commands are issued can be arranged according to a given recipe.

Table 2
The hierarchy in PN-based system models for sequential operations

Level	Component models
1	Timer, operator, PLC
2	Valve, pump, compressor
3	Process unit
4	Sensor



(a)



(b)

Fig. 1. (a) The generalized PN model representing the input–output relations of an operator/controller. (b) The generalized PN model describing the output conditions of an internal clock.

If the initiation signals are generated by an internal clock, an additional sub-PN should be included in the component model. In particular, this clock can be represented with the Petri net given in Fig. 1b. The places PS(i)s in this figure can be regarded as the clock signals marking the switching times of two successive operating periods. The delay time t_i associated with transition TC(i) is the elapsed time of period i.

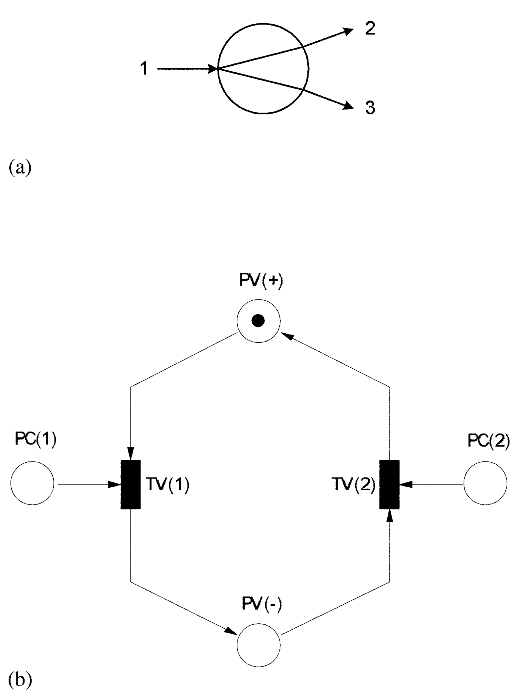


Fig. 2. (a) The flow diagram of a 3-way valve. (b) The PN model describing the equipment states of a 3-way valve.

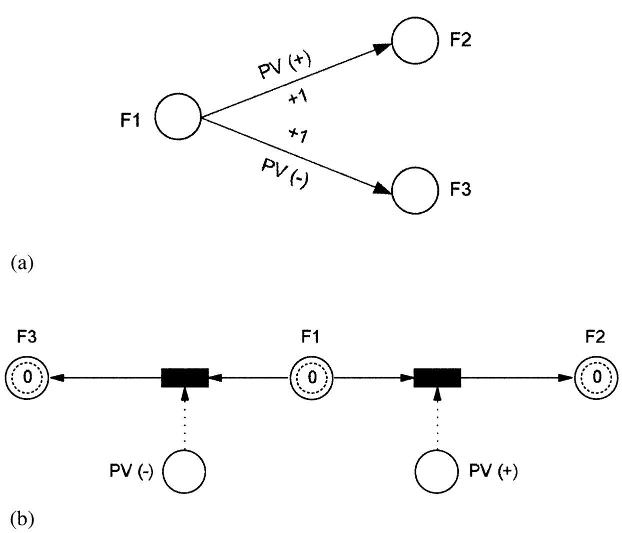


Fig. 3. (a) The digraph model representing the input–output relations of a 3-way valve. (b) The PN model representing the input–output relations of a 3-way valve.

3.2. Level 2

All second-level components can be described with two alternative equipment states. The equipment states of these components determine the process configuration, the operation mode and possibly the equipment states of some process units in the third level. Let us consider the 3-way valve presented in Fig. 2a as an example. The corresponding component model for the equipment states can be found in Fig. 2b. In this Petri net, the places PV(+) and PV(−) denote two alternative valve positions connecting lines 1 and 2 and 1 and 3, respectively, and the transitions TV(1) and TV(2) represent the valve-switching actions from PV(+) to PV(−) and vice versa. Notice that the input places PC(1) and PC(2) of the two transitions TV(1) and TV(2) are associated with the corresponding operation commands issued by controller/operator. The equipment states of other level-2 components can be described with essentially the same PN structure.

The causal relations between the input and output conditions of a level-2 component can be described *qualitatively* by digraphs with conditional edges (Lapp & Powers, 1977). This task can also be accomplished effectively with a PN model. Let us use the 3-way valve in Fig. 2a again as example. The relation between its input and output flow rates can be modeled either with the digraph in Fig. 3a or with the Petri net in Fig. 3b. Notice that the places in the latter model should be considered as a new extension developed in this study. They are referred to as the *deviation places* in this paper. As shown in Fig. 3b, each deviation place is represented with two circles. The outer circle is drawn with a solid line and the inner one a dotted line.

This extension is created to properly describe input–output relations implied in digraphs and also to facilitate simulation of the fault propagation behaviors in sequential operations. In particular, only integers are allowed to be used as the token numbers in deviation places. The value 0 is treated as an indication of normal condition. On the other hand, positive and negative integers are used to reflect the qualitative levels of deviations from the normal state. If a transition is the output of one or more deviation place, it is enabled only when an updated token number is introduced in every input place. After firing, the token numbers in its input places remain unchanged and the those in the output places are determined according to a set of user-supplied mathematical functions. A more detailed characterization of the deviation place can be found in Appendix A.

Finally, it should be noted that the process configuration can be uniquely defined by the equipment states of all level-2 components in the system. A change in process configuration may alter the operation modes and equipment states of certain level-3 components.

3.3. Level 3

Basically all process units in the P&ID can be considered as the third-level components. As mentioned previously, a component model consists of two parts. A general description of these two distinct elements is provided below.

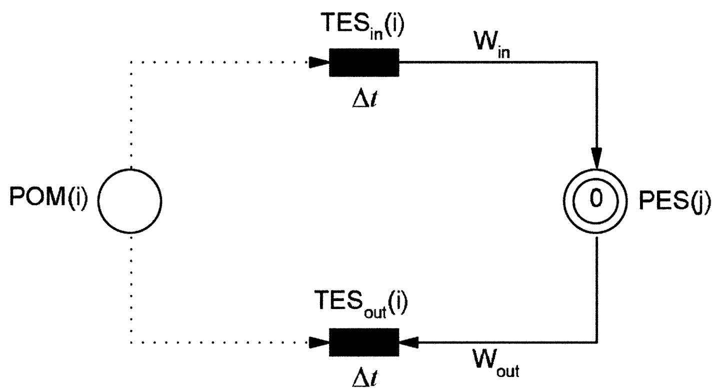


Fig. 4. The generalized PN model describing the equipment state of a process unit in level 3.

3.3.1. Equipment state

In some cases, the equipment state of a process unit can be safely assumed to be unchanged under normal operating conditions. However, this assumption may not be valid if:

1) there is a continuous accumulation (or depletion) of mass and/or energy in the unit, e.g. the storage tank and the batch reactor, or;
2) the performance of a unit deteriorates quickly during operation, e.g. the fixed-bed catalytic reactor and adsorption column.

Thus, it is necessary to describe the transients in these process units. The continuous places are suitable for describing the equipment states of level-3 components *quantitatively*. The general PN model of any state variable can be found in Fig. 4. Here, the continuous place PES(j) ($j = 1, 2, \ldots$) represents the jth equipment state used to characterize a level-3 component; the discrete place POM(i) ($i = 1, 2, \ldots$) denotes the ith operation mode defined by the equipment states of level-2 components; $TES_{in}(i)$ and $TES_{out}(i)$ are time-delayed transitions enabled after the ith mode is activated in operation; the weight function w_{in} and w_{out} denote, respectively, the amounts of increase and decrease in the state variable during a very small time increment Δt.

If the above Petri net is used for modeling every level-3 component in a large system, the computation demand for simulating the fault propagation behaviors may become unnecessarily high. A qualitative model is often sufficient for such applications. In particular, the range of each state variable can be discretized into a finite number of intervals and a positive integer or zero can be used to signify a qualitative level. Therefore, the continuous place PES(j) in Fig. 4 can usually be replaced with a discrete one in large system models. In addition, a *finite* delay time Δt should be used in this case and $w_{in} = w_{out} = 1$.

3.3.2. Input–output conditions

Although the continuous places can be used to quantitatively represent the input–output conditions of a level-3 component, it is in general more convenient to use the deviation places to construct a qualitative model for the purpose of hazard analysis. Let us consider the fictitious relations described with the digraph presented in Fig. 5a. Here, the edge conditions ES_a and ES_b denote two distinct equipment states. Notice that the input–output relations under the same equipment state may be invoked according to the logic operator 'OR.' The same relations can be expressed with the Petri net presented in Fig. 5b. Noticed also that two additional features may be introduced into this model:

1) The delay time associated with each transition may be used to reflect the system response time with respect to the a corresponding input disturbance.
2) It is also possible to model an output response caused by simultaneous input disturbances. For example, the Petri net in Fig. 5b should be changed to Fig. 5c if the disturbances in the first two input conditions must both occur to create an output response.

For illustration purpose, let us consider a specific process unit, i.e. a heat exchanger in which a hot stream HS is cooled with the cooling water CW (see Fig. 6a). The qualitative model representing a part of its input–output conditions can be found in Fig. 6b.

3.4. Level 4

The equipment states and/or input–output conditions of a third-level component can be monitored via sensors in the fourth level. Notice that there is no need to model the equipment state of a sensor since it is always in the working state during normal operation. The input–output relation of any sensor can also be represented with a special version of Fig. 5b, i.e. the PN in Fig. 7.

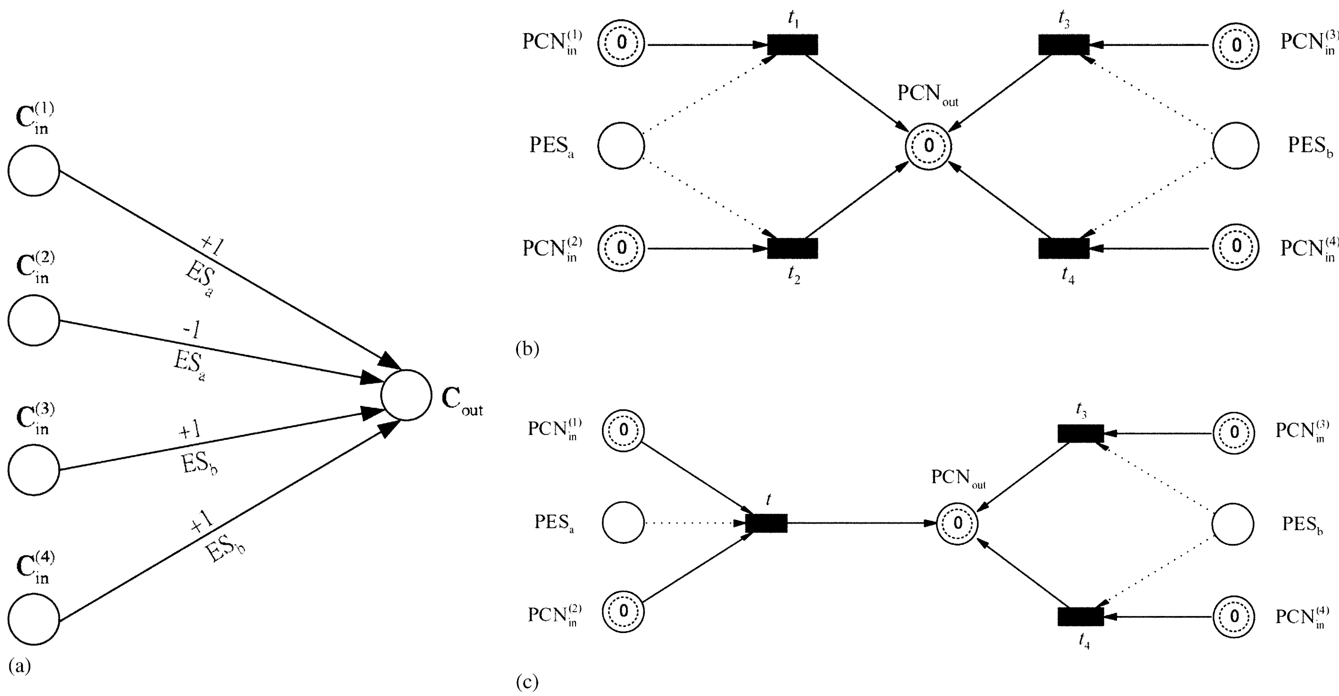


Fig. 5. (a) A digraph model representing the input–output relations of a process unit in level 3. (b) A PN model representing the input–output relations of a process unit in level 3. (c) Another PN model representing the input–output relations of a process unit in level 3.

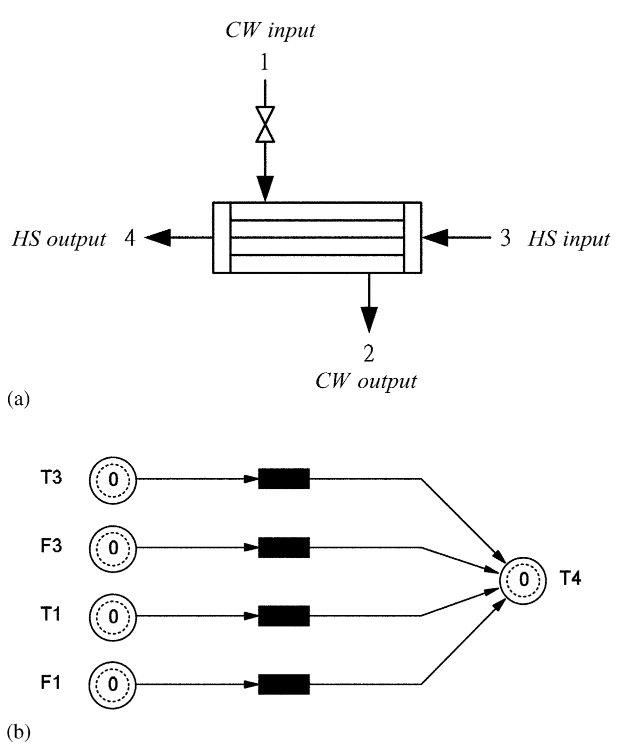


Fig. 6. (a) The flow diagram of a heat exchanger. (b) The PN model representing the input–output relations of a heat exchanger.

The places PCN and PMS in Fig. 7 denote, respectively, the true process condition of a third-level component and its measurement signal.

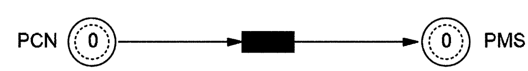


Fig. 7. The PN model representing the input–output relation of a sensor.

4. The failure mechanisms in component models

So far only the PN models representing the normal component behaviors have been reported in the previous section. To facilitate hazard analysis, it is still necessary to incorporate additional elements in each component model to depict the fault propagation behaviors caused by various equipment failures. A generalized failure model can be found in Fig. 8. In this model, the direct outcome of a failure is treated as a change in the equipment state of a component. The equipment state caused by the ith failure is represented by the place PFS(i) ($i = 1, 2, \ldots$). The effects of a failure are regarded as the outcomes created by replacing a set of routine events occurred during normal operation with an alternative set of abnormal events. These effects can be readily modeled with a combination of the inhibitor arcs and test arcs (see Fig. 8). The former arcs are used to disable the transitions corresponding to the routine events, i.e. TN(j) ($j = 1, 2, \ldots, m$), and the latter activate the alternative transitions representing the failure events, i.e. TF(k) ($k = 1, 2, \ldots, n$).

To facilitate better understanding of this modeling practice, four simple examples are provided in Fig. 9a–

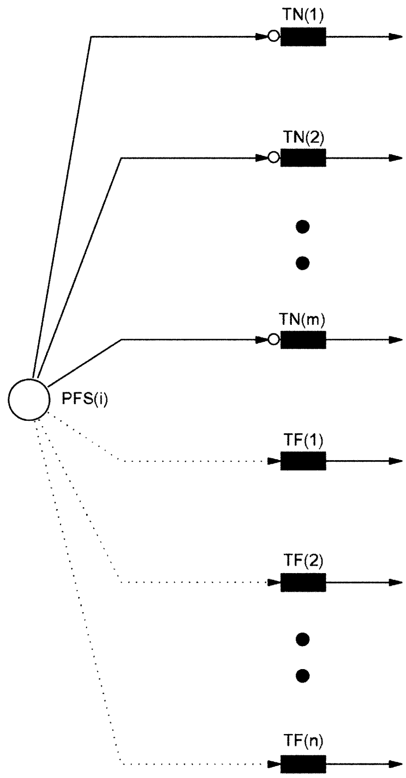


Fig. 8. A generalized failure model.

d. Following is a brief description of these failure models:

- A controller/operator failure is described in Fig. 9a, i.e. an extra operation step is carried out mistakenly. Notice that the generalized model for the normal control/operator behaviors (Fig. 1a) is repeated here and, for the sake of clarity, the corresponding failure model is enclosed with dotted line. In this case, the place PC′(k) and the transition TS′(k) denote, respectively, the status of the extra operation command and the event of issuing this command.
- The Petri net in Fig. 9b represents the fault propagation mechanism resulting from the failure '3-way valve sticking.' Again the PN used for modeling normal operation (Fig. 2b) is included here and the failure model is marked with dotted line. The transitions denoting the valve-switching events, i.e. TV(1) and TV(2), are disabled by inserting a token in the place denoting the valve failure.
- The effects of 'heat exchanger fouling' on the output temperature of hot stream arc modeled in Fig. 9c. This failure causes a disruption of the normal equipment state arid also an increase in the outlet temperature, i.e. T4(+1).
- The failure 'temperature sensor failing low' can be described with a modeling approach similar to that in the previous example. The corresponding Petri net is presented in Fig. 9d. Notice that, other than the obvious consequence that the sensor is no longer in its normal equipment state, this failure yields a lower-than-normal measurement value while the true temperature is still kept at the normal level. In other words, the token number in the deviation place T_{meas} may be -1 when that in T_{true} is still 0.

5. The model construction procedure

In building a PN-based system model for hazard analysis, the component models should be constructed and validated first and then connected in sequence from top to bottom level according to the piping and instrumentation diagram. The connection between two adjacent component models can be described with Fig. 10. Basically, the output conditions and, in some cases, the equipment states of a downstream component are controlled by the output conditions of an up-stream component. However, if the equipment states of a third-level component are time-variant, the transient behaviors of these states may also be affected by its operation mode, which is uniquely defined by the equipment states of one or more level-2 component.

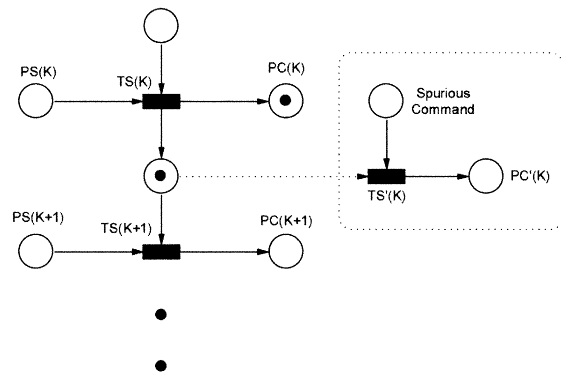
In principle, all component models should be included to ensure the comprehensiveness of analysis. However, some of them may be excluded for the sake of simplicity. Specifically, a component can be neglected if:

1) its failure mechanisms are not of interest;
2) there is only one normal equipment state, and;
3) it is a single-input-and-single-output (SISO) component.

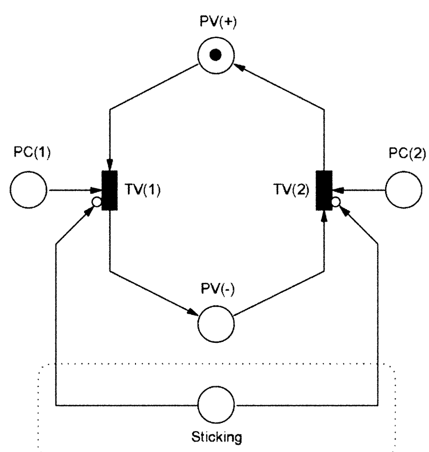
Finally, it should be noted that the validity of the system model can be confirmed by testing it with known scenarios. In other words, the equipment states and process conditions of every component at different stage of the batch operation should be simulated and compared with the expected system behavior before actual implementation of the proposed hazard identification procedure.

Let us use, the simple mixing process given in Fig. 11 as an example to illustrate the proposed model construction procedure. Here, tank 3 is being fed from the other two tanks. Initially, the amount of liquid A in tank 1 is 1 l and that of liquid B in tank 2 is 2 l. The mixing operation begins when valve V1 and valve V2 are opened by an operator. It is assumed that the flow rates of these two feed streams are the same: 1/60 l/s. The operator is instructed to close valve V2 whenever tank 1 is empty (step 1) or vice versa (step 2). The PN model for this batch operation can be found in Fig. 12.

The first-level component is the operator. For simplicity, only the two operation steps performed after opening V1 and V2 are modeled here. Since they are



(a)



(b)

Fig. 9. (a) A failure model of the operator/controller. (b) A failure model of the 3-way valve. (c) A failure model of the heat exchanger. (d) A failure model of the sensor.

not required to be carried out in a specific order, the input and output places associated with each step, i.e. PS(i) and PC(i) ($i = 1, 2$), can be merged to simplify the model structure.

There are two components in the second level, i.e. valves V1 and V2. Their equipment states can be described with two discrete places denoting ‘open’ and ‘closed.’ Two types of valve failures are considered in this example, i.e. sticking and failing closed. The corresponding failure models are included in this PN. If the event ‘valve sticking’ occurs, it always disables a transition representing the action to change valve position. The corresponding token is, therefore, locked in its input place. On the other hand, if a valve is originally open and the event ‘valve failing closed’ occurs during operation, such a failure always moves the token from the place representing the open position to the other place denoting the opposite valve state.

The tanks in this example are the third-level components. To characterize their equipment states, it is necessary to trace the variations of the liquid levels in all three tanks. Three continuous places are thus adopted to represent these state variables. Notice that the dead times of all time-delayed transitions are set to 1 s. Consequently, the weights on the output arcs from and input arcs to these continuous places should be 1/60, which is the same as the normal flow rate. The discrete places F1 and F2 are used to reflect the output conditions of Tank 1 and 2, respectively. If the flow rate from Tank 1 (or Tank 2) to Tank 3 is maintained at a normal level, then a token should be introduced into the place F1 (or F2).

In this example, the possibility of sensor failures is excluded and the sensor measurements are assumed to be identical to the equipment states of Tank 1 and 2. As a result, the sensor models can be omitted. It is also assumed that the required mixing ratio of A–B is 1. Thus, an off-spec product may be produced if the amounts of A and B in Tank 3 are not equal. This undesirable outcome is flagged with a discrete place in Fig. 12.

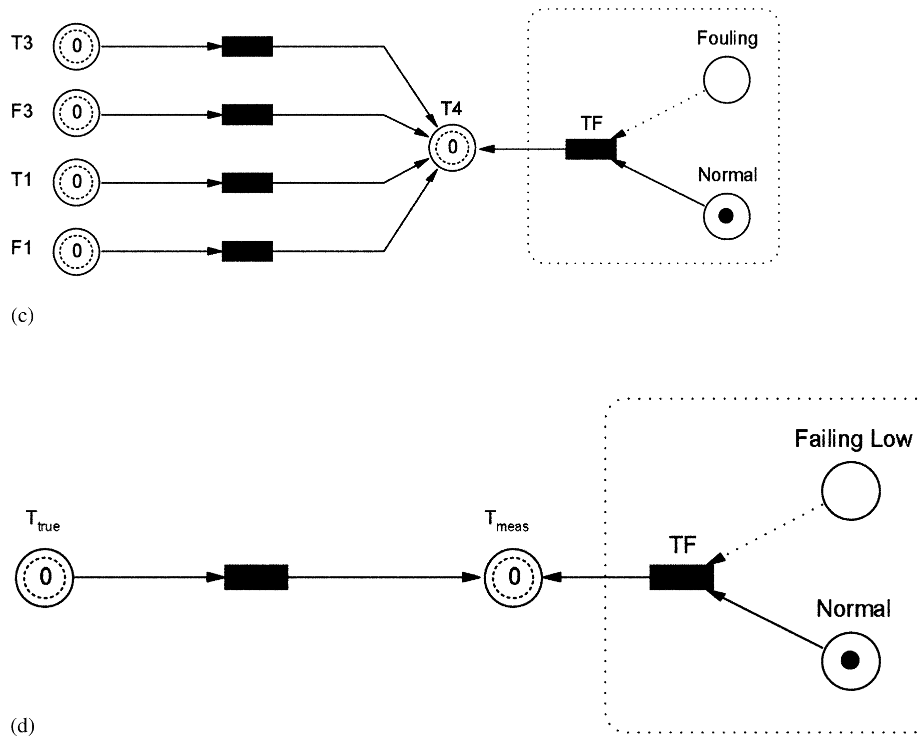


Fig. 9 (*Continued*)

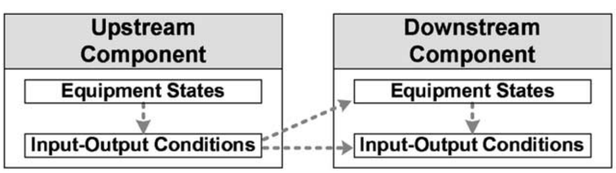


Fig. 10. The connection between two adjacent component models.

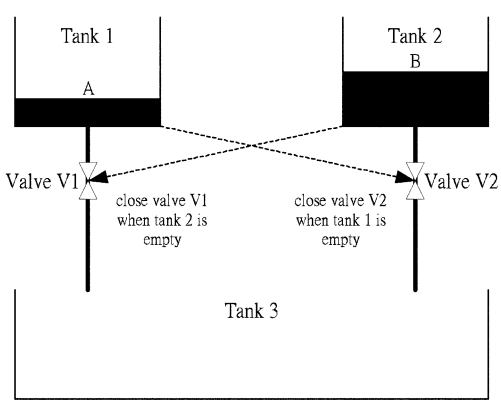


Fig. 11. The process flow diagram of a mixing process.

The fault propagation behaviors resulting from the valve failures given in Fig. 12 have been simulated with an existing commercial software VISUAL OBJECT NET++ (Drath, 1998a). Initially, all places are empty except the two continuous places representing the amounts of materials in Tanks 1 and 2. Their initial marks are 1.0 and 2.0, respectively. The failures were introduced later in simulation. For the undesirable condition 'off-spec product,' the simulation results can be found in Tables 3 and 4. It is clear from these results that the causes for the condition 'off-spec product' occurring between 0 and 1 min are {valve V1 failing close between 0 and 1 min} and {valve V2 failing close between 0 and 1 min} and the cause for the same condition occurring between 1 and 2 min is {valve V2 sticking between 0 and 1 min}.

6. The object-oriented abbreviations

Strictly speaking, the PN models constructed with the above procedure are only suitable for analyzing small systems with moderately complex recipes. This is mainly due to state-space explosion caused by the need to describe not only the process configurations but also the operation steps in an industrial-size system model. More specifically, the total number of places and transitions tends to be overwhelmingly large in the corresponding Petri nets. In order to handle this practical problem, the object-oriented abbreviations (Drath, 1998b) have been utilized in this study to simplify model structure and to reduce the model-building effort. The inherent characteristics of those abbreviations satisfy the basic needs in constructing realistic models for sequential operations, e.g. encapsulation, abstraction, inheritance, reusing, information hiding and message passing, etc.

As mentioned previously, a complete system model consists of a large number of interacting components.

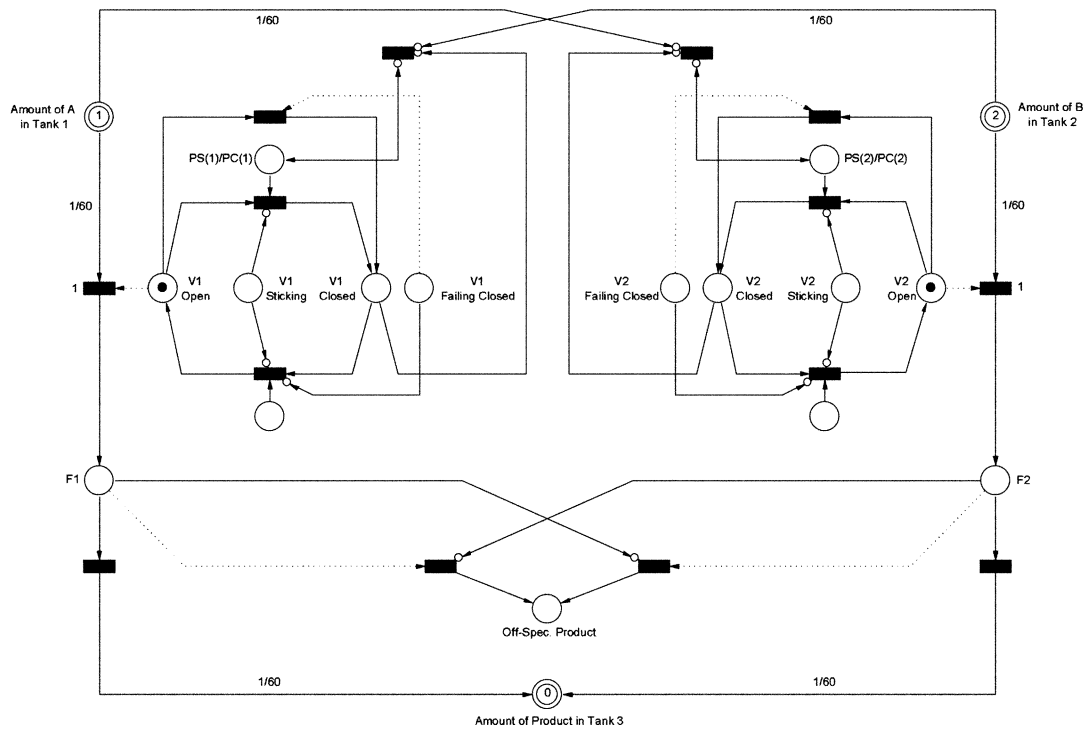


Fig. 12. The PN model of a mixing process.

Each component can be treated as an object. Basically, every object can be fabricated according to a three-layer structure. In the upper layer, it is only necessary to build an object frame. For illustration clarity, this object frame is always labeled with a heading and equipped with multiple interface ports. Generally speaking, the input and output ports can be configured according to Fig. 10. The inputs should be taken from the output ports of its up-stream objects and the outputs should be passed to the input ports of its downstream objects. There are two connected sub-frames in the underlying second layer. They are used to encapsulate the PNs in the bottom layer for describing equipment states and input–output conditions, respectively. The structures of these two sub-frames are essentially identical to that of the object frame. The outputs from the first, i.e. the equipment states, are used as inputs to the second sub-frame. The input and output ports on the object frame in the upper layer are connected to those on these sub-frames in the middle layer. As an example, the object frame for a 3-way valve and its two sub-frames can be found in Fig. 13a. The sub-frames and the encapsulated PNs representing the equipment states and input–output conditions of the 3-way valve can be found in Fig. 13b and c, respectively.

7. Application

A practical example concerning an air-drying process is presented here to demonstrate the feasibility of the proposed model construction procedure and the usefulness of PN models in hazard assessment for the sequential operations. Although a detailed description of this process can be found in Shaeiwitz, Lapp and Powers (1977), a brief review is still provided in the sequel for the sake of completeness.

Table 3
Simulation results of ‘valve sticking’ in mixing process

Valve number	Failure time (θ)	Occurrence time of ‘off-spec product’	Final valve state
V1	$0<\theta<1$	–	V1: open
	$1<\theta<2$	–	V2: closed
V2	$0<\theta<1$	>1	V1: closed V2: open
	$1<\theta<2$	–	V1: open V2: closed

Table 4
Simulation results of ‘valve failing closed’ in mixing process

Valve number	Failure time (θ)	Occurrence time of ‘off-spec product’	Final valve state
V1	$0<\theta<1$	$>\theta$	V1: closed V2: open
	$1<\theta<2$	–	V1: closed V2: closed
V2	$0<\theta<1$	$>\theta$	V1: open V2: closed
	$1<\theta<2$	–	V1: open V2: closed

7.1. Process description

Fig. 14 is the flow diagram of a sequential process for drying air by using fixed alumina beds. Ambient air, which contains water vapor enters in stream 9, The air passes through a bed of alumina, where the water vapor is adsorbed. The dried air passes out of the process in stream 25. In order to maintain a continuous supply of dry air, two beds are employed. When one bed is removing water from air, the other is being regenerated and then cooled. Regeneration involves passing hot air through a bed, which has been loaded to capacity with water. The hot air strips the water from the alumina. After leaving the regenerating bed, it is then passed through a cooler and a separator in turn to remove the water vapor. Eventually, this air is recycled through the lower port of the proportionating Valve and sent to the bed currently in service. The regenerated bed must then be cooled with the inlet air for a specific time period before returning to its intended air-drying operation.

Both beds experience the same operation cycle. Table 5 gives the detailed recipe in a complete cycle.

7.2. Model construction

The proposed model construction procedure can be followed to build the PN for hazard analysis. Following is a brief description of the component models in each level.

7.2.1. Level 1

The first-level component in this system is the timer, which can be viewed as a device consisting of a controller with an internal clock. The component model for describing its normal behaviors can be assembled by combining the two Petri nets in Fig. 1a and b ($n=4$). There are two timer failures considered in this study. One is concerned with the controller. Notice from Table 5 that the 4-way valves are turned every two operation periods when the initialization signals are generated by the clock at the starting times of periods 1 and 3. It is assumed that erroneous operation commands may be issued by the controller to switch one or both of them to the other position when period 2 or 4 begins. The corresponding failure model can be found in Fig. 9a. The other timer failure studied in this example is due to clock malfunction. It is assumed that this clock stop producing initiation signals should such an event occur. This failure can be modeled with inhibitor arcs pointing to the transitions TC(i)s ($i=1$, 2, 3, 4) in Fig. 1b.

7.2.2. Level 2

The second-level components are the 3-way valve 3W and the two 4-way valves 4W-I and 4W-II. The equipment states of these three valves can determine the system configuration. The position of valve 3W determines the route of inlet air flow. The fresh air can either be directed to the heater or simply bypass it. The position of valve 4W-I defines the connections between the alumina beds and their air supplies. The air consumed in each bed can be taken either from system inlet (for regeneration or cooling) or from the lower port of proportionating valve (for dehumidification). The position of valve 4W-II governs the destinations of the exit airs from these two beds, i.e. the air can be either discharged or recycled.

Every valve in this system can only be switched to two alternative positions, i.e. PV(+) and PV(−). The relationships between the valve positions and the stream connections are shown in Table 6. The model structures for these three valves are essentially the same. The equipment states of a normal valve can always be represented with the Petri net presented in Fig. 2b. The failure model associated with ‘valve sticking’ can then be attached according to Fig. 9b. The corresponding model of the input–output conditions can be built on the basis of Fig. 3b. In this case, the relations between the input and output temperatures and water concentrations should also included in the same fashion. Specifically, the PNs for these relations can be constructed according to Table 7.

7.2.3. Level 3

Six third-level components can be readily identified from the P&ID given in Fig. 14, i.e. the two alumina beds, the heater, the cooler, the separator and the

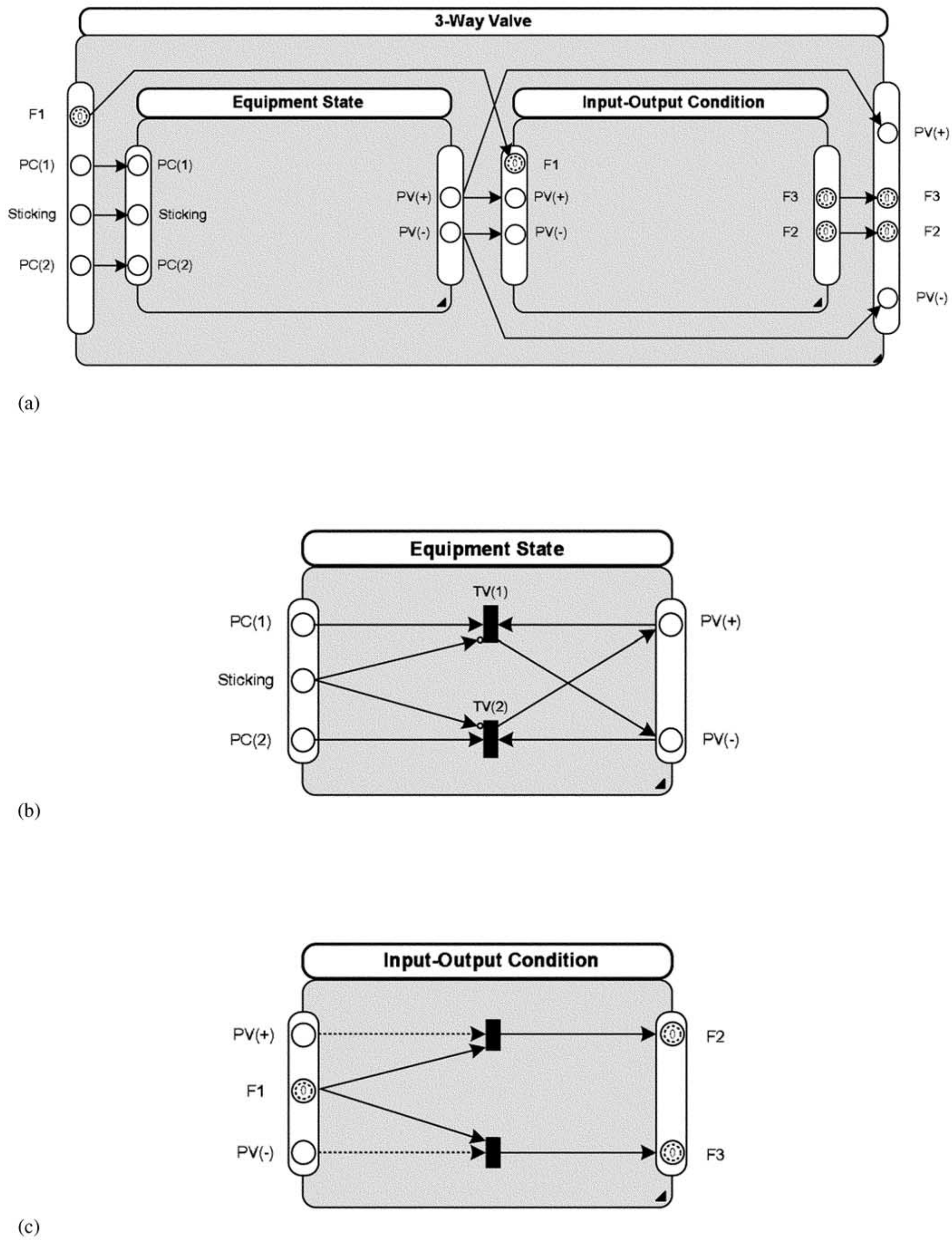


Fig. 13. (a) The object net of a 3-way valve. (b) The sub-object net of a 3-way valve (equipment state). (c) The sub-object net of a 3-way valve (input–output condition).

proportionating valve. In addition, the joint connecting lines 16, 17 and 18 is also treated as a level-3 component here. It is referred to as a *mixer* in this example. Other than the beds, only one equipment state is needed to characterize each level-3 component. The Petri nets representing their qualitative input–output relations can be developed according to the model structure presented in Fig. 5b. The correspondence between the inputs and outputs of each one-state component is given in Table 8. Notice that, instead of presenting the PN models explicitly in this table, the edge gains in the corresponding digraphs (see Fig. 5a) are specified for the sake of conciseness.

The equipment states of each alumina bed can be described with two parameters, i.e. the bed temperature and water content. From a careful analysis of the operation procedure for the air-drying process, it can be observed that the main controlling factor of bed temperature is the temperature of in-coming air. Within one time period, hot air should raise the bed temperature until reaching an upper bound and, conversely, cool air should decrease it to a lower limit. On the other

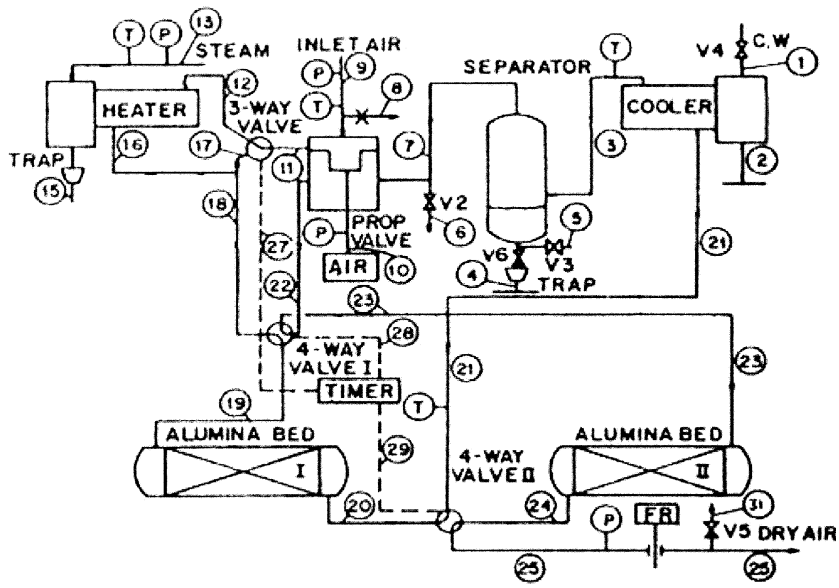


Fig. 14. The process flow diagram of a utility air drying process (Shaeiwitz et al., 1977).

Table 5
Operating procedure for fixed-bed air drying system

Time period	Valve position			Bed status	
	3W	4W-I	4W-II	Bed-I	Bed-II
1	11 → 12	18 → 19 22 → 23	20 → 21 24 → 25	Regeneration	In service
2	11 → 17	18 → 19 22 → 23	20 → 21 24 → 25	Cooling	In service
3	11 → 12	18 → 23 22 → 19	20 → 25 24 → 21	In service	Regeneration
4	11 → 17	18 → 23 22 → 19	20 → 25 24 → 21	In service	Cooling

hand, the water content is a function of the temperature of the inlet air and also the bed temperature. If both temperatures are low and the bed is unsaturated, the water content in alumina bed can be increased by passing either fresh air from environment or recycled air from the proportionating valve. Eventually, the amount of water should reach a saturation level in at most two time periods. A saturated bed cannot be used for dehumidification purpose. Therefore, hot air should be introduced in the adsorption beds to strip water from the alumina. Here, it is assumed that the bed can be dried 'completely' in one time period.

Table 6
The relationships between valve positions and stream connections

Valve	Valve position	Stream connection
3W	+	11 → 12
	−	11 → 17
4W-I	+	18 → 19 and 22 → 23
	−	18 → 23 and 22 → 19
4W-II	+	20 → 21 and 24 → 25
	−	20 → 25 and 24 → 21

From the above discussions, it is clear that the equipment states of an alumina bed are manipulated in this system by switching from one operation mode to another each time when a new period begins. These operation modes can be instituted by adjusting the positions of 3-way and 4-way valves according to Table 9. In this table, the symbols H, C, P, E and R represent different operation modes of an alumina bed. The first three are concerned with the input connections of the bed. In particular, H is used to represent the facts that the in-coming air is taken from environment and it is pre-heated; C denotes that cool fresh air is used in bed; P indicates that the entering air is obtained from the proportionating valve. Notice that these modes are defined by the positions of the 3-way valve 3W and the first 4-way valve 4W-I. On the other hand, the last two labels reflect the output connections. As mentioned

Table 7
The inputs and outputs of the second-level component models

Component	Equipment state	Input	Output
3-Way valve	+	F11	F12
		T11	T12
		C11	C12
	−	F11	F17
		T11	T17
		C11	C17
4-Way valve (I)	+	F18	F19
		T18	T19
		C18	C19
		F22	F23
		T22	T23
		C22	C23
	−	F18	F23
		T18	T23
		C18	C23
		F22	F19
		T22	T19
		C22	C19
4-Way valve (II)	+	F20	F21
		T20	T21
		C20	C21
		F24	F25
		T24	T25
		C24	C25
	−	F20	F25
		T20	T25
		C20	C25
		F24	F21
		T24	T21
		C24	C21

before, these connections are governed by the second 4-way valve 4W-II. Specifically, the out-going air can be either recycled (R) or sent downstream (E).

Since the equipment states of an alumina bed is independent of the output conditions, the corresponding PN model can be constructed by considering only the operation modes listed in the first four rows of Table 9. Although the bed temperature and water content are basically continuous quantities, a discrete version of Fig. 4 is employed here to represent their transient behaviors qualitatively. This practice is adopted mainly to reduce model complexity. As an example, let us consider the Petri net for the equipment states of Bed-I (Fig. 15). The discrete places I-T and I-M are used to represent the bed temperature and water content, respectively. The number of tokens in each place denotes the qualitative value of the corresponding parameter. An empty place represents the parameter is at its lowest level. Its upper limit can be set by the capacity, i.e. the maximum allowable token number, of the same place. In this example, the capacities of I-T and I-M are 1 and 2, respectively. A token in the place I-M denotes that the water content in Bed-I is 'partially' saturated. The other three discrete places, i.e. I-H, I-C and I-P, are used to represent the three operation modes listed in the first four rows of Table 9. Notice that the prefix 'I' in this Petri net indicates that this model is associated with Bed-I. The PN model for the equipment states of Bed-II can be obtained simply by adopting 'II' as the prefix of each place in Fig. 15.

For the alumina beds, the qualitative causal relations of input and output conditions are dependent upon not only the equipment states but also the operation modes. During normal operation, the input connections and initial states of Bed-I in each time period can be characterized with the token numbers in I-H, I-C, I-P, I-T and I-M (see Table 10). Since the bed temperature, water content and also input air temperature in the four time periods are not the same, different input–output models should be adopted accordingly. Furthermore, in addition to the conditions listed in Table 10, there are other possible scenarios which may be encountered

Table 8
The input–output relations of the one-state level-3 components

Component	Input	Output	Edge gain
Proportionating valve	F7	F11,F22	+1, +1
	T7	T22	+1
	C7	C22	+1
	F9	F11, F22	+1, +1
	T9	T11,T22	+1, +1
	C9	C11,C22	+1, +1
Mixer	F16	F18	+1
	T16	T18	+1
	C16	C18	+1
	F17	F18	+1
	T17	T18	+1
	C17	C18	+1
Air heater	F12	F16,T16	+1, −1
	T12	T16	+1
	C12	C16	+1
	F13	T16	+1
	T13	T16	+1
Cooler	F21	F3,T3,C3	+1, +1, +1
	T21	T3,C3	+1, +1
	C21	C3	+1
	F1	T3,C3	−1, −1
	T1	T3,C3	+1, +1
Separator	F3	F7	+1
	T3	T7,C7	+1, +1
	C3	C7	+1

Table 9
The relationships between valve positions and bed operation modes

Valve positions			Operation modes	
3W	4W-I	4W-II	Bed-I	Bed-II
+	+		H	P
−	+		C	P
+	−		P	H
−	−		P	C
		+	R	E
		−	E	R

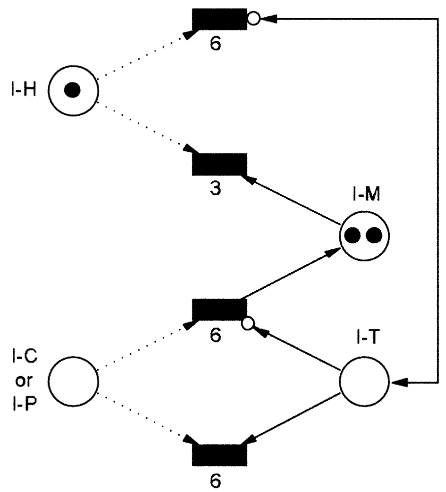


Fig. 15. The PN model describing the equipment states of Bed-I.

Table 10
The input connections and initial states of Bed-I in each time period

Time period	I-H	I-C	I-P	I-T	I-M
1	1	0	0	0	2
2	0	1	0	1	0
3	0	0	1	0	0
4	0	0	1	0	1

during abnormal operations. To facilitate hazard analysis, it is also necessary to develop the corresponding input–output models. From the facts that (1) the operation modes I-H, I-C and I-P are mutually exclusive and (2) there are only two possible token numbers in I-T (i.e. 0 and 1) and 3 in I-M (i.e. 0, 1, 2), it can be deduced that the number of all possible combinations should be 18. In this example, these conditions are classified into five groups according to Table 11 and the corresponding models are presented in the first part of Table 12. Notice that the values specified in the brackets in Table 11 are the token numbers in the corresponding places. It can be seen that the conditions listed in Table 10 are also embedded in Table 11. Thus, models 1 and 2 in Table 12 can be used under the normal operating conditions

Table 11
The input–output relations of Bed-I

Model number	Model conditions
1	I-H[1]+I-T[0]+I-M[1,2]
2	I-C[1]+I-T[1]+I-M[0,1,2]
	I-P[1]+I-T[1]+I-M[0,1,2]
3	I-P[1]+I-T[0]+I-M[0,1]
	I-C[1]+I-T[0]+I-M[0,1]
4	I-C[1]+I-T[0]+I-M[2]
	I-P[1]+I-T[0]+I-M[2]
5	I-H[1]+I-T[0]+I-M[0]
	I-H[1]+I-T[1]+I-M[0,1,2]

Table 12
The input–output relations of the multi-states level-3 components

Component	Model number	Input	Output	Gain
Alumina Bed (I)	1	F19	F20,T20,C20	+1, +1, −1
		T19	T20,C20	+1, +1
		C19	C20	+1
	2	F19	F20,T20	+1, −1
		T19	T20	+1
		C19	C20	+1
	3	F19	F20,C20	+1, +1
		T19	T20,C20	+1, +1
		C19	C20	+1
	4	F19	F20	+1
		T19	T20	+1
		C19	C20	+1
	5	F19	F20,T20	+1, +1
		T19	T20	+1
		C19	C20	+1
Alumina Bed (II)	1	F23	F24,T24,C24	+1, +1, −1
		T23	T24,C24	+1, +1
		C23	C24	+1
	2	F23	F24,T24	+1, −1
		T23	T24	+1
		C23	C24	+1
	3	F23	F24,C24	+1, +1
		T23	T24,C24	+1, +1
		C23	C24	+1
	4	F23	F24	+1
		T23	T24	+1
		C23	C24	+1
	5	F23	F24,T24	+1, +1
		T23	T24	+1
		C23	C24	+1

during time period 1 and 2, respectively, and model 3 can be used for the normal operation in both periods 3 and 4. Finally, it should be noted the input–output relations of Bed-II can be classified on the basis of Table 11. In particular, every prefix ‘I’ in this table should be replaced with an ‘II’.

Finally, all level-3 component failures considered in this example are listed in the third column of Table 13. Each failure can be described according to the model structure in Fig. 9c.

7.2.4. Level 4

It is assumed in this example that the measurement instruments are not used in implementing the operation procedure. Consequently, all level-4 component models are neglected.

7.2.4.1. The complete system model. All component models can be encapsulated in object frames and then connected according to the P&ID presented in Fig. 14. The resulting system model can be found in Fig. 16.

Table 13
The failure models of level-3 components

Component	Model number	Failure	Output deviation
Proportionating valve	–	Failing height	F11(+1), F22(−1)
Air heater	–	Steam leak into air	F16(+1), T16(+1), C16(+1)
Cooler	–	External fire	T3(+1), C3(+1)
Separator	–	Trap plugged	F7(+1), C7(+1)
Alumina Bed (I)	1	Channeling	T20(+1), C20(−1)
		Leak out	F20(−1)
	2	Channeling	T20(+1)
		Leak out	F20(−1)
	3	Channeling	C20(+1)
		Leak out	F20(−1), C20(−1)
Alumina Bed (II)	1	Channeling	T24(+1), C24(−1)
		Leak out	F24(−1)
	2	Channeling	T24(+1)
		Leak out	F24(−1)
	3	Channeling	C24(+1)
		Leak out	F24(−1), C24(−1)

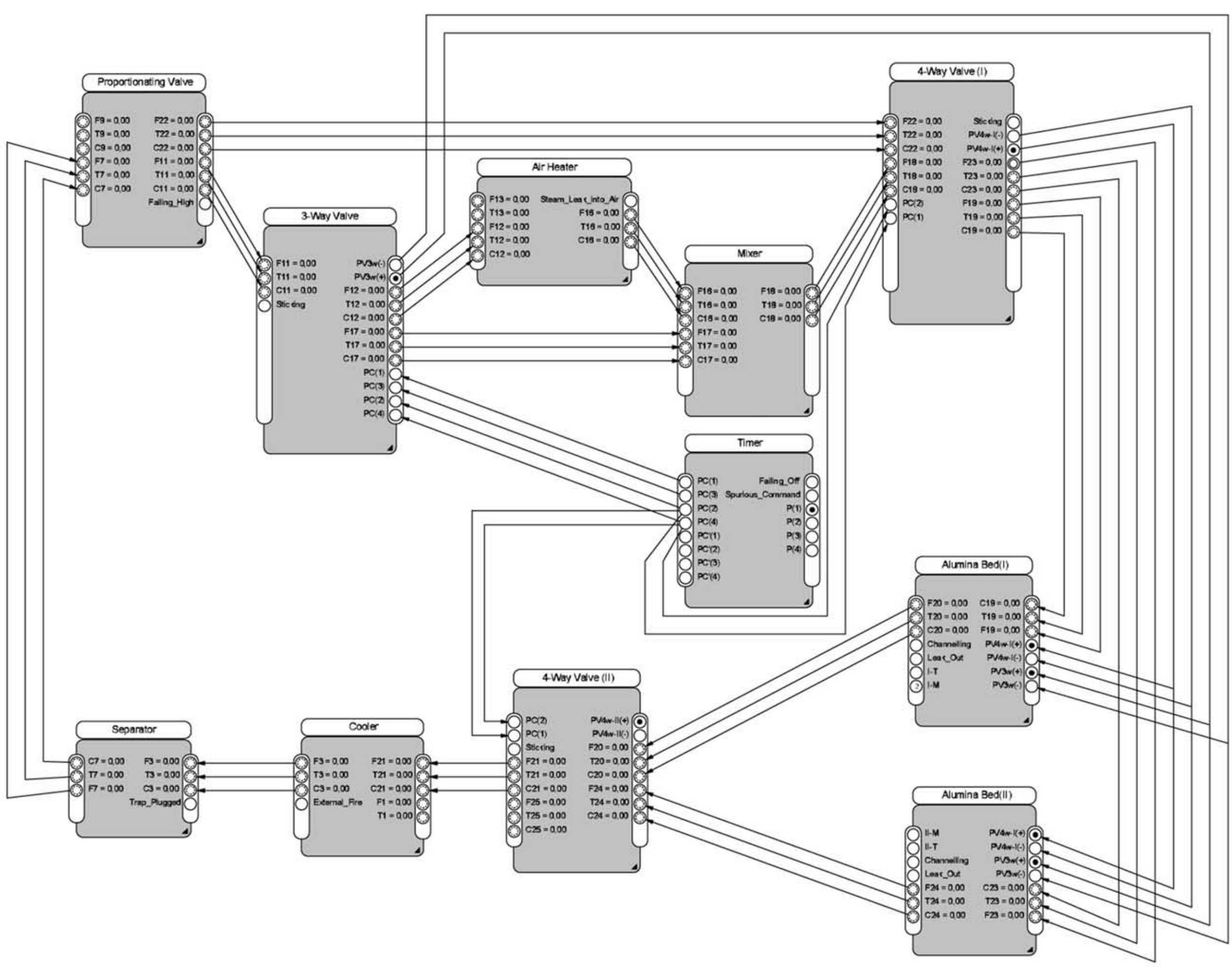


Fig. 16. The complete PN model of a utility air drying process.

7.3. Auxiliary devices

The fault propagation behaviors caused by all possible combinations of failures and/or disturbances are simulated with the Petri net presented in Fig. 16. Obviously, an extremely large number of case studies must be carried out for a comprehensive hazard analysis. It is, therefore, necessary to install additional auxiliary devices in this PN model to facilitate efficient and systematic implementation. These auxiliary devices are described as follows.

7.3.1. The triggering devices

A failure should be introduced in simulation by inserting a token in the place representing the equipment state of failed component at a designated time. This task can be performed more conveniently with the help of a failure-triggering device. The generalized version of the corresponding PN model is presented within the dotted line in Fig. 17a. In this Petri net, the delay time Δt of the transition on the left can be considered as the time increment of a clock. The places PM(i)s ($i = 1, 2, \ldots, n$) denote the failures to be triggered during a particular simulation run. Notice that the weights on the two input arcs to transition TM(i) ($i = 1, 2, \ldots, n$) are the same and they are both set to be the token number in place PM(i). Thus, the ith failure can be triggered at a designated time in simulation by assigning the appropriate number of time increments as its initial token number. Notice also that the outward arcs of the transitions TM(i)s are connected to the places representing the equipment states of failed components, i.e. the PFS(i)s in Fig. 8.

An external disturbance can also be introduced in a similar fashion. It can be observed from Fig. 14 that the external disturbances can only enter the air-drying process via three source streams, i.e. streams 1, 9 and 13. The disturbance effects can thus be simulated by putting a token in the place representing an input deviation of the heater, cooler or proportionating valve. Notice that the input–output conditions of these components can be described according to the model structure given in Fig. 5b and the deviation places $PCN_{in}^{(i)}$s are associated with their input disturbances. A disturbance triggering device can be constructed by attaching the Petri net in Fig. 17b to an appropriate transition TM(i) in Fig. 17a. Notice that a nonzero integer can be assigned as the token number of PD(i) to represent the direction of deviation. It is obvious that the Petri net in Fig. 17b can be adopted more than once to introduce multiple disturbances and, also, any combination of disturbances and failures can be triggered with the triggering devices presented in Fig. 17a and b.

7.3.2. The termination devices

It should be noted that the system model presented in Fig. 16 is a live Petri net. In other words, the simulation can proceed indefinitely even after failures and/or disturbances occur. Although VISUAL OBJECT NET++ (Drath, 1998b) can always be terminated by specifying a fixed simulation time for every possible scenario, manual examination of all simulation results is still required to identify the potential causes of system hazards. Consequently, there is a need to stop executing the computer program once a pre-determined hazard condition is reached and to automatically generate a report of the corresponding failure mechanisms.

A reasonable condition for hazard analysis may be 'H_2O concentration in stream 25 is too high.' This is due to the fact that, if the outlet air from the air-drying process contains too much water, a large number of valuable instruments downstream may be damaged. Thus, a termination mechanism can be built with a set of inhibitor arcs originated from the deviation place C25. A weight of +1 should be assigned to every one of them. These arcs are used to disable two clocks in the system. One is located in the timer and the other in the triggering device. In particular, the inhibitor arcs should be connected to transitions TC(i)s in Fig. 1b and T in Fig. 17a.

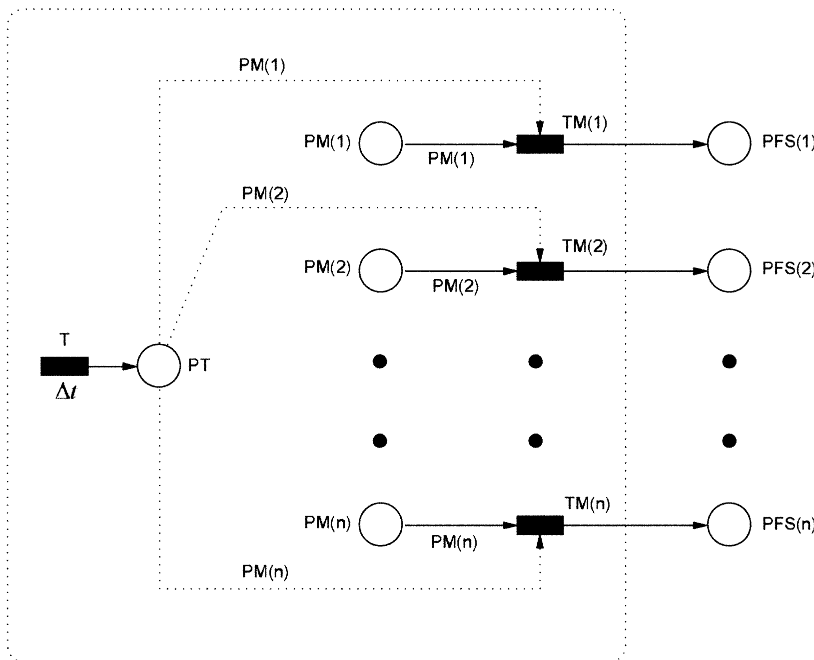
Furthermore, according to the process description, the above undesirable consequence could also be caused by:

i) temperature of served bed is too hot;
ii) adsorbents in served bed are saturated, and;
iii) inlet air temperature in served bed is too hot.

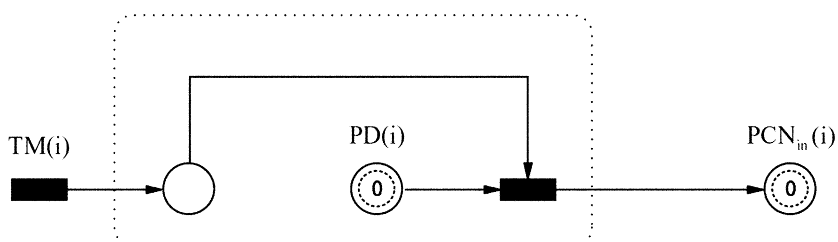
The combinations of places that cause at least one of the above three sufficient conditions in Bed-I are listed in Table 14. The same combinations can be obtained for Bed-II if all prefixes in this table are replaced by 'II'. Since water concentration in stream 25 is guaranteed to rise to an unacceptable level under these listed conditions, the same technique can be used to institute the needed termination mechanisms.

7.4. Hazard analysis

In this study, simulation runs have been carried out to confirm if a given set of failures and/or disturbances can be considered as the root cause of the designated event 'H_2O concentration in stream 25 is too high.' Notice first that the undesirable Bed-I conditions listed in Table 14 can only be reached by triggering level-1 and/or level-2 component failures. To identify the corresponding root causes, all possible combinations of timer and valve failures were thus tested in a series of exhaustive case studies. The simulation results concerning the single-failure cases are summarized in Table 15. Notice that the



(a)



(b)

Fig. 17. (a) The failure triggering device. (b) The disturbance triggering device.

Table 14
The outcome places associated with the sufficient conditions of undesirable consequence '$C25(+1)$'

Sufficient conditions	Outcome places
(i)	I-H[1]+I-E[1]+I-T[1]+I-M[0,1,2]
	I-C[1]+I-E[1]+I-T[1]+I-M[0,1,2]
	I-P[1]+I-E[1]+I-T[1]+I-M[0,1,2]
(ii)	I-H[1]+I-E[1]+I-T[0,1]+I-M[2]
	I-C[1]+I-E[1]+I-T[0,1]+I-M[2]
	I-P[1]+I-E[1]+I-T[0,1]+I-M[2]
(iii)	I-H[1]+I-E[1]+I-T[0,1]+I-M[0,1,2]

occurrence times of the designated event are specified in the second column, and the root causes and their triggering times are provided in the third column. Let us consider two scenarios resulting from the failure 'valve 3W sticking' as examples, i.e. rows 7 and 10. If valve 3W sticks in period 1, the inlet air for regeneration should pass through the heater in period 2. Thus, the regenerated bed is not cooled in the same period. Because of the fact that condition (i) is satisfied, the designated undesirable condition should occur in the next time period. On the other hand, if valve 3W sticks in period 4, the inlet air for cooling should bypass the heater in period 1 in the next cycle and thus Bed-I cannot be regenerated. When the alumina bed is in service during period 3 in the next cycle, it should still be saturated with water. Since condition (ii) is satisfied, the designated undesirable condition is bound to occur in this period.

Naturally, the above condition may also be the result of various combinations of multiple timer and valve failures. All 2-failure and 3-failure scenarios resulting in

Table 15
The single-failure causes involving level-1 and level-2 components

Outcome places	Occurrence time	Root causes
I-H[1]+I-E[1]+I-T[0]+I-M[0]	(3)	Spurious controller command to 4W-I (2)
	(3)	4W-I sticking (1)
	(3)	4W-I sticking (2)
I-H[1]+I-E[1]+I-T[0]+I-M[2]	(1)	4W-II sticking (3)
	(1)	4W-II sticking (4)
I-C[1]+I-E[1]+I-T[1]+I-M[0]	(2)	Spurious controller command to 4W-II (2)
I-P[1]+I-E[1]+I-T[1]+I-M[0]	(3)	3W sticking (1)
I-P[1]+I-E[1]+I-T[0]+I-M[2]	(1)	Clock failing off (3)
	(1)	Clock failing off (4)
	(3)	3W sticking (4)

the undesirable Bed-I conditions in Table 14 are presented in Tables 16 and 17, respectively. Let us

Table 16
The 2-failure causes involving level-1 and level-2 components

Outcome places	Occurrence time	Root causes
I-H[1]+I-E[1]+I-T[1]+I-M[0]	(2)	3W sticking (1), spurious controller command to 4W-II (2)
	(3)	3W sticking (1), 4W-I sticking (1)
	(3)	3W sticking (1), 4W-I sticking (2)
I-H[1]+I-E[1]+I-T[0]+I-M[1]	(4)	3W sticking (3), spurious controller command to 4W-I (4)
I-C[1]+I-E[1]+I-T[0]+I-M[2]	(1)	4W-II sticking (3), 3W sticking (4)
	(1)	3W sticking (2), 4W-II sticking (3)
	(1)	3W sticking (2), 4W-II sticking (4)
	(1)	3W sticking (4), 4W-II sticking (4)
	(2)	3W sticking (4), spurious controller command to 4W-II (2)
	(3)	3W sticking (4), spurious controller command to 4W-I (2)
	(3)	3W sticking (4), spurious controller command to 4W-I (4)
	(3)	3W sticking (4), 4W-I sticking (1)
	(3)	3W sticking (4), 4W-I sticking (1)
I-P[1]+I-E[1]+I-T[1]+I-M[0]	(2)	Spurious controller command to 4W-I (2) and 4W-II (2)
I-P[1]+I-E[1]+I-T[0]+I-M[2]	(1)	4W-I sticking (3), 4W-II sticking (3)
	(1)	4W-I sticking (3), 4W-II sticking (4)
	(1)	4W-I sticking (4), 4W-II sticking (4)
	(1)	4W-II sticking (3), 4W-I sticking (4)
	(1)	4W-II sticking (3), spurious controller command to 4W-I (4)
	(1)	4W-II sticking (4), spurious controller command to 4W-I (4)

Table 17
The 3-failure causes involving level-1 and level-2 components

Occurrence time	Root causes
(1)	3W sticking (2), spurious controller command to 4W-I (2), 4W-II sticking (3)
(1)	3W sticking (2), spurious controller command to 4W-I (2), 4W-II sticking (4)
(2)	3W sticking (4), 4W-I sticking (4), spurious controller command to 4W-II (2)
(2)	3W sticking (4), spurious controller command to 4W-I (2), spurious controller command to 4W-II (2)
(2)	4W-I sticking (3), 3W sticking (4), spurious controller command to 4W-II (2)
(2)	Spurious controller command to 4W-I (4), 3W sticking (4), spurious controller command to 4W-II (2)

consider the root causes shown in the 1st row of Table 16 in detail. If valve 3W sticks in period 1, the system should behave normally during the same period. If, in addition, valve 4W-II is abnormally reversed in period 2, the inlet air should be misdirected to Bed-I and it is still hot due to 3W sticking. Thus, the outlet air from Bed-I must be discharged to stream 25. Hence, the temperature and moisture content in stream 25 should be abnormally high in period 2.

As mentioned before, the level-1 and level-2 component failures reported in Tables 15–17 are only the root causes of the abnormal Bed-I states listed in Table 14. It should be noted that the undesirable consequence 'H_2O concentration in stream 25 is too high' may also be attributed to Bed-II conditions. These missing root causes can be easily recreated by subtracting two periods from the occurrence times listed in the second and third columns of Tables 15–17. Notice also that the advantages of the Petri net, models can be clearly observed from a comparison between the above results and those obtained with digraphs. Specifically, the fault propagation scenarios identified by Shaeiwitz et al. (1977) are limited to only the cases in which the basic and top events occur in the same operation period. In other words, the possibilities of earlier failure(s) causing the designated undesirable consequence in a later time period are not considered in the conventional fault-tree analysis. This restriction can be successfully removed with Petri nets in the present work.

Since the above scenarios are only concerned with level-1 and/or level-2 component failures, it is still necessary to examine other possibilities, i.e. the external disturbances and the level-3 component failures. From the P&ID presented in Fig. 14, it is clear that changes in the upstream conditions, i.e. flow rate, temperature or H_2O concentration, can be introduced into cooling water (stream 1), inlet air (stream 9) and steam (stream 13). Simulation runs can thus be carried out by installing

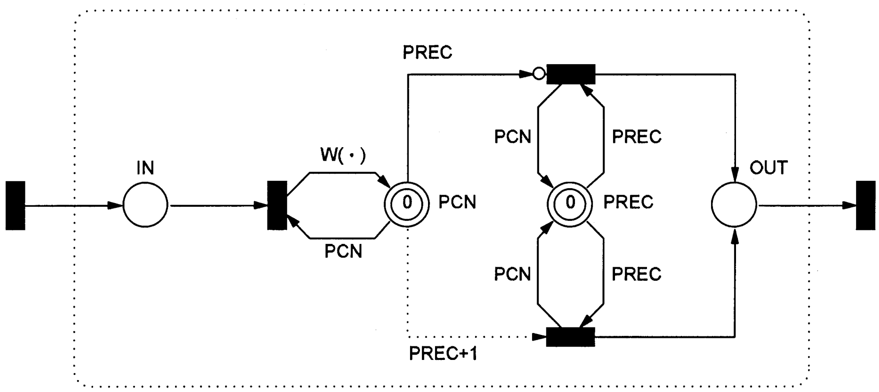


Fig. 18. The PN model of a deviation place.

the disturbance-triggering devices in Fig. 17a and b accordingly. It can be observed that the undesirable consequence can be caused by any of the following seven external disturbances during the same operation period; (1) F1(−1); (2) T1(+1); (3) F9(+1); (4) T9(+1); (5) C9(+1); (6) F13(+1); and (7) T13(+1). On the other hand, the effects of level-3 component failures in Table 13 can also be assessed by simulation. Notice that each component failure can be modeled on the basis of Fig. 9c. The effects of these failures can be introduced in simulation using the failure-triggering device presented in Fig. 17a. It was found that an increase in the H_2O concentration of stream 25 can be caused by any of the following five level-3 component failures during the same operation period:

1) proportionating valve failing high;
2) external fire near cooler;
3) separator trap plugged;
4) Bed-I channeling in period 3 and 4;
5) Bed-II channeling in period 1 and 2.

Finally, it should be noted that the possibility of the designated undesirable consequence cannot be ruled out even if it does not occur during the same period in which a disturbance or level-3 component failure is introduced. The corresponding fault propagation behaviors in later time periods can be easily simulated with the proposed system model. In order words, it is possible to trace from the event ‘C25(+1)’ to its root causes occurred in earlier time periods. Since the detailed discussions of these more subtle cases are quite lengthy, they are not included in the present paper for the sake of brevity.

8. Conclusions

A hierarchical approach is proposed in this study to construct a comprehensive PN model for any sequential operation. Systematic simulation techniques are also developed to describe the effects of a given set of component failures and/or external disturbances. By following the proposed methodology, identification and enumeration of critical fault propagation scenarios become very efficient. It is clear from the application results that the proposed PN models can indeed be used as the basis for rigorous hazard analysis.

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Appendix A: The deviation places

The properties of a deviation place can be clearly characterized with existing places and transitions. The resulting Petri net is presented in Fig. 18. Notice that the token numbers allowed in the continuous place PCN, here, are the same as those in the corresponding deviation place. Furthermore, the Petri net in Fig. 18 can be divided into two distinct components by removing PCN. The component on the left can be regarded as a ‘receiver.’ A token in the place IN indicates that its input transition has been fired. The existing token number in PCN is then replaced with a new one. This newly received token number is determined according to a user-supplied weight function $W(\bullet)$. The independent variables of this function are the token numbers of the upstream deviation places. Basically, any desired input–output relation can be specified with $W(\bullet)$. On the other hand, the component on the right can be considered as an ‘activator,’ To facilitate simulation of the propagation behaviors of external disturbances, a continuous place PREC is used, here, to store the old token number in the deviation place before a new number is received in PCN. In order to ensure that the fault propagation mechanism is activated only when the token numbers in PCN and PREC are different, an inhibitor arc and a test arc are attached to PCN as outputs to two separate transitions. Notice the weight on the former arc is PREC. Thus, its output transition is enabled if the token number in place PCN is less than that in place PREC. Notice also that the weight on the latter arc is PREC+1. This implies that, its output transition is enabled only when the token number in place PCN is greater than or equal to that in place PREC. It is obvious from this structure that only one of these two transitions can be fired at any given time. After firing, the new token number in PCN should be introduced into PREC to replace the old one and, also, a token should be inserted in place OUT to trigger its output transition.

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