Zhong HAN
Jianmin GAO

OPTYMALNA ALOKACJA ZAPEWNIAJĄCA BEZPIECZEŃSTWO W UKŁADACH PROCESOWYCH OPARTA NA PRZEPŁYWACH SIECIOWYCH

NETWORK FLOW-BASED OPTIMAL ALLOCATION FOR SAFETY IN PROCESS SYSTEMS

Bezpieczeństwo stanowi w inżynierii procesowej czynnik krytyczny, o którym należy pamiętać podczas całego czasu eksploatacji układów procesowych. W niniejszym artykule przedstawiono nową metodę optymalnej alokacji zasobów, opartą na przepływach w sieci, mającą zapewnić bezpieczeństwo układów procesowych. Istniejące optymalne alokacje zasobów wspierające bezpieczeństwo opierają się na rozwiązaniach fizycznych (np. unowocześnianiu podstawowych elementów wyposażenia i wbudowywaniu nadmiarowości) nieodpowiednich dla układów procesowych, które ulegają częstym awariom. Takie rozwiązania pociągają za sobą konieczność częstych alokacji fizycznych, które poważnie zakłócają normalne działanie całego układu. Dodatkowo, metody fizyczne stosuje się tylko wtedy, kiedy uszkodzenia układu nawarstwią sie do pewnego stopnia. Stan układu procesowego w inżynierii chemicznej często ulega wahaniom z powodu wielu czynników, takich jak niekontrolowane uwolnienie energii czy użycie niejednolitych materiałów produkcyjnych. Częste wahania mogą prowadzić do awarii układu. Konieczna jest zatem umiejętność unikania akumulacji błędów poprzez kontrolę wahań i stabilizację stanu układu, co prowadzi do zapewnienia bezpieczeństwa układu procesowego. W niniejszej pracy przedstawiamy metodę optymalnej alokacji, opartą na przepływach w sieci, która umożliwia osiągnięcie powyższego celu. Wedle nowej metody, przepływy osiągalne konstruuje się na podstawie przepływów w sieci układu, stanu wyposażenia układu oraz wymagań procesu. Wzory rozwiązań dla zmiennych stanu konstruowanych przepływów osiągalnych dają wartości korygujące, które używane są do kontrolowania wahań systemu i stabilizacji jego stanu. Prezentowane studium przypadku demonstruje możliwe zastosowania i efektywność proponowanej metody.

Słowa kluczowe: *przepływ w sieciach; przepływ osiągalny; optymalna alokacja; układ procesowy.*

Safety is a critical factor to be considered throughout the entire lifetime of process systems in process engineering. This paper presents a novel optimal resource allocation method based on network flows for assuring the safety of process systems. Existing optimal resource allocations for safety mainly depend on physical ways (for example, updating core equipments, and incorporating redundancies), which are not suitable for process systems experiencing frequent malfunctions. As a result, frequent physical allocations are needed, which severely interrupt the normal operation of the entire system. In addition, the physical methods are applied only when system faults accumulate to some extent. The state of a process system in chemical engineering often dithers due to many factors such as uncontrollable energy release and inconsistent production of materials. The frequent dithering can lead to the system failure. It is necessary to be able to avoid the accumulation of errors by controlling the dithering and stabilizing the system state, thus assuring the safety of the process system. In this paper, we propose a network flow-based optimal allocation method to achieve the above goal. Feasible flows will be constructed based on the system's network flow, system equipment status, and process requirements. The solution formulas to the state variables of the constructed feasible flows give the adjustment values, which are used to control the dithering of the system, thus stabilize the system state. A case study is given to show the application and effectiveness of the proposed method.

Keywords: *network flow; feasible flow; optimal allocation; process system.*

1. Introduction

Recently, accidents have occurred frequently in large-scale industrial production, which brings the risk and loses in equipment, personnel casualty, and environment pollution. So, guaranteeing the safety production has become an urgent problem, and safety requirements are becoming very important in process systems. At present, plenty of research results have achieved the optimal allocation for the safety and reliability of complex systems. These optimal allocations have been carried out according to the system composition structure to find weak points ([5, 14]), in terms of component states to indentify an aging degree ([12-13]), or aiming at the special facts to adopt an effective strategy [5, 20, 27-28]. By analyzing research achievements, it will be easily discovered that these optimal allocations are implemented after the system has aged to some extent and will be disable. Most allocation actions are used to exchange old equipment for new ones. However, the physical change is not suitable for the frequent operation of the process system specifically. In addition, the aging of equipment is often caused by the dithering of system states. As well as existing research results are rarely considered effects of multi-medium flow changes (matter flows, energy flows, and control flows) to device conditions ([2, 19, 30]). The safety analysis shows that the dithering of the multi-medium flow often results in the instability and danger of using the system operation in practice. So, a novel optimal allocation based on network flows for process systems is presented to stabilize system states and reduce the risk for the system safety.

The network flow theory is widely applied in systems engineering such as energy transfers ([1, 18, 25]), traffic controls

([17, 22, 24, 26]) and so on. In applications, the network flow is used to obtain feasible solutions for system designs in the initial stage ([4, 6-9, 15-16, 23, 29]) and solve the maximal flow and minimal cost in the system running and maintenance stage ([3, 10-11, 21]). In the paper, a series of models based on network flows are constructed for the process system. The network cut and load balance principle is used to analyze flow states on the basics of the network model. The optimal function solving the maximal system safety and maximal network flow is set up to achieve optimal feasible flows. Labeling algorithm is adapted to allocate flows in the network, and many variables are introduced such as the adjustable quantity, requiring adjusting quantity, adjusting quantity and so on. In addition, presented methods have complementarities and extensibilities to existing allocation methods for the system safety.

2. Analysis and modeling

2.1. Overall analysis

The network flow model is set up firstly to carry out the optimal allocation of the system safety. The inflow and outflow through network nodes are analyzed and flow change laws are explored on the basis of this model. All inflows and outflows of nodes must be cooperated in networks to keep the system's normal work. The network cut principle is used to construct the feasible flow of the network. The purpose of optimal allocations is the maximal system safety and the maximal network flows. Network flow states are always monitored in practice. Network flow states will be adjusted according to requirements of feasible flows when they run out of the normal range. Some solution formulas are defined in the paper. All adjustment variables will be calculated according to those formulas. Allocation processes are accomplished by utilizing the labeling algorithm, so, the system may be stabilized under a balance environment and the safety.

2.2. Building network model

Some formal models for network flows must be constructed to achieve the optimal allocation for process systems' safety. The following definitions of modeling are:

Definition 1: A connected directed acyclic network graph is represented by G=(V, E), the node set is represented by V, and the edge set is represented by E. Formed network model is shown in fig. 1.

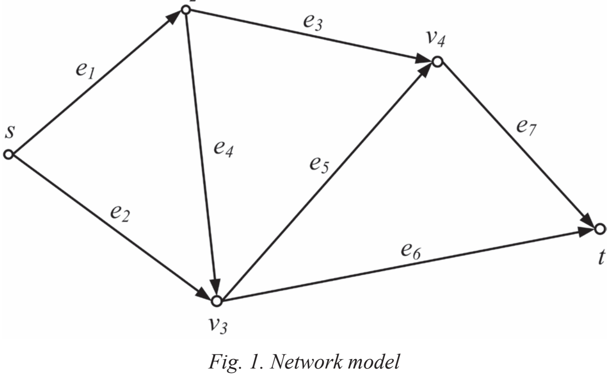


Fig. 1. Network model

Supposing v_i, $v_j \in V$ (i, j=$1...n$), then arbitrary edge e_{ij} denotes a connection between node v_i and node v_j, and there is $e_{ij} \in E$.

Definition 2: The real flux through edge e_{ij} is represented by f_{ij}, the most carrying capability of the edge e_{ij} is represented by h_{ij}, called the flux upper bound; the lowest carrying capability is represented by l_{ij}, called the flux lower bound. Then the following equation may be obtained:

$$l_{ij} \leq f_{ij} \leq h_{ij} \tag{1}$$

So, the network weight is often represented by f_{ij}, h_{ij} and l_{ij}.

Definition 3: In network G, the outflow amount denoted by $\sum_{j \in V} f_{kj}$ from node k is called flow value f of node k denoted by f_k, which is represented by $f_k = \sum_{j \in V} f_{kj}$ also; similarly, the inflow amount denoted by $\sum_{k \in V} f_{kj}$ to node k is called flow value f of node k denoted by f_j, which is represented by $f_j = \sum_{k \in V} f_{kj}$.

Definition 4: In network G, for all middle nodes m, there is the relationship as the following formula:

$$\sum_{i \in V} f_{im} = \sum_{j \in V} f_{mj} \tag{2}$$

Definition 4 is expressed that the inflow amount equals the outflow amount for each processing unit (node). Taken fig. 2 as an example to illuminate the network flow condition, a pair figures are labeled in each edge. Here, this edge capability is expressed in the first figure and this edge flux is expressed in the second figure.

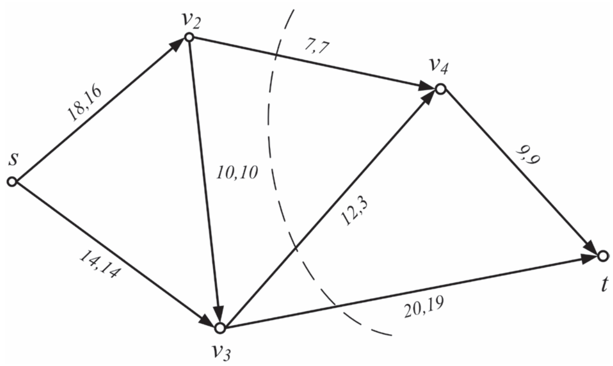


Fig. 2. Network flow

There are two characteristic nodes in a process system network, only one has the outflow, called the beginning node denoted by s; the other has the inflow, called the ending node or the final node denoted by t. All others simultaneously have the outflow and inflow, namely called the middle node denoted by m above stated. Beginning node s often represents the input equipment of the system, while ending node t often represents the output equipment. Middle node m represents different kinds of equipment such as reactors. All equipment is regarded as nodes of the system network, and the processing capacity of equipment represents the flux of this node.

For a complex network system, network performances are often considered in research. Maximal network flow and maximal system safety are concerned to solve the optimization for system safety in this paper, so, an objective function is constructed to achieve the maximal network flow and maximal system safety. Furthermore, this problem is converted into obtaining the maximal feasible flow of the network under constrained conditions of the system.

Definition 5: In network *G*, flow value *f* satisfied the maximal system safety and maximal network flow is called the optimal feasible flow.

In the following, this method will gradually get the optimal feasible flow.

2.3. Constucting feasible flows

In a real process system, some constraints are often set for the network flow, for example, the flux of each edge must be in between the maximal capability and the minimal capability, or each edge must have an upper bound and a lower bound. Under normal condition, all nodes working in the constraint range are thought to be safe. However, any abnormal dithering is caused when uncontrolled energies are released, non-uniform materials are processed, or device performances suddenly degrade. Then the dithering will result in that some nodes deviate from normal work states. Because of network characteristics of the system, the abnormal dithering is propagated to other adjacent nodes. Adjacent nodes are deflected normal work states; furthermore, the whole system will go out of the work. In the conditions, past physical allocation methods aren't obviously able to solve these kinds of problem. Therefore, a novel allocation method based on optimal feasible flow is adopted to stabilize system work states and guarantee the system safety. The network cut is used to construct the optimal feasible flow. The building process of the feasible flow is introduced as follows.

Define 6: For each edge e_{ij}, there are some constraints of upper bound t_{ij}, lower bound b_{ij}, and relationship $b_{ij} \le t_{ij}$. Supposing flow f_{ij} satisfies the following equation:

$$b_{ij} \le f_{ij} \le t_{ij} \tag{3}$$

Then, flow *f* satisfying formula (3) is called the feasible flow of this network.

In terms of equation (3), arbitrary edge has to work in the interval range, and has the upper constraint and lower constrain, which are basic function constraints of nodes composing the system. The feasible flow of system network has to exist if systems can normally operate. So, the network cut is used to analyze the conditions of feasible flow existence in the following.

For network *G*, arbitrary feasible flow *f* and arbitrary cut $(S,\overline{S})$, there is the following held:

$$\sum_{\substack{i\in S\\ j\in \overline{S}}} b_{ij} - \sum_{\substack{i\in \overline{S}\\ j\in S}} t_{ji} \le f_{ij} \le \sum_{\substack{i\in S\\ j\in \overline{S}}} t_{ij} - \sum_{\substack{i\in \overline{S}\\ j\in S}} b_{ji} \tag{4}$$

Therefore, arbitrary two cuts $(S_1,\overline{S_1}),(S_2,\overline{S_2})$ in complex network, there must are:

$$\sum_{\substack{i\in S_1\\ j\in \overline{S_1}}} b_{ij} - \sum_{\substack{i\in \overline{S_1}\\ j\in S_1}} t_{ji} \le f_{ij} \le \sum_{\substack{i\in S_1\\ j\in \overline{S_1}}} t_{ij} - \sum_{\substack{i\in \overline{S_1}\\ j\in S_1}} b_{ji} \tag{5}$$

$$\sum_{\substack{i\in S_2\\ j\in \overline{S_2}}} b_{ij} - \sum_{\substack{i\in \overline{S_2}\\ j\in S_2}} t_{ji} \le f_{ij} \le \sum_{\substack{i\in S_2\\ j\in \overline{S_2}}} t_{ij} - \sum_{\substack{i\in \overline{S_2}\\ j\in S_2}} b_{ji} \tag{6}$$

Disposing equation (5) and (6), the following formula is obtained:

$$\sum_{\substack{i\in S_1\\ j\in \overline{S_1}}} b_{ij} - \sum_{\substack{i\in \overline{S_1}\\ j\in S_1}} t_{ji} \le \sum_{\substack{i\in S_2\\ j\in \overline{S_2}}} t_{ij} - \sum_{\substack{i\in \overline{S_2}\\ j\in S_2}} b_{ji} \tag{7}$$

$$\sum_{\substack{i\in S_2\\ j\in \overline{S_2}}} b_{ij} - \sum_{\substack{i\in \overline{S_2}\\ j\in S_2}} t_{ji} \le \sum_{\substack{i\in S_1\\ j\in \overline{S_1}}} t_{ij} - \sum_{\substack{i\in \overline{S_1}\\ j\in S_1}} b_{ji} \tag{8}$$

So, the system feasible flow is existent if network flows satisfy equation (7) and (8).

If network flows satisfy the following equations (9) and (10), then the feasible flow is inexistent. It also indicates that the operating network is under instable or unsafe states.

$$\sum_{\substack{i\in S_1\\ j\in \overline{S_1}}} b_{ij} - \sum_{\substack{i\in \overline{S_1}\\ j\in S_1}} t_{ji} > \sum_{\substack{i\in S_2\\ j\in \overline{S_2}}} t_{ij} - \sum_{\substack{i\in \overline{S_2}\\ j\in S_2}} b_{ji} \tag{9}$$

$$\sum_{\substack{i\in S_2\\ j\in \overline{S_2}}} b_{ij} - \sum_{\substack{i\in \overline{S_2}\\ j\in S_2}} t_{ji} > \sum_{\substack{i\in S_1\\ j\in \overline{S_1}}} t_{ij} - \sum_{\substack{i\in \overline{S_1}\\ j\in S_1}} b_{ji} \tag{10}$$

So, in a process network, flows of all edges have constraints of upper bound t_{ij} and lower bound b_{ij}, all cuts $(S,\overline{S})$ have to satisfy formula (11). Then, it implies that this system is running in optimal work states.

$$\max f_{ij} = \min\{\sum_{\substack{i\in S\\ j\in \overline{S}}} t_{ij} - \sum_{\substack{i\in \overline{S}\\ j\in S}} b_{ji}\} \tag{11}$$

3. Optimal allocation processes

3.1. Optimal allocation functions

Now, utilizing the optimal feasible flow to establish the optimal allocation model, the maximal safety constraint function of work states for arbitrary edge e_{ij} can be determined. These variables such as the adjustable quantity, requiring adjusting quantity, and requiring adjusting state, are introduced to illuminate the optimal allocation process and to determine methods are given for these variables.

Therefore, the optimal allocation model is given as follows to realize the stability of network *G* and to guarantee the system safety.

$$\begin{aligned} &\max \sum_{e_{ij}\in E} s_{ij}(f_{ij}) \\ &s.t.\ \ If_v = a \\ &q \le f_v \le w \end{aligned} \tag{12}$$

In equation (12), e_{ij} is the edge of that the forward node is v_i and sequence node is v_j. $s_{ij}(f_{ij})$ is safety importance function of edge e_{ij}. *I* is the node relation matrix, f_v is the flux, and *a* is a constant. *q* and *w* are the flux range under process conditions, which forms constraints of the upper and lower bounds of network flows.

An auxiliary edge is designed from ending node *t* to beginning *s* for the network, edge flow value is represented by *f*. Initially, the lower bound is zero, the upper bound and safety importance is infinite. Supposing that solving flow value of network *G* is f_v, and then flow *f* equals f_v according to the flow balance principle. In this way, equation (12) may be converted into the equivalent loop to solve the flux value.

$$\begin{aligned} &\max \sum_{e_{ij}\in E} s_{ij}(f_{ij}) \\ &s.t.\ \ If_v = 0 \\ &q \le f_v \le w \end{aligned} \tag{13}$$

Further, refining ways can be carried out when equation (13) has the optimal solution, and then the following formula is further obtained:

$$\frac{\partial s_{ij}}{\partial f_{ij}} = p_{ij}\ , \quad \text{if} \quad q_{ij} \le f_{ij} \le w_{ij} \tag{14}$$

$$\frac{\partial s_{ij}}{\partial f_{ij}} \ge p_{ij}\ , \quad \text{if} \quad f_{ij} = q_{ij} \tag{15}$$

$$\frac{\partial s_{ij}}{\partial f_{ij}} \le p_{ij}\ , \quad \text{if} \quad f_{ij} = w_{ij} \tag{16}$$

In the above equation (14), (15) and (16), p_{ij} is the coupling parameter variable corresponding node v_i, v_j, is called the node state related edge e_{ij}. It represents these objective physical variables of the practice process system such as the temperature, presses, and fluxes. So, node state p_{ij} can relatively and objectively reflect work states of these physical variables. Equation (14), (15), and (16) is the optimal condition of the model function for the network flow.

If network flow f_{ij} and state p_{ij} under current status is in expandable increasable safety range and edge e_{ij} satisfies the optimal condition, which can be made out from equation (14), (15), and (16). So, when flow f_{ij} and state p_{ij} are observed they are not in the expandable increasable safety range, the edge flux or node state must be adjusted to satisfy the optimization condition. Under processing conditions, node states are often fixed, while edge fluxes are adjusted to satisfy optimal conditions. The maximal flux can be increased by adjusting the edge flux, which is called the positive maximal adjustable quantity of this edge, denoted by Δf_{ij}^{+}; while the maximal flux can be reduced by adjusting the edge flux is called the reverse maximal adjustable quantity, denoted by Δf_{ij}^{-}. The minimal flux can be increased or reduced by adjusting the edge flux corroding to practice desires is called the requiring adjusting quantity of the edge, denoted by Δf_{ij}^{n}. In addition, when optimal conditions of the edge still cannot be reached by adjusting the edge flux, it will be satisfied by adjusting node states. The minimal node state which can be increased or reduced is called the requiring adjusting state of the edge, denoted by Δp_{ij}^{+}. When $f_{ij} < q_{ij}$ or $f_{ij} > w_{ij}$ conditions hold to still satisfy the optimal conditions, then the node state will be adjusted and the requiring adjusting state is set into a positive indefinite. Simultaneously, $\left| \partial s / \partial f \right|_{f_{ij}=q_{ij}} - p_{ij} \Big|$ is defined as reverse state difference of the edge, and $\left| \partial s / \partial f \right|_{f_{ij}=w_{ij}} - p_{ij} \Big|$ as positive state difference of the edge, denoted by Δp_{ij}^{-}, Δp_{ij}^{+} respectively.

After allocation according to the requiring adjusting quantities, optimal work system will have these rules as follows:

1) If optimal conditions of network nodes or edges are satisfied, then its requiring adjusting quantities are zero. If adjustable quantities of nodes or edges are zero, it verifies that optimal conditions of edges or nodes have been satisfied.
2) If requiring adjusting quantities of all nodes and edges of network are zero, it shows that the optimal solution for the system safety has been obtained.

3.2. Algorithm description

The core idea of the algorithm for the optimal allocation is that an expandable increasable route of the network is found out and that the increasing flux is accomplished. The labeling method is adopted to find the expandable increasable route according to node states, and a series of formulas is given to obtain these values of adjusting quantities. Processes of the finding route and the increasing flux are repeated until requiring adjusting quantities of all edges are equal to zero or requiring states are equal to zero.

Supposing a route connected from beginning node s to ending node t is r in the network, defining a route direction from s to t is regarded as a positive direction; contrarily, as a reverse direction. Then edges in route r will be divided into two kinds according to these directions: one is called positive edge, whose direction is same with this route direction; another is called reverse edge, its direction is opposite with this route direction. All positive edges are denoted by r^{+}, and all reverses are denoted by r^{-}. Each edge e_{ij} belonging to r has that $e_{ij} \in r^{+}$ and Δf_{ij}^{+} is large zero, or $e_{ij} \in r^{-}$ and Δf_{ij}^{-} is large zero, they all are called an expandable increasable route of r. Algorithm is divided into four part works: adjusting quantity computation, labeling process, adjusting flux, adjusting node states. The description is given as follows.

1) Adjusting quantity computations.

Requiring adjusting quantities, positive maximal adjustable quantities, and reverse maximal adjustable quantities of edges are figured out for arbitrary initial solutions satisfied the flux balance condition.

The calculating formula of adjustable quantities for positive edges is given as follows.

$$\Delta f_{ij}^{+} = w_{ij} - f_{ij} \tag{17}$$

The formula for reverse edges is also obtained as follows.

$$\Delta f_{ij}^{-} = f_{ij} - q_{ij} \tag{18}$$

The formula of requiring quantities for positive edges is gotten.

$$\Delta f_{ij}^{n} = \min\{\Delta f_{ij}^{+}, \sum_{p \in V} f_{pt}\} \tag{19}$$

The formula of requiring quantities for reverse edges is hold as follows.

$$\Delta f_{ij}^{n} = \min\{\Delta f_{ij}^{-}, \sum_{t \in V} f_{pt}\} \tag{20}$$

Increasable flux of route r is calculated out as follows.

$$\delta = \min\{\min_{r^{+}}(\Delta f_{ij}^{+}), \min_{r^{-}}(\Delta f_{ij}^{-}), \Delta f_{ij}^{n}\} \tag{21}$$

2) Labeling process.

A. The beginning node is labeled with (s^{+},∞).

B. Non-labeled adjacent node j of node i is labeled according to the following steps.

a) When $e_{ij} \in E$ and $f_{ij} < w_{ij}$, node v_j is labeled with (v_j^{-}, δ_j); when $f_{ij} = w_{ij}$, node v_j is not labeled.

b) When $e_{ji} \in E$ and $f_{ji} > q_{ji}$, node v_j is labeled with (v_j^{-}, δ_j); when $f_{ji} = q_{ji}$, node v_j is not labeled.

c) Step 2 is continuously repeated until ending node t is labeled, or all nodes have been labeled. When ending node t is labeled, it shows that there is an expandable increasable route from s to t, the programming will jump into step 3) to adjust the flux. When ending node t can't be labeled, it shows that there is not an expandable increasable route from s to t, so the algorithm is ended, this state is also the optimal network flow.

3) Adjusting flux.

A. Each expandable increasable route begins from beginning node s. From expandable increasable route definition, it is known as $\delta > 0$. When $\delta = +\infty$, an infinite flow may be increased in the expandable increasable route, means that limited optimal solution is inexistence, and the algorithm is stopped. These illumines that expandable increasable route r is inexistence in network G, the programming jumps to step 4) to adjust node states.

B. When node v_j labeled is with (v_j^+, δ_j), then,

$f_{ij} = f_{ij} + \delta_j, \quad if \quad e_{ij} \in r^+.$

When node v_j labeled is with (v_j^-, δ_j), then,

$f_{ij} = f_{ij} - \delta_j, \quad if \quad e_{ij} \in r^-.$

C. When $v_j=s$, all labels are taken out, and the program comes back to step 2 of labeling process 2). Otherwise, it comes back to the adjusting flow process, and next node will achieve the increasing flux.

4) Adjusted node states.

When the expandable increasable route is inexistence above stated in network G, the network cut principle is adopted to adjust node states. From minimum-cut maximum-flow theorem it is known that a minimum cut $(S, \overline{S})$ is formed in network G under these states. Set E_1 and E_2 is defined as follows.

$$E_1 = \{e_{ij} \mid i \in S, j \in \overline{S}, e_{ij} \in E\}$$

$$E_2 = \{e_{ij} \mid i \in \overline{S}, j \in S, e_{ij} \in E\}$$

When using Δf_m expresses total adjustable quantities in $(S, \overline{S})$, then the following formula will be obtained:

$$\Delta f_m = \sum_{e_{ij} \in E_1} \Delta f_{ij}^+ + \sum_{e_{ij} \in E_2} \Delta f_{ij}^- \tag{22}$$

Node states in set $\overline{S}$ are adjusted according to the following formula:

$$p_j = p_i + \Delta p, \quad j \in \overline{S} \tag{23}$$

The following formula is obtained by adjusting node states to solve state adjustable quantity ΔP:

$$\Delta f_{ij}^n = \Delta f_m \tag{24}$$

Firstly, upper bound ΔP_{max} of state adjustable quantity is determined, and sets:

$$\Delta P_{\max} = \max\{\max_{e_{ij} \in E_1}(\Delta p_{ij}^+), \max_{e_{ij} \in E_2}(\Delta p_{ij}^-)\} \tag{25}$$

When $\Delta p_{\max} > \Delta p_{ij}^n$, then sets

$$\Delta P_{\max} > \Delta p_{ij}^n .$$

Taking $\Delta P = \Delta P_{\max}$, node states in set $\overline{S}$ are adjusted according to equation (9). If there is $\Delta f_{ij}^n > \Delta f$, this illuminates that the feasible solution is inexistent for original problem, then the algorithm stops. Otherwise, system safety effects caused by each edge increasing flux have astringency, so some state adjusting quantity ΔP has existed in range $[0, \Delta P_{\max}]$, and equation (25) is hold.

State adjusting quantity ΔP satisfied equation (25) will be searched out in range $[0, \Delta P_{\max}]$, then node states in set $\overline{S}$ are adjusted according to the equation (24).

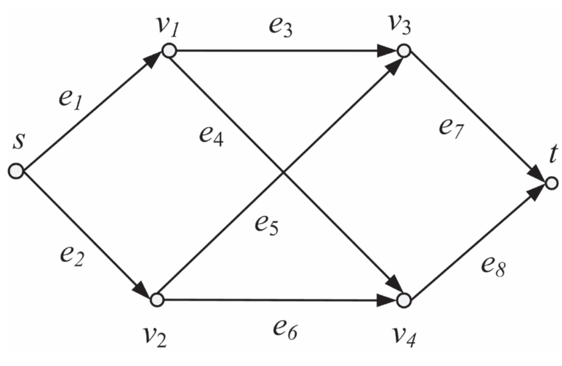
Next, the programming comes back to step 2).

4. An example

This research is partly supported by the National High-Tech Project (863) of China and by the NSF of US. The optimal allocation for the safety of process systems is a part of the whole research. The development of the application system has been completed. A heat supply exchange system of the chemical system is regarded as the research prototype. The equipment in the system is regarded as nodes of the network model, multiple medium flows in the system forms the relationship of the network model. Then, the network flow method is used to allocate the equipment by their states, and carry out the cooperation work of the whole system.

The fuel and steam is used as the raw material of the heat supply exchange system, and required energies are offered uniformly and equably for the chemical process. From fig. 3, it may see that the abstract model of the system is composed of 6 nodes and 8 edges, which express 6 processing units and 8 couplings of the system. These equipment cooperate each other to complete these functions of the oil supply, steam supply, heat transfer, and waste oil treatment.

Optimal allocation processes of the system safety are illuminated by the abstract model, given in fig. 4. The work para-



nodes	name
s	store room
v_1	knob valve 1
v_2	flanged valve 1
v_3	kindling room 1
v_4	kindling room 2
t	firebox

Fig. 3. Model of the heat supply exchange system

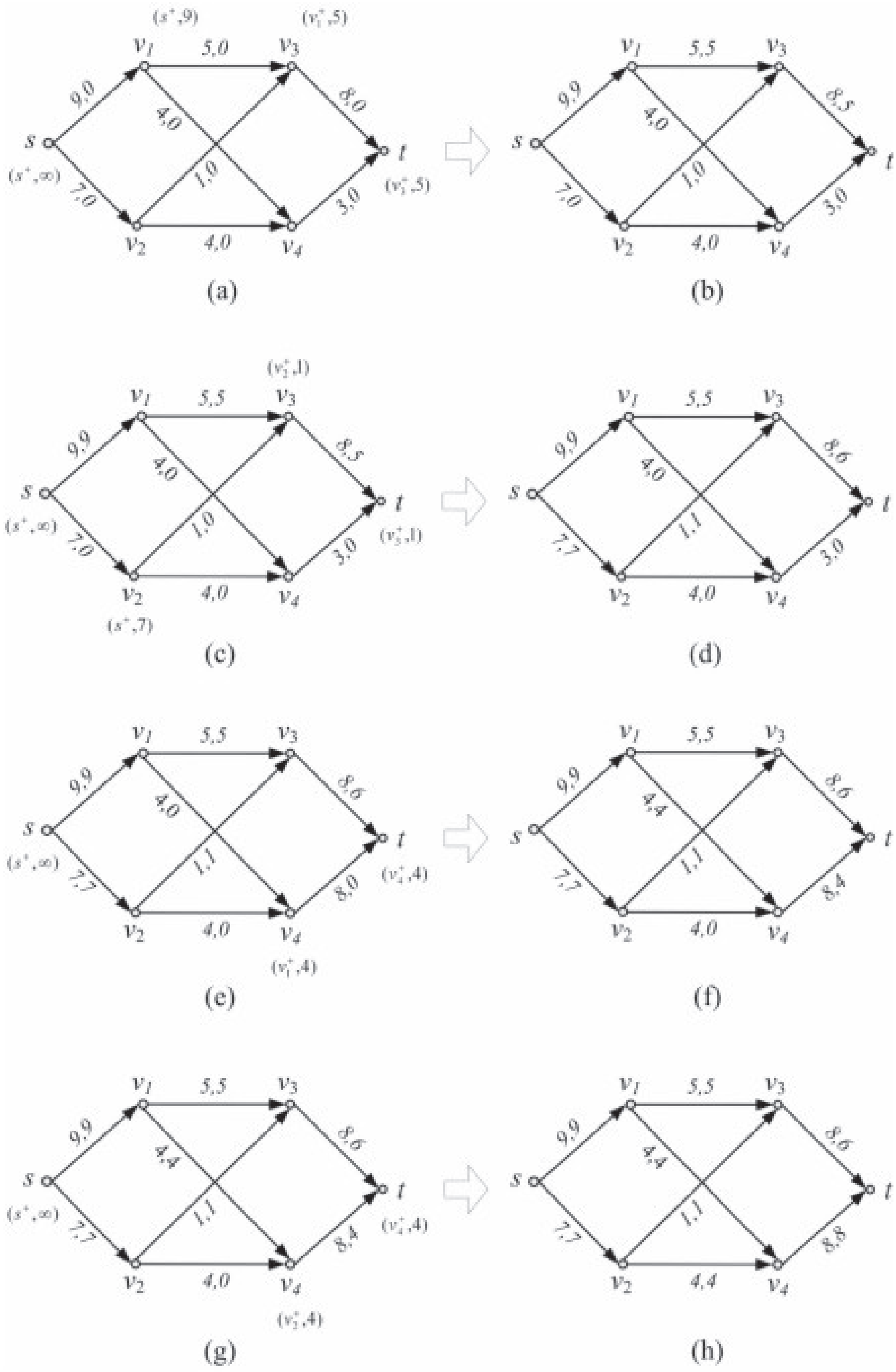


Fig. 4. Optimal allocation processes

meters of network nodes and edges under processing conditions are labeled in fig. 4(a). When the work states of monitored nodes produce a dithering and jump out limited state range, the suggested method is applied to adjust the work states of each unit, and then the system is guaranteed to go into the stable work states. Thus, a real-time optimal allocation process of the system safety is achieved.

1) Adjusting quantities of network flows are calculated.
   A. The calculated result of the increasing quantity for the beginning s is labeled $\delta = \infty$, seeing fig. 4(a).
   B. For node v_1, having $w_{s1} = 9$ and $f_{s1} = 0$, adjustable quantity $\Delta f_{s1}^{+} = w_{s1} - f_{s1} = 9$ and requiring adjusting quantity $\delta_1 = \min\{\infty, 9\} = 9$ are obtained according to formula (17).
   C. Computing processes of other nodes all are same. Labeling processes of adjacent nodes are continued until ending node t is labeled. This labeling process is illustrated in fig. 4.
2) The labeling of nodes is finished.
   A. Beginning node s is labeled with (s^{+}, ∞), seeing fig. 4(a).
   B. Adjacent node v_1 and v_2 of node s is labeled.
   C. For node v_1, having $w_{s1} = 9$ and $f_{s1} = 0$, adjustable quantity $\Delta f_{s1}^{+} = w_{s1} - f_{s1} = 9$ and requiring adjusting quantity $\delta_1 = \min\{\infty, 9\} = 9$ are obtained according to formula (17). So, node v_1 is labeled with $(s^{+}, 9)$.
   D. Labeling processes of adjacent node are continued until ending node t is labeled, and seeing fig. 4 in detail.
3) Adjusting flow processes are implemented.
   A. Expandable increasable route s-v_1-v_3-t can be obtained from s to t by the labeling process, seeing fig. 4(b).
   B. $\delta = \min\{\infty, 5\} = 5$ is figured out according to formula (21).
   C. All labels are gotten rid of, then a new network is obtained. The increasing flow and labeling process will be recalculated.
   D. The program jumps to step 4) to adjust node states if $\delta > 0$, $\delta = +\infty$. Adjusting computations is executed according to equation (22)-(25) in steps. Then the program comes back step 2).

The increasing network is finally obtained, seeing fig. 5. The maximal flow and minimal cut of this network is 14 from this figure.

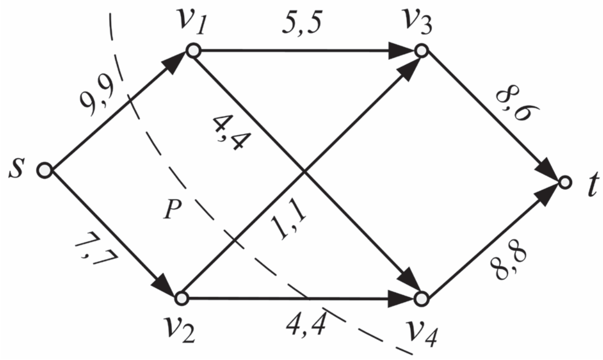


Fig. 5. Optimal network flow

5. Conclusions

The network flow-based optimal allocation for the process system safety is presented in this paper. This method has a powerful complement and extensibility to past optimal resource allocation for system safety. The suggested method can guarantee the system safety in nature because some of system faults are caused by the dithering of system states. The system safety can be guaranteed both on the whole and in detail by using the network flow. The proposed method can be effectively applied in the accident prevention and real-time state control for system safety. In the allocation, the solving of each objective function can be treated easy, and it may be very suitable in the complex system safety. However, the optimal allocation function is only given a basic definition description in this text, how the specific function is determined is a valuable study in the future, and which directly affects the allocation accuracy for the system safety.

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Dr. Zhong HAN
Prof. Jianmin GAO
State Key Laboratory for Manufacturing Systems Engineering
Xi'an Jiaotong University
Xi'an, 710049, P.R.China
e-mail: hanyaozhong@sina.com; gjm@mail.xjtu.edu.cn.