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Synthesis of Valve and Pump Operations in Complex Plants by Using Functional Modeling *

Mengchu Song* Akio Gofuku** Morten Lind***

* Graduate School of Natural Science and Technology, Okayama University, 700-8530 Okayama, Japan (e-mail: song.m.mif@s.okayama-u.ac.jp)
** Graduate School of Interdisciplinary Science and Engineering in Health Systems, Okayama University, 700-8530 Okayama, Japan (e-mail: gofuku-a@okayama-u.ac.jp)
*** Department of Electrical Engineering, Technical University of Denmark, 2800 Kongens Lyngby, Denmark (e-mail: mli@elektro.dtu.dk)

Abstract: It is crucial to provide operators supports for operation planning in complex process plants. This paper presents an operation searching approach used for synthesis of valve and pump operations to establish specific pipe routes. Instead of modeling pipeline fragments, a functional modeling methodology called Multilevel Flow Modeling (MFM) is adopted to represent plant knowledge. Relying on causality feature of MFM, one can identify required state changes of specific functions in the model, and accordingly operations. Since relationships between functions, components, and operations are independent to the modeling object, these generic principles can be implemented into a rule-based reasoning system for inferring operational conditions of pipe routes, namely, operations. An example in the literature has been used to demonstrate the presented approach and application of the software.

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Keywords: Operation planning, operating procedure synthesis, functional modeling, multilevel flow modeling, process industry.

1. INTRODUCTION

In the operation of complex process plants such as nuclear or chemical plants, it always needs operators to plan component operations to establish plant configurations that can achieve some goals. Because plant situations cannot be completely predicted, it is not realistic to prepare operation solutions for all requirements and constraints in advance. Due to complexity and unpredictability, it is necessary for operators to have external support such as relying on computer techniques for the planning activity.

Artificial Intelligence (AI) has been recognized as a solution for real world problems such as operation planning support. There are generally two aspects involved in the AI application: knowledge representation and inference. (Aylett et al., 2000) At first, the plant knowledge can be modeled in different formats such as state graphs (Ivanov et al., 1980), action template (Rivas and Rudd, 1975), and system ontology (O’Shima, 1978), which are used to develop knowledge-based systems for operation planning.

Operation planning is naturally formulated as a searching problem. Operations on specific components should be found out to achieve a required plant configuration. Since there are generally enormous numbers of components, mostly valves and pumps of pipework, there can be many operation combinations and accordingly many pipe routes, as referred to the situation of combination explosion (Rivas and Rudd, 1974). In other words, the searching space would be huge even though most of the combinations are not likely for the current plant situation. Therefore, it needs good heuristics rather than blind searching to find a small group of alternative operation solutions from the large searching space. Different modeling methodologies plant knowledge can have respective advantages to provide a proper heuristic for searching component operations.

Foulkes et al. (1988) presented a work of searching possible pipe routes to establish charging paths in a blending system. The plant knowledge is modeled by means of "fragments" of pipelines. Prolog (Programming in Logic) language is adopted as the searching approach because it is suitable for problems involving logic, pattern matching and searching. Then, requirements of operations on valves and pumps for establishing pipe routes are searched using a forward strategy. Although modeling plant knowledge as pipeline fragments is simple, it is still a massive and loss-prone work to model all the fragments.

This paper presents an operation synthesis approach based on a graphical functional modeling called Multilevel FLow Modeling (MFM) (Lind, 2011) to solve the same problem in Foulkes et al. (1988). MFM is capable to model inten-
tional knowledge of process plants in terms of system goals and functions. Not only the physical level of pipework, the other abstraction levels of plants such as abstract functions and system objectives can be represented. Moreover, the causal aspect of MFM can explain cause-consequence relations between components represented by functions, which are therefore potential for making causal reasoning, such as fault diagnosis and action planning (Lind and Zhang, 2014; Song and Gofuku, 2018).

The paper is constructed as follows: Section 2 presents the problem statement for operation searching and synthesis. Section 3 briefly introduce the theory of MFM. How to search operations on valves and pumps based on MFM is illustrated in Section 4. Section 5 presents the application of a rule-based reasoning system for synthesizing operations. Finally, conclusions are drawn in Section 6.

2. PROBLEM STATEMENT

To simplify demonstration, the system used in this paper is extracted from the original case, as shown in Fig. 1. It is a blending system used for blending materials from different sources that includes 2 storage tanks, 2 blenders, 2 pumps and 20 valves. The initial problem was to develop a software that can produce one or multiple pipe routes to achieve an operational goal of charging materials from a storage tank to a blender such as:

Transport fluid materials from a1 to b1.

Pipe routes are those descriptions of desired states of specific components in the system, which thus can be also expressed as requirements of component operations.

2.1 Modeling "Fragments"

Foulkes et al. (1988) modeled the plant knowledge by representing "fragments" of pipeline via which materials can flow through. For instance, the actual flow in the pipeline from tank a1 to the center of valve v01, namely j01 can be modeled as:

\[ \text{link a1 to j01 by [v01(op)]} \]  \hspace{1cm} (1)

The square bracket indicates conditions that are required for the statement "link a1 to j01", in the above fragment there is just one condition, i.e. v01 open, which means that materials can flow from a1 to j01 only if valve v01 is open. Some pipeline fragments can have several conditions including state requirements on multiple components, the following is the pipeline from the center of valve v10 (j10) to the center of valve v06 (j06),

\[ \text{link j10 to j06 by [v01(cl), v10(op), v06(op)]} \]  \hspace{1cm} (2)

Where op and cl represent the valve state of open and close, respectively. ru emerged in the following expressions of pipeline fragments can represent the running state of pumps. Note that the flow via valve v10 can have two possible directions, either from valve v10 to valve v06 or valve v01 to valve v10. Apart from the fragment (2), hence, the following fragment that includes valve v10 also exists,

\[ \text{link j01 to j10 by [v01(op), v10(op), v06(cl)]} \]  \hspace{1cm} (3)

The pipeline containing pump can be described as,

\[ \text{link j06 to j07 by [v06(op), p01(ru), v07(op)]} \]  \hspace{1cm} (4)

2.2 Searching for Paths

A program should be designed to collect fragments until a flow path from a specific start to a specific end can be found. For instance, a set of fragments as following can be identified to establish a flow path from a1 to b1:

\[ \text{link a1 to j01 by [v01(op)]} \]
\[ \text{link j01 to j06 by [v01(op), v10(cl), v06(op)]} \]
\[ \text{link j06 to j07 by [v06(op), p01(ru), v07(op)]} \]
\[ \text{link j07 to j38 by [v07(op), v38(op), v39(cl)]} \]
\[ \text{link j38 to j08 by [v38(op), v08(op), v09(cl)]} \]
\[ \text{link j08 to b1 by [v08(op)]} \]

Conditions in the square bracket of each identified fragment can be collected as the conditions for the found flow path. These conditions also indicate the necessary operations on valves and pumps on this identified path. In above case, therefore, the required operations are:

| v01, v06, v07, v38, v08 open | v10, v39, v09 close |
| p01 start |

3. MULTILEVEL FLOW MODELING

Instead of describing the plant topology by pipeline fragments, in this paper, a graphical functional modeling called Multilevel Flow Modeling (MFM) (Lind, 2011) is adopted for modeling plant knowledge.
3.1 Modeling Language

In MFM, plant’s intentional knowledge, such as functions and goals are decomposed and integrated along means-end and whole-part dimensions. MFM has its own modeling language, i.e. graphical symbols, as shown in Fig. 2. There are six basic functional primitives being able to describe functions that involve flows of materials, energy, and information. Relations are used to describe dependencies between functions.

| Structure | Objective | Threat |
|-----------|-----------|--------|
| Flow functions | | |
| Source | Barrier |
| Sink | Balance |
| Transport | Storage |
| Control functions | | |
| Produce | Maintain |
| Destroy | Suppress |

Fig. 2. Basic MFM symbols

3.2 Causality Feature

Besides representing plant knowledge, MFM is also able to reason about plant performance, majorly causes and consequences relationships. Once there is an evidence or assumption of a state change occurred in a function, the influence can be propagated to the neighboring functions along different consequence paths, as shown in Fig. 3. Meanwhile, this evidence or assumption can also result from the neighboring functions. Therefore, there can be several paths that can be tracked back along to know about where the influences come from. Note that above causal aspect of MFM exists in not only the whole-part dimension, but also the means-end dimensions.

Fig. 3. Reasoning about causes and consequences in MFM

Descriptions of functions by MFM are more intuitive and effective way for modeling pipelines like those expressed as "link A to B". While the capability of reasoning about causes provides a potential approach for searching establishment conditions, i.e. how functions change their states in potential pipe routes. Because functions in MFM are corresponded to components, the conditions on functions are able to provide requirements for components, i.e. operations. In Section 4, the strategy for searching operations based on MFM will be introduced.

4. OPERATION SEARCHING STRATEGY

4.1 The MFM model

Modeling of two-way pipeline Fig. 4 shows a strategy for modeling a common pipework connection, i.e. two-way pipelines, in which materials can flow along either two opposite directions. Two transport functions in opposite directions are modeled between two balance functions representing pipe branches. Because only one transport function can be valid at one time, the modeling of influence relations between transport functions and balance functions should ensure that even existence of transport function in another direction will not propagate any influence on transport function in the current direction. The modeling strategy is to use participant relation at the downstream of transport function and influencer relation is used at the upstream. In the definition of MFM, participant means that the functions pointed by the relation cannot affect the current function.

Fig. 4. Modeling of two-way pipeline by MFM

The actuator role In MFM, roles can be defined to describe how functions are related to the structural entities (Lind, 2010). If a function state can be directly achieved by an operation on the corresponding component, an actuator role can be defined for this function to describe a feature of controllability for the function. The category of the actuator role is defined according to the category of component. As shown in Fig. 5, the actuator role is graphically designed as a circle with α in the middle. In this paper, two actuator roles, i.e. valve-operation (vao) and pump-operation (puo) are defined for the transport function to indicate that there can be an operation on valve and pump, respectively. The symbol of the actuator role can be used for generating specific operations, which will be explained in the following.

Fig. 5. Graphical definition of the actuator role in MFM

The whole MFM model of the blending system is shown in Fig. 6, which will be later used as the knowledge base for the operation searching. The model is basically constructed according to the abstraction level of pipework distribution. Two-way pipelines are modeled with above modeling strategy. There is only one mass flow structure, in which two source functions represent two storage tanks,
Fig. 6. The MFM model of the blender system

and two sink functions describe two blenders. Flow trans-
fers in the system are represented by transport function
regardless of what component it represents. As for pumps
and valves, the transport function is used to describe the
flow from a piece of pipeline in the upstream of component
to that in the downstream. Balance function is used to
describe pipe branches and the other connections between
transport functions. transport functions that can be con-
trolled by components are attached with actuator roles.

4.2 A rule-based operation searching strategy

In terms of MFM, the goal of synthesizing operations
for establishing charging pipe routes could be to make the
sink function representing the prescribed blender in
a high state. Therefore, the operation searching should
start from setting an assumption of a high state in the
sink function. The causality feature of MFM will be used
for reasoning about conditions, i.e. function states for
possible pipe routes. The identified conditions will provide
requirements for operations. There are two categories of
generic reasoning rules that can be adopted for searching
desired contents in the MFM model.

Causal reasoning rules
In MFM, there exists depen-
dency relations between different function connections,
which reflect general disciplines of physical phenomenons
and thus are independent to the specific modeling ob-
ject. All the dependency relations in MFM have been
implemented as rules for reasoning about causes and con-
sequences of abnormal states in process plants. (Zhang
et al., 2013). Table 1 shows the typical causal reasoning
rules of MFM that may be used in the case of this pa-
er. Because the system is modeled with only one flow
function structure, only parts of causal reasoning rules
for MFM patterns connected by influence relations are
used. Full causal reasoning rules can be found in Zhang
et al. (2013). Note that there are many MFM patterns in
the case involved in transport-balance connections, hence
combinations of rules of No.(3-5) in Table 1 can be used
for continuous causal reasoning.

Operation identifying rules
Assumptions in functions
will provide requirements of component states, and hence

| No. | MFM pattern Assumption Conclusion (cause) |
|-----|------------------------------------------|
| 1   | tra1 high                                | tra1 high |
| 2   | tra1 high                                | sou1 high |
| 3   | tra2 high/bal1 normal                    | tra1 high |
| 4   | tra1 low/bal1 normal                     | n/a       |
| 5   | tra3 high/bal1 normal                    | tra2 high |
|     |                                         | tra1 low  |

Table 2. Rules for identifying operations

| No. | MFM pattern Assumption Conclusion (operation) |
|-----|-----------------------------------------------|
| 1   | vao1 tra1 high                               | vaol open |
| 2   | puo1 tra1 high                              | puol start |
|     | tra1 low                                   | puol stop  |

4.3 Operation Searching Process

Before searching operations, it is assumed that there has
been a charging path in the plant only it is unknown
which the path it is. The aim here is to identify the cause-
consequence relations behind this possible path. With the
knowledge base constructed based on MFM, thus, the
process of searching operations for establishing pipe routes
would be:
Step 1 Determine the sink function that represents the prescribed blender expected to be charged. Assume a high state of this sink function.

Step 2 Identify a state of a neighboring function of the initial sink function that can result in the goal state by matching a generic rule of MFM.

Step 3 If there is an actuator role that is attached to the identified function and an operation identifying rule can be matched, then generate the operation. If not, go to Step 4.

Step 4 If the function state in Step 2 is a high state of the source function that describes the prescribed source of charging paths, i.e. storage tank, then a pipe route has been found, go to Step 5. Otherwise, set this function state as the new assumption. Go to Step 2.

Step 5 Present results.

The process for searching operations is essentially similar to the rule-based method presented by Zhang et al. (2013). More rules are implemented for the special requirements. The causal reasoning rules are used for reasoning about conditions for possible pipe routes, and the operation identifying rules are used for reasoning about the operation realization for pipe routes.

5. APPLICATION

5.1 The Rule-based Reasoning System

A rule-based reasoning system has been developed by using Drools for realizing the operation searching process based on MFM. Fig. 7 shows the algorithm behind the system. The core of the system is a rule engine, which implements an optimized Rete Algorithm called ReteOO. (Kumar, 2011) The rule engine can match working memory (or facts) and production memory (or rules) to infer conclusions. Situations that multiple rules are matched can be solved by the conflict resolution strategy to select the most proper rules. Firing rules will result in actions, which may generate new facts and update the rule base. There is also truth maintenance that can be used to avoid duplicated or conflicted results of inference.

![Fig. 7. The mechanism of the rule-based reasoning system](image)

During searching operations, the first assumption on function, namely high state of the sink function can be set and stored in the working memory. One causal reasoning rule can be matched and fired to generate a new assumption on function, which will be stored in the working memory as well. Meanwhile, operation identifying rule might also be matched to generate an assumption on actuator, i.e. operation. The new assumption on function will result in firing the other rules until no rule can be matched. All inferred results that are stored in the working memory can be output as a tree structure.

5.2 The results

The rule-based reasoning system is applied into the case presented in the Section 2. In order to generate pipe routes realizing the original goal, i.e. transport fluid materials from a1 to b1, we set the consequence of establishment of possible pipe routes as the first assumption, i.e. [sin1, high] and input it into the reasoning system. The results generated by the system is a tree structure rooted by the first assumption. All the other assumptions derived from this root node are listed in the branches. The whole result for the case is not shown here. A piece of the generated tree structure shown in Fig. 8 is used for demonstrating different categories of nodes in the result.

![Fig. 8. Demonstration of node colors in the inference result](image)

Green and blue nodes mean that operation identifying rules can be matched to generate operations on pumps and valves, respectively, which are placed on above of the corresponding assumptions on functions. Grey nodes are low state of transport functions derived from high state of transport functions, and accordingly operation of closing. In reality, they are invalid to contribute to a pipe route, because we cannot expect to establish a charging by closing valves. The operation of closing valve is only valid for isolating alternative paths, which has not been discussed at the moment. Red nodes are inferred assumptions on sink functions, which means that no rules can be further matched to generate inference. Orange nodes are the other assumptions of function states.

Different pipe routes that can achieve the goal can be identified from the tree structure. Each path starting from sou1 high in the terminal branch, ending with sin1 high on the root can indicate a valid charging pipe. The
assumptions on the actuator role attached to the identified paths, therefore, are the requirements of operations on corresponding valves and pumps. Note that there must be a pump operation to provide pressure resource for each identified pipe route. In summary, there are eight pipe routes, accordingly eight operation solutions of for achieving the original goal, as follows:

(1) Open \( v_01, \) open \( v_06, \) start \( p_01, \) open \( v_07, \) open \( v_39, \) open \( v_33, \) open \( v_25, \) open \( v_15; \)

(2) Open \( v_01, \) open \( v_10, \) open \( v_11, \) open \( v12, \) start \( p_02, \) open \( v_13, \) open \( v_16, \) open \( v_17, \) open \( v_09, \) open \( v_38, \) open \( v_39, \) open \( v_33, \) open \( v_25, \) open \( v_15; \)

(3) Open \( v_01, \) open \( v_10, \) open \( v_11, \) open \( v_12, \) start \( p_02, \) open \( v_13, \) open \( v_14, \) open \( v_15; \)

(4) Open \( v_01, \) open \( v_06, \) start \( p_01, \) open \( v_07, \) open \( v_38, \) open \( v_09, \) open \( v_17, \) open \( v_16, \) open \( v_14, \) open \( v_15; \)

(5) Open \( v_01, \) open \( v_06, \) start \( p_01, \) open \( v_07, \) open \( v_38, \) open \( v_08; \)

(6) Open \( v_01, \) open \( v_10, \) open \( v_11, \) open \( v_12, \) start \( p_02, \) open \( v_13, \) open \( v_14, \) open \( v_25, \) open \( v_33, \) open \( v_39, \) open \( v_38, \) open \( v_08; \)

(7) Open \( v_01, \) open \( v_06, \) start \( p_01, \) open \( v_07, \) open \( v_39, \) open \( v_33, \) open \( v_25, \) open \( v_14, \) open \( v_16, \) open \( v_17, \) open \( v_09, \) open \( v_08; \)

(8) Open \( v_01, \) open \( v_10, \) open \( v_11, \) open \( v_12, \) start \( p_02, \) open \( v_13, \) open \( v_16, \) open \( v_17, \) open \( v_09, \) open \( v_08. \)

Apparently, (5) is the “shortest” path, that is, the pipe route that needs least equipment items, or operations, which is one of the criteria proposed in Foulkes et al. (1988).

It is also important to generate alternative paths for one goal in case of component failures in abnormal situations. With the presented reasoning system, it could be flexible to switch paths when some paths are not available due to component failures. In the future, the capacity of the reasoning system on planning alternative pipelines should be tested with some failure scenarios, in which parts of components may not be able to work.

6. CONCLUSION

Although operations of opening valves and starting pumps for establishing pipe routes of material charging can be inferred by applying the rule-based reasoning system, it is difficult to generate "off" operations, such as closing valves and stopping pumps for isolating a pipe route from all alternatives since pipe routes are found by searching influences of opening valves that can establish flows, how the influences of closing valves to isolate flows is not considered. But it is clear that at least neighboring valves of each identified pipe routes should be closed. In addition, the issue of synthesizing operation sequences after identification of pipe routes has not been discussed in the paper. The other operating constraints concerned with valves and pumps, as well as safety conditions should be further considered for an appropriate operation sequence.

MFM has advantages of describing multiple abstraction levels of plant’s intentional knowledge. The MFM model in this paper only shows an abstraction level as same as what presented in the pipeline configuration. From a larger scale of plant, systems may have different inten-

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