Generation of operating procedures for a mixing tank with a micro genetic algorithm

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ABSTRACT

This paper explores the use of a micro genetic algorithm that uses variable-length chromosomes and a seeding scheme based on tabu search. The problem is to find the sequence of actions that have to be executed in the shortest time possible, but also in a way that minimizes the possibility of situations that may endanger the plant personnel and plant facilities. The proposed approach was tested on the generation of the optimum sequences for startup and shutdown of a mixing vessel similar to the equipment used in the synthesis of acrylic acid. The results show that the proposed method outperforms the traditional GA algorithm both in terms of the quality of the solution and computational effort.

1. Introduction

A significant number of serious incidents occur in the process industry during shutdown or startups operations (IChemE, 2006). However, contrasting to industrial applications of scheduling algorithms, the generation of operating procedures is still left to expert engineers and plant personnel.

In an early study, Benson and Perkins (1997) concluded that improving the control of startups, shutdowns and grade changes presented a potential of world benefits of about 100 million US$ per year. More recently, a site study conducted by the Abnormal Situation Management Consortium revealed the average cost of $2.6 million per year due to incidents that had procedural operations as a contributing factor (Kucharyson, 2006).

The generation of operating procedures can be described as a planning problem where the objective is to find an ordered sequence of plant actions to take the process from an initial state to a goal state. In general, the sequence of actions needs not only to be carried out in the shortest time possible, but also in a way that minimizes the possibility of situations that may endanger the plant personnel or cause damages to the plant.

The generation of operating procedures has a relatively long history going back to the work of Rivas, Rudd, and Kelly (1974) whose method is based on the General Problem Solver (Batres, Soutter, Asprey, & Chung, 2002). The majority of the approaches for the

generation of operating procedures falls into one of the two categories: state-based planning or simulation-based planning approaches.

State-based planning approaches have origins in the artificial intelligence planning techniques. These planning methods represent operations as a function that consists of preconditions and effects represented as first-order predicate calculus propositions. Such representation approach works well for static environments, but is inappropriate for many real problems where the duration of an action should be considered.

One example of a state-planning approach is the method proposed by Fusillo and Powers (1987) who implement a planner in which the problem is stated as a state-space graph where operations are used to move between states. In their work, a state is defined as a vector that combines qualitative values of process variables with positions of valve actuators and pump switches.

A specific kind of state-planning approach is given by the action ordering systems in which the actions are given by the design of the plant. For example, Lakshmanan and Stephanopoulos (1988) introduced a methodology based on the planning approach proposed by Chapman (1987). Their methodology incorporates the use of a hierarchical representation of the plant structure, which is utilized for constraint propagation and subgoaling, as a strategy to reduce the search space. Another strategy in their methodology is the use of temporal constraints and binary qualitative mixing constraints. Temporal constraints are expressed in terms of precedence relations such as T should precede S. An example of their mixing constraints is "A and B should not come into contact with each other."

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Soutter and Chung (1995, 1996) describe the chemical engineering planner (CEP), which implements a non-linear, partial-order algorithm similar to the approach used by Weld (1994). In CEP, goals are translated into subgoals by means of an inference engine that uses backward chaining. This planner also implements domain knowledge for the representation of the plant topology and constraints. Specifically, constraints represent situations to be avoided such as those that prevent a heat-exchanger to be operated before starting a pump that creates a flow through the exchanger.

Some attempts have also been made to generate operating procedures for batch processes. Viswanathan, Johnsson, Srinivasan, Venkatasubramanian, and Ärzen (1998a, 1998b) describe an interactive technique that uses a hierarchical description of operations based on the procedural representation defined in ISA S88 (ISA, 1995). The construction of the procedures starts with the generation of a graph in which some of the nodes represent material flows and others represent unit procedures. Subsequently, depth-first search is used to find paths that connect raw materials with products. Finally, equipment is assigned to the unit procedures by matching against the equipment capabilities.

While some researchers identified the necessity of providing optimum plans, the above mentioned methods focused on feasibility rather on optimization of time or cost. Another limitation of such planning methods is that they can only handle qualitative constraints such as 'chemicals A and B should not be mixed together.' Simulation-based approaches attempt to address both issues.

However, little has been reported on efforts for determining operation sequences in the presence of quantitative safety constraints and dynamic behaviors. In this vein, Yang, Li, and Xu (2011) emphasize the benefits of dynamic simulation for identifying optimal startup procedures. For example, improvements can be made to operate a unit to obtain safer startup trajectories that reach the goal in less time.

Mixed-integer dynamic optimization (MIDO) that combines dynamic optimization with discrete variables can be used to obtain optimal sequences such as in the N_2, O_2, CH_4 mixture changeover reported by Galán and Barton (1997) and Barton, Banga, and Galán (2000). However, such approach is useful in situations where a globally optimal solution is not required and one can settle for plan feasibility.

In another effort, Asprey, Batres, Fuchino, and Naka (1999) proposed a two-layer method to generate startup sequences for a mixing problem similar to the one described by Galán and Barton (1997). The method proposed by Asprey et al. explicitly takes into account time optimality while maintaining realizable actions (e.g., their approach prevents actions such as opening a valve 0.05% for 0.3 s, which is not physically realizable). In order to guarantee realizable actions, the time dimension is discretized through the introduction of the *operator time constant*, which denotes the time duration for which a combination of valve positions is maintained. The upper layer uses simulated annealing to optimize the overall operations time by adjusting the *operator time constant*, which is passed to the lower layer. In the lower layer, a path-constrained optimization determines the sequence of valve operations that minimize the difference between the current mixture composition and the goal state. Due to the fact that the quantitative constraint (a flammability envelope) introduces non-convexity into the problem, the A^* (read A-star) search method is introduced. Despite the fact that the two-layer method has the ability to generate a global optimal solution, it does so at the expense of a high number of function evaluations. Moreover, keeping the same operator-time-constant for all the operations misses solutions that would otherwise be obtained with heterogeneous values for this parameter.

As investigated by Asprey et al., path constraints such as those associated to flammability envelopes result in non-convex optimization problems. For this reason, in this paper we investigate an approach based on micro genetic algorithms (μGAs) and variable-length chromosomes to generate startup and shutdown operating procedures.

μGAs are characterized by a small population size and consist of restarting the population several times while keeping the very best fit individual (Krishnakumar, 1989). Thanks to the small populations, convergence can be achieved faster and less memory is required to store the population.

Another feature of the proposed approach is the use of variable-length chromosomes. Perhaps the earliest attempt to use variable-chromosomes is the work of Robbins (1995), who applied a variable-length representation to solve the traveling salesman problem. A simple alternative is the use of a fixed-length chromosome. However, a fixed-length chromosome would have to be sufficiently large, resulting in some of the genes actually active and the rest inactive. As a result, fixed-length chromosomes would require more memory.

Variable-length chromosomes have been applied with success in artificial intelligence planning in situations that share similar characteristics to the problem considered in this paper. In a planning problem, the objective is to find an ordered sequence of actions that achieve a goal given an initial state, provided that templates for those actions are available. For example, Westerberg and Levine (2001) use variable-length chromosomes to represent feasible but not necessarily optimum plans. Their GA implementation extends traditional algorithms by incorporating a shrinking operator that deletes a randomly selected action from the parent chromosome. Brie and Morignot (2005) describe a genetic algorithm that besides the shrinking operator of Westerberg and Levine also uses an operator for enlarging a chromosome (by inserting new actions), an operator for swapping two genes, and an operator that modifies a parameter of a randomly selected action. In these two variable-length chromosome implementations, the respective algorithms are applied to the so-called blocks-world problem.

This paper is structured as follows. Section 2 describes the problem statement. Next, the proposed methodology is presented in Section 3. Then, Section 4 discusses the numerical experiments that were conducted to evaluate the proposed approach. Finally, Section 5 presents the conclusions and discussion.

2. Problem statement

We adopt time optimality as a performance criterion. Therefore, the general problem for generating operating procedures for startup or shutdown can be written as follows:

$$\text{Min} \quad A \int_{t_0}^{t_f} dt + B||x_f - x(t_f)|| \tag{1}$$

subject to

$$f(x(t), \dot{x}(t), u(t)) = 0 \tag{2}$$

$$x(t_0) = x_0 \tag{3}$$

$$g(x) \leq 0 \tag{4}$$

$$u(t) \in U, \quad U = [u_1, u_2, \ldots, u_n]^T \tag{5}$$

where $\int_{t_0}^{t_f} dt$ is the time that the system takes to get from the initial state to the final state; $x(t)$ represents the state that characterizes the evolution of the system through time; x_0 and x_f are vectors that represent the initial state and final state respectively; $u(t)$ is a vector that represents a set of operations performed at time t; are a set of algebraic differential equations describing the process behavior; $g(x)$ is a vector of inequalities representing process, safety, and