Energy Proceedings
Vol 39, 2024
ISSN 2004-2965

Predictive Scheduling of Parallel Pump Systems Based on Airport Gate Assignment

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ABSTRACT

The pipe network fuel supply system plays a crucial role in guaranteeing the secure and uninterrupted operation of the airport. The issue of high energy consumption in parallel pump systems has attracted much attention and concern. A predictive scheduling method based on airport gate assignment is proposed to achieve closed-loop control. Serving as the foundation for supply optimization, airport gate assignment problem is solved to determine corresponding gates for flight refueling. The hydraulic steady state simulation is carried out to identify the position of the lowest-pressure fuel hydrant. In order to reduce operational energy consumption, the dichotomy method is employed to determine the minimum allowable pressure at the inlet of the pipe network. Taking into account pump switch times as an indicator for pump maintenance, the optimal scheduling strategy is finally achieved through dynamic programming. Operational and maintenance costs are proved to be significantly reduced with the application of the proposed predictive scheduling strategy.

Keywords: parallel pump, pipe network, predictive control, airport gate assignment

NONMENCLATURE

Abbreviations	
VFDs	Variable Frequency Drivers
MPC	Model Predictive Control
EMPC	Economic Model Predictive Control

1. INTRODUCTION

For the sake of both economy and convenience, fuel is often supplied to aircrafts through pipe networks in large and medium-sized airports. Parallel pumps are widely employed to guarantee that the pressure at the refueling hydrants consistently meets requirements even under high-flow conditions. The optimization of pump operating costs[1], while simultaneously ensuring the safe and stable operation of the refueling system, has attracted much attention.

Given the frequent departure from the high-efficiency range, especially in systems subject to substantial demand fluctuations, pumps are often equipped with variable frequency drivers (VFDs) to improve efficiency[2]. The optimization problem of pump status and speed for minimum energy consumption under specified flow and pressure has been thoroughly studied[3,4].

Further, based on the change curves of demand flow and pressure, the open-loop dynamic optimization problem is typically addressed through a quasi-steady-state approach. When the actual demand deviates from the initially predicted demand, the open-loop dynamic optimization problem will be resolved based on the current state and adjusted future demand, which is referred to as closed-loop dynamic optimization.

Open-loop dynamic optimization problems can be solved using branch-and-bound methods[5] and heuristic algorithms[6,7]. During operation, most industrial systems can be conceptualized as Markov processes, well-suited for optimization through dynamic programming. In order to reduce the state space, a reduced dynamic programming algorithm[8] was developed to achieve optimal scheduling of a single pump, and an extended

This is a paper for 15th International Conference on Applied Energy (ICAE2023), Dec. 3-7, 2023, Doha, Qatar.

method[9] was put forward afterwards for multiple pumps.

In terms of closed-loop optimization, the model predictive control (MPC) framework finds extensive application[10,11], and its integration with economic considerations leads to the development of economic model predictive control (EMPC) techniques. Taking into account nonlinear friction properties of pipeline flow, when the decision variables include the operating statuses (on/off) of pumps, mixed integer nonlinear programming problems need to be continuously solved throughout the predictive scheduling process. A two-layer optimal control strategy[12] was proposed to reduce the computational complexity. The nonlinear EMPC is employed to determine the configuration parameters of pump stations in the upper layer. Meanwhile, the mixed-integer optimization problem is solved for pump scheduling in the lower layer. In addition to the energy consumption costs associated with pump operation, frequent starts and stops elevate the risk of pump failures, escalating maintenance expenses, and potentially disrupting systems' regular operation, which also gathers significant attention.

It has been proposed[13] that demand forecasting plays a large role in predictive scheduling optimization for parallel pumps, which can avoid unnecessary repeated pump operations. However, the flow change curves at the demand nodes are all directly provided in the studies mentioned above. Therefore, a closed-loop control framework for airport refueling systems based on predictive scheduling was proposed. Firstly, the solution to the airport gate assignment problem, a topic extensively examined, serves as demand forecast information for conducting predictive scheduling optimization for parallel pumps. Gate assignments are determined based on estimated flight arrival information and current gate occupancy. For the critical role of fuel supply pressure in influencing energy consumption during operations, the demand head is determined according to the demand of each refueling hydrant. Given that apron pipe networks typically feature a single entrance, the essential task is to identify the location of the network's lowest pressure node and subsequently determine the minimum allowable pressure using the bisection method. After forecasting demand flow and head, dynamic programming is carried out to optimize pump scheduling, all while considering maintenance costs. In the event of alterations in flight information, it is crucial to perform a re-optimization of pump scheduling to guarantee the safety and efficiency of the system's operation.

2. METHODS

The closed-loop optimization framework consists of two distinct segments: open-loop optimization and rolling correction. Within the open-loop component, there are three fundamental phases: airport gate assignment, demand head plan and pump predictive scheduling. The first two stages determine the demand flow and head, which establish the groundwork for the third stage.

2.1 Airport Gate Assignment

In order to ensure the robustness of airport gate assignments, the primary objective is to minimize the variance of all idle periods (Eq. (1)). Both uniqueness and exclusivity constraints need to be satisfied in airport gate assignment problems (Eq. (2), (3)). Each aircraft is limited to occupying a single gate and each gate can accommodate up to one aircraft during a given time period. The network simplex method is applied to achieve the minimum cost flow, which represents the optimal airport gate assignment solution.

$$\min J = \sum_{k=1}^{m}\sum_{i=1}^{n+1}(S_{i,k}x_{i,k} - \bar{S})^2 \tag{1}$$

$$\sum_{k=0}^{m} x_{ik} = 1 \tag{2}$$

$$x_{ik}x_{jk}(d_j - a_i)(d_i - a_j) \le 0 \tag{3}$$

Where n, m respectively represent the number of aircrafts and gates, $x_{i,k}$ is the decision variable indicating whether aircraft i is assigned to gate k, $S_{i,k}$ represents the length of the idle period of gate k when aircraft i arrives, $S_{n+1,k}$ represents the length of the last idle period of gate k, $\bar{S}$ represents the average length of idle periods for all gates, d, a respectively represent the departure and arrival time of the aircraft.

2.2 Demand Head Plan

Fuel supply pressure is the key to the energy consumption of pump operation. Airport refueling systems typically rely on a single oil depot to provide fuel to the apron pipe network. Therefore, the primary focus of demand head plan becomes determining the location of the lowest pressure node through hydraulic simulation. The essence of pipe network hydraulic simulation lies in the resolution of a system of equations concerning node pressure and pipe flow. In accordance with the principle of mass conservation, the total flow entering a node must equal the total flow exiting the node (Eq. (4)). The pressure differential between the inlet and the outlet is governed by pipe hydraulic characteristics (Eq. (5)). A system of nonlinear equations concerning node pressure can be derived by substituting Eq. (4) into Eq. (5), which can be solved through Newton-Raphson method. After identifying the position of the lowest pressure fuel hydrant, the bisection method is adopted to determine the lowest allowable pressure at the inlet of the pipe network.

$$q_i + \sum_{j=1}^{m_i} Q_{i,j} = 0 \tag{4}$$

$$P_{inlet} - P_{outlet} = \lambda \frac{l}{d} \frac{\rho Q^2}{2A^2} \tag{5}$$

Where q_i represents the inflow of node i, M_i represents the set of pipes connected to node i, Q_j represents the flow through pipe j, P_{inlet}, P_{outlet} respectively represent the pressure at the inlet and outlet of the pipe, λ represents friction coefficient, l represents pipe length, d represents pipe diameter, ρ represents liquid density, A represents pipe section area.

2.3 Pump Predictive Scheduling

Characterized as a Markov process, the pump scheduling problem can be resolved through dynamic programming based on demand flow and head. It's commonly believed[14,15] that parallel pump systems, consisting of pumps with identical characteristic, achieve the highest operational efficiency when operating at the same speed, which is adopted in this paper for optimal control. In the decision-making process, the state x corresponds to the number of operating pumps, while the action a is starting or stopping pumps. The action-value function Q(x, a) is the sum of the value function $V_e(x, a)$ representing the average operating power and the value function $V_p(x, a)$ representing the converted additional power consumption caused by starting or stopping the pump. When $V_p(x, a)$ is assumed to be large enough, it implies that the optimization goal is to minimize the pump switch number. Both value functions can be achieved by recurrence equations (Eq. (7), (8)). The decision path leading to the lowest cost in the final state represents the optimal pump scheduling plan.

$$Q_{k+1}(x,a) = V_{e,k+1}(x,a) + V_{p,k+1}(x,a) \tag{6}$$

$$V_{e,k+1}(x,a) = \frac{V_{e,k}(x)T_k + E_c}{T_{k+1}} \tag{7}$$

$$V_{p,k+1}(x,a) = V_{p,k}(x) + C_p \tag{8}$$

Where T_k, T_{k+1} respectively represent the time at stages k and k+1, E_c, C_p respectively represent energy consumption and converted power consumption after taking action a.

3. RESULTS AND DISCUSSIONS

Pipeline refueling is the mainstream mode of oil supply in large and medium-sized airports. It utilizes the parallel pump system to pressurize and transport aviation kerosene (the density is 800 kg/m^3 and the viscosity is 2×10^{-6} m^2/s) to refueling hydrants through the apron pipe network. The fuel depot is equipped with 5 parallel pumps (the nominal flow is 200 m^3/h and the nominal power is 110 kW). The schematic diagram of an apron pipe network with 59 pipes is shown in Fig. 1. Pipes are represented by thick solid lines, in which thicker pipes (DN300) are denoted by blue lines, and thinner pipes (DN200) are denoted by purple lines. The figure also includes black circles representing normal nodes, green squares representing hydrants, and the numbers inside the circles and squares denote the respective node numbers.

A total of 143 aircrafts expected to arrive have been designated to park at 34 gates and the assignment plan is visually presented in the form of a Gantt chart (Fig. 2). Various colored bars within the Gantt chart symbolize distinct aircrafts, with the length of each bar indicating the duration of the respective aircraft's stay. Once the assignment plan is established, the evolution of the lowest pressure hydrant over time can be obtained through pipe network hydraulic simulation. By configuring fuel hydrants' minimum pressure to 0.6 MPa for adequate refueling speed, the dichotomy method is applied to determine the pressure set value at the inlet of the pipe network like Fig. 3.

Throughout the dynamic programming process, it is imperative to guarantee that the operational flow of each pump remains within the permissible range (50~200 m^3/h). Excessive overflow may cause damage to valves and other equipment. In the event that the allowable minimum flow is excessively low, it can result in protracted and unnecessary operation of multiple pumps, thereby diminishing overall operating efficiency. Based on demand flow and head, the pump scheduling results obtained using dynamic programming are shown in Tab. 1. As the penalty function increases, the pump switch number decreases. In addition, it can be seen from the table that the increase in the pump switch number can slightly reduce the operating energy consumption. This phenomenon arises from the decrease in the number of active pumps during the intervals of pump stop and start. In contrast to the slight reduction in operating energy consumption achieved by increasing the frequency of pump starts and stops, the paramount considerations are the maintenance costs and the assurance of the safe operation of refueling systems. When the penalty function is greater than 1, the reduction in the pump switch number becomes less pronounced. Consequently, the optimal parameter choice is to set the penalty function equal to 1 and the resulting solution is depicted in Fig. 4. Pumps are cycled on and off a total of ten times over a three-hour period to maintain the refueling pressure and the working flow of each pump is within the allowable range. The proposed strategy is proved to be effective when applied to airport refueling systems.

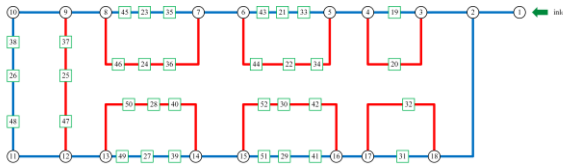

Fig. 1. Schematic diagram of pipe network

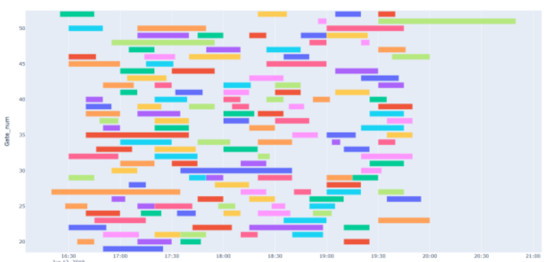

Fig. 2. Airport gate assignment

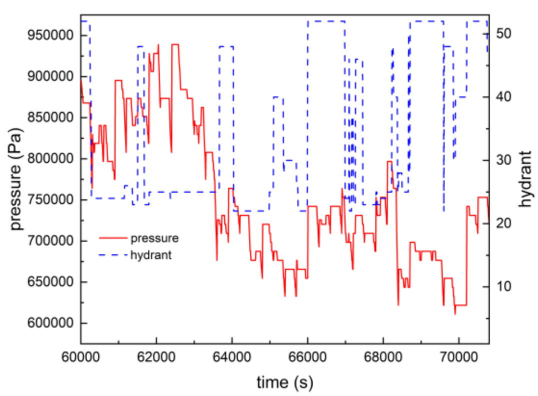

Fig. 3. Pump pressure plan

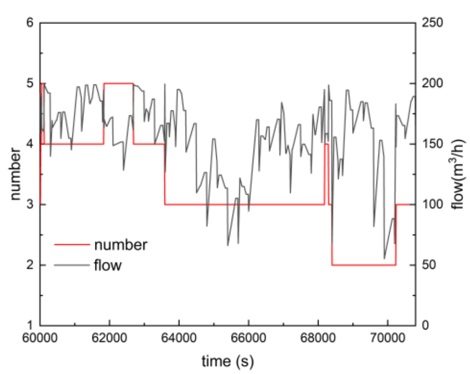

Fig. 4. Pump scheduling plan (C_p=1)

Tab. 1. Pump scheduling

Penaly C_p (kW)	Pump switch number N_s	Average operating power V_e (kW)	Total average power Q (kW)
0.001	38	185.82	185.86
0.01	30	185.85	186.15
0.1	22	185.93	188.13
1	10	187.75	197.75
10	7	189.39	259.39

4. CONCLUSIONS

The safety and stability of the fuel supply within the airport's pipe network serve as the bedrock for the smooth operation of large and medium-sized airports. Highlighting the significance of future refueling demands for predictive control, a comprehensive closed-loop control framework is proposed for airport refueling systems combined with airport gate assignment.

Initially, parking gates are strategically assigned to enhance robustness, accounting for expected flight data and current gate configuration. Subsequently, the lowest pressure nodes over time are identified based on forecasted flow demand at each hydrant and the pipe network's structure. The bisection method is employed to conduct necessary adjustments in pump head for energy saving, considering the allowable minimum pressure at refueling hydrants. Dynamic programming is finally carried out to formulate an optimal scheduling that hinges on demand flow and pressure. When flight information changes or unforeseen disturbances disrupt the originally optimized schedule, the system dynamically re-executes the scheduling process.

Verification of the proposed strategy is carried out with a parallel pump set consisting of 5 pumps and an apron pipe network with 59 pipes. The results show that while increasing the frequency of pump switch can marginally reduce operational energy consumption, the primary focus should be on maintenance costs and safe operations. When the reduction in the pump switch number becomes less pronounced, the penalty parameter is selected for optimal control. The proposed predictive control strategy is proved to be effective when applied to airport refueling systems.

ACKNOWLEDGEMENT

This work was supported by the Science Foundation of China University of Petroleum, Beijing [grand number 2462023BJRC018, 2462020YXZZ045], both of which are gratefully acknowledged.

DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

REFERENCE

[1] Wang Y, Too Yok K, Wu W, et al. Minimizing pumping energy cost in real-time operations of water distribution systems using economic model predictive control[J]. Journal of Water Resources Planning and Management, 2021, 147(7): 04021042. DOI:10.1061/(ASCE)WR.1943-5452.0001399.

[2] Tirmizi S A, Gandhidasan P, Zubair S M. Performance analysis of a chilled water system with various pumping schemes[J]. Applied energy, 2012, 100: 238-248. DOI:10.1016/j.apenergy.2012.05.052.

[3] Olszewski P. Genetic optimization and experimental verification of complex parallel pumping station with centrifugal pumps[J]. Applied Energy, 2016, 178: 527-539. DOI:10.1016/j.apenergy.2016.06.084.

[4] Da Costa Bortoni E, De Almeida R A, Viana A N C. Optimization of parallel variable-speed-driven centrifugal pumps operation[J]. Energy Efficiency, 2008, 1(3): 167-173. DOI:10.1007/s12053-008-9010-1.

[5] Costa L H M, De Athayde Prata B, Ramos H M, et al. A branch-and-bound algorithm for optimal pump scheduling in water distribution networks[J]. Water resources management, 2016, 30: 1037-1052. DOI:10.1007/s11269-015-1209-2.

[6] Lopez-Lbanez M , Prasad T D , Paechter B. Ant Colony Optimization for Optimal Control of Pumps in Water Distribution Networks[J]. Journal of Water Resources Planning & Management, 2008, 134(4):337-346. DOI:10.1061/(ASCE)0733-9496(2008)134:4(337).

[7] Moradi-Jalal M, Karney B W. Optimal design and operation of irrigation pumping stations using mathematical programming and genetic algorithm (GA)[J]. Journal of Hydraulic Research, 2008, 46(2): 237-246. DOI:10.1080/00221686.2008.9521858.

[8] Zhuan X, Xia X. Development of efficient model predictive control strategy for cost-optimal operation of a water pumping station[J]. IEEE Transactions on Control Systems Technology, 2012, 21(4): 1449-1454. DOI:10.1109/TCST.2012.2205253.

[9] Zhuan X, Xia X. Optimal operation scheduling of a pumping station with multiple pumps[J]. Applied Energy, 2013, 104: 250-257. DOI:10.1016/j.apenergy.2012.10.028.

[10]Han H, Qiao J. Nonlinear model-predictive control for industrial processes: An application to wastewater treatment process[J]. IEEE Transactions on Industrial Electronics, 2013, 61(4): 1970-1982. DOI:10.1109/TIE.2013.2266086.

[11]Ellis M, Christofides P D. Integrating dynamic economic optimization and model predictive control for optimal operation of nonlinear process systems[J]. Control Engineering Practice, 2014, 22: 242-251. DOI:10.1016/j.conengprac.2013.02.016.

[12]Wang Y, Puig V, Cembrano G. Non-linear economic model predictive control of water distribution networks[J]. Journal of Process Control, 2017, 56: 23-34. DOI:10.1016/j.jprocont.2017.05.004.

[13]Filipe J, Bessa R J, Reis M, et al. Data-driven predictive energy optimization in a wastewater pumping station[J]. Applied Energy, 2019, 252: 113423. DOI:10.1016/j.apenergy.2019.113423.

[14]Wu P, Lai Z, Wu D, et al. Optimization research of parallel pump system for improving energy efficiency[J]. Journal of Water Resources Planning and Management, 2015, 141(8): 04014094. DOI:10.1061/(ASCE)WR.1943-5452.0000493.

[15]Lai Z, Wu P, Wu D. Application of fuzzy adaptive control to a MIMO nonlinear time-delay pump-valve system[J]. ISA transactions, 2015, 57: 254-261. DOI:10.1016/j.isatra.2015.01.010.