同行专家业内评价意见书编号：20250854437

附件1

浙江工程师学院（浙江大学工程师学院）
同行专家业内评价意见书

姓名：陈铎文

学号：22260001

申报工程师职称专业类别（领域）：电子信息

浙江工程师学院（浙江大学工程师学院）制

2025年05月09日

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一、个人申报

（一）基本情况【围绕《浙江工程师学院（浙江大学工程师学院）工程类专业学位研究生工程师职称评审参考指标》，结合该专业类别(领域)工程师职称评审相关标准，举例说明】

1. 对本专业基础理论知识和专业技术知识掌握情况(不少于200字)

在攻读电子信息类控制工程专业学位期间，我系统性地掌握了过程系统工程领域的基础理论和专业技术知识。在理论方面，我深入学习了流程工业过程优化、系统辨识、模型预测控制等先进控制理论；在专业技术方面，我熟练掌握了虚拟DCS系统构建、过程动态模型构建、MATLAB/基于MPF框架的C#编程、OPC通信等技术，并深入研究了空分装置的工艺原理、停车过程特性。通过企业实践，我还掌握了深冷空分装置的工艺流程、停车操作标准，对DCS系统组态、虚拟仿真平台搭建等工程实践技能有深入了解，为解决实际工程问题奠定了坚实的理论和技术基础。

2. 工程实践的经历(不少于200字)

在杭氧集团股份有限公司实践期间，我深度参与了面向深冷空分装置的停车操作培训系统和自动停车辅助系统研发项目。该项目针对传统空分停车流程中存在的操作复杂、人工依赖性强、安全风险高等问题，开发了一种融合规则逻辑与模型预测控制的自动停车解决方案。我主要负责建立数据驱动的空分停车过程模型、设计混合整数模型预测控制算法、开发仿真验证平台和参与系统集成测试。工作内容包括现场调研与需求分析、DCS数据采集与处理、过程建模与验证、控制算法设计、OTS系统和APAS系统研发以及现场部署测试等。通过这段工程实践经历，我不仅将所学的理论知识应用于真实工业场景，还锻炼了跨部门协作能力，并深刻理解了先进控制技术在流程工业中的实际应用价值与挑战。

3. 在实际工作中综合运用所学知识解决复杂工程问题的案例（不少于1000字）

在杭氧集团股份有限公司实践期间，我参与了深冷空分装置自动停车辅助系统(APAS)的研发工作。深冷空分装置作为工业气体生产的核心设备，其停车过程涉及多变量、强耦合、非线性的动态特性，传统依靠人工操作的停车方式存在以下问题：
操作复杂，需多名操作员协同完成，人力成本高；
操作随机性强，操作质量依赖操作员经验；
安全风险高，错误操作可能导致设备损坏或安全事故；
效率低下，停车时间长，造成能源浪费。
尽管目前已实现基于硬编码规则逻辑的一键自动停车技术，但该方法灵活性不足，参数依赖性强，难以适应不同工况和环境变化。因此，需要一种更智能、更灵活的自动停车解决方案。
针对上述问题，我综合运用所学的控制理论和工程实践知识，提出了一种基于数据驱动建模和混合整数模型预测控制(MI-MPC)的自动停车辅助系统解决方案。该方案主要包括以下几个核心部分：
阶段一、数据驱动的空分过程动态建模
1. 收集和分析来自南京钢铁股份有限公司制氧厂2#20000Nm³/h外压缩深冷空分装置在2019-2024年间多次停车的DCS历史数据；
2. 引入Granger因果分析方法识别变量间的因果关系，降低冗余因果关系，提高模型可辨识性；
3. 采用两阶段渐近辨识法建立描述停车全过程的动态模型，模型能够精确捕捉设备在停车过程中的动态特性；
4. 通过与实际工业数据的对比验证了模型的准确性。

阶段二、混合整数模型预测控制算法设计
1.针对空分停车过程中存在的连续操作变量(如阀门开度)和离散操作变量(如设备启停状态)的混杂特性，设计基于MI-MPC的控制框架;
2.将空分停车过程划分为多个控制阶段，引入二值决策变量表示各阶段激活状态;
3.将标准操作规程(SOP)中的顺序规则转换为逻辑约束，并嵌入MI-MPC框架;
4.构建多目标优化函数，平衡被控变量跟踪性能、控制变量平稳性和顺序规则遵循性;
阶段三、空分停车操作培训系统(OTS)研发
1.实现一套虚拟DCS环境，通过解析和编译物理DCS组态文件，完整复现DCS功能;
2.集成前述停车过程模型作为OTS的核心过程模型;
3.实现OPC通信机制，确保虚拟DCS与停车模型之间的实时数据交互;
4.开发多维度的决策评估系统，从操作顺序规范性、操作精准性、操作时间和响应及时性等方面评价操作员决策水平。
阶段四、自动停车辅助系统(APAS)开发
1.将MI-MPC控制算法与规则逻辑相结合，开发自动停车辅助系统
2.设计模块化系统架构，解耦复杂的工艺控制过程
3.开发直观的人机交互界面，实现停车过程的可视化监控
4.设计自动模式和手动模式功能，实现一键停车和人机协同操作。
上述研究依托南京钢铁股份有限公司技术开发项目："南钢制氧厂两万外压缩深冷空分装置仿真培训、评估与决策辅助系统"的研发工作，并以第一作者身份发表了学术论文"Efficient Identification and Accurate Evaluation for Shutdown operation flow of Cryogenic Air Separation Units"，被第35届中国过程控制会议(CPCC 2024)录用。论文中提出的方法已成功应用于实际工程项目中，为企业解决了技术难题，取得了良好的应用效果和经济效益。此外，我完成的硕士学位论文"基于模型的深冷空分自动停车预测控制方法与应用研究"系统总结了我在杭氧集团实践期间的研究成果，展示了我在控制工程领域的专业能力和工程实践水平。

（二）取得的业绩（代表作）【限填3项，须提交证明原件（包括发表的论文、出版的著作、专利证书、获奖证书、科技项目立项文件或合同、企业证明等）供核实，并提供复印件一份】

1.

公开成果代表作【论文发表、专利成果、软件著作权、标准规范与行业工法制定、著作编写、科技成果获奖、学位论文等】

成果名称	成果类别 ［含论文、授权专利（含发明专利申请）、软件著作权、标准、工法、著作、获奖、学位论文等］	发表时间/授权或申请时间等	刊物名称/专利授权或申请号等	本人排名/总人数	备注
Efficient Identification and Accurate Evaluation for Shutdown Operation Flow of Cryogenic Air Separation Units	会议论文	2024年05月15日	中国过程控制会议	1/6	已收录

2. 其他代表作【主持或参与的课题研究项目、科技成果应用转化推广、企业技术难题解决方案、自主研发设计的产品或样机、技术报告、设计图纸、软课题研究报告、可行性研究报告、规划设计方案、施工或调试报告、工程实验、技术培训教材、推动行业发展中发挥的作用及取得的经济社会效益等】

（三）在校期间课程、专业实践训练及学位论文相关情况	
课程成绩情况	按课程学分核算的平均成绩： 83 分
专业实践训练时间及考核情况(具有三年及以上工作经历的不作要求)	累计时间： 1 年（要求1年及以上） 考核成绩： 81 分
本人承诺	
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2226001

二、日常表现考核评价及申报材料审核公示结果

日常表现考核评价	非定向生由德育导师考核评价、定向生由所在工作单位考核评价： ☑优秀　　□良好　　□合格　　□不合格 德育导师/定向生所在工作单位分管领导签字（公章）：徐刚　2025 年 5 月 26 日
申报材料审核公示	根据评审条件，工程师学院已对申报人员进行材料审核（学位课程成绩、专业实践训练时间及考核、学位论文、代表作等情况），并将符合要求的申报材料在学院网站公示不少于5个工作日，具体公示结果如下： □通过　　□不通过（具体原因：　　） 工程师学院教学管理办公室审核签字（公章）：　　年　月　日

浙 江 大 学 研 究 生 院

攻读硕士学位研究生成绩表

学号：22260001	姓名：陈铎文	性别：男	学院：工程师学院	专业：控制工程	学制：2.5年
毕业时最低应获：26.0学分		已获得：30.0学分		入学年月：2022-09	毕业年月：
学位证书号：			毕业证书号：		授予学位：

学习时间	课程名称	备注	学分	成绩	课程性质	学习时间	课程名称	备注	学分	成绩	课程性质
2022-2023学年秋季学期	研究生英语		2.0	免修	公共学位课	2022-2023学年冬季学期	产业技术发展前沿		1.5	88	专业学位课
2022-2023学年秋季学期	工程技术创新前沿		1.5	81	专业学位课	2022-2023学年冬季学期	最优化与最优控制		2.0	70	专业选修课
2022-2023学年秋季学期	数值计算方法		2.0	93	专业选修课	2022-2023学年春季学期	自然辩证法概论		1.0	84	公共学位课
2022-2023学年秋季学期	研究生英语能力提升		1.0	免修	跨专业课	2022-2023学年夏季学期	研究生论文写作指导		1.0	91	专业学位课
2022-2023学年秋季学期	研究生英语基础技能		1.0	免修	公共学位课	2022-2023学年春夏学期	优化算法		3.0	76	专业选修课
2022-2023学年秋季学期	线性系统理论		2.0	84	专业选修课	2022-2023学年春夏学期	高阶工程认知实践		3.0	86	专业学位课
2022-2023学年秋冬学期	工程伦理		2.0	87	公共学位课	2022-2023学年春夏学期	人工智能制造技术		3.0	78	专业学位课
2022-2023学年冬季学期	新时代中国特色社会主义理论与实践		2.0	92	公共学位课		硕士生读书报告		2.0	通过	

说明：1. 研究生课程按三种方法计分：百分制，两级制（通过、不通过），五级制（优、良、中、及格、不及格）。

2. 备注中"*"表示重修课程。

学院成绩校核章：

成绩校核人：张梦依

打印日期：2025-06-03

浙江大学研究生（60）成绩校核章

第35届中国过程控制会议论文集 会议论文集

Efficient Identification and Accurate Evaluation for Shutdown Operation Flow of Cryogenic Air Separation Units

Duowen Chen[1] Guanghui Yang[2,3] Hongfeng Lou[4] Xiongfeng Feng[2] Zuhua Xu[3] Zhijiang Shao[2,3]
1.Department of Polytechnic, Zhejiang University 2.Huzhou Institute of Industrial Control Technology
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4.Hangzhou Oxygen Plant Group Co., Ltd.

摘要： During the operation of air separation units(ASU), planned short-term shutdowns are often required to ensure a balance between supply and demand of downstream air separation products, and maintain equipment performance and ensure production safety. Making the device shut down smoothly and safely is a key measure in air separation production. However, this process highly relies on manual participation and carries risks and uncertainties. In response to this practical demand, we propose an ASU Shut...
更多

关键词： Air Separation Unit; Shut down; Identification algorithm; Evaluation algorithm; Operation flow;

会议名称： 第35届中国过程控制会议

会议时间： 2024-07-25

会议地点： 中国海南三亚

专辑： 工程科技Ⅰ辑

专题： 无机化工

DOI： 10.26914/c.cnkihy.2024.020171

分类号： TQ116.11

第 35 届中国过程控制会议（CPCC2024）

录用通知

尊敬的作者：

首先感谢您对中国过程控制会议的支持！

第 35 届中国过程控制会议论文审稿工作已经全部结束。经过程序委员会的严格评审，我们高兴地通知您，您的以下论文已被录取。我们在此诚挚地邀请您参加将于 2024 年 7 月 25-27 日在中国·三亚举办的 CPCC2024 并宣读您的成果。

论文编号: 0286

题目: Efficient Identification and Accurate Evaluation for Shutdown Operation Flow of Cryogenic Air Separation Units

作者: Duowen Chen, Guanghui Yang, Hongfeng Lou, XIONGFENG FENG

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如果您有任何问题欢迎您随时与会议秘书处联系。

李少远

第 35 届中国过程控制会议程序委员会主席

2024 年 5 月 30 日

Efficient Identification and Accurate Evaluation for Shutdown Operation Flow of Cryogenic Air Separation Units

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Abstract: During the operation of air separation units(ASU), planned short-term shutdowns are often required to ensure a balance between supply and demand of downstream air separation products, and maintain equipment performance and ensure production safety. Making the device shut down smoothly and safely is a key measure in air separation production. However, this process highly relies on manual participation and carries risks and uncertainties. In response to this practical demand, we propose an ASU Shutdown operation flow assistance system (SOFAS). We firstly build a standard logical model based on the actual shutdown process and develop algorithms to assist in executing standardized and safe shutdown operations. Then, we propose an operation flow identification algorithm to identify the shutdown operation flow, and an evaluation algorithm to quantitatively analyze the efficiency and safety of the operation flow using two performance indicators. Finally, the effectiveness of the method was verified through experimental analysis using the actual operational data of ASU.

Key Words: Air Separation Unit, Shut down, Identification algorithm, Evaluation algorithm, Operation flow

1 Introduction

Air separation unit(ASU) separates products such as nitrogen, oxygen, argon, etc., from the air. Industrial air separation production mainly uses the cryogenic rectification method, which utilizes the differences in the relative volatility of the components in the air. ASU is an important equipment in the national economic field, widely used in fields such as steel, pharmaceuticals, semiconductors, petrochemicals, metallurgy, aerospace [1-3].

Air separation production often faces planned short-term shutdown during operation to keep the balance between supply and demand of downstream air separation products, and maintain equipment performance and ensuring production safety [4]. ASU Shutdown requires operators to strictly follow the shutdown operation tickets, shutdown plans, and operating procedures, involving a series of complex safety measures and operational steps. Safe and stable shutdown of the device is a key measure in air separation production, which helps to extend the service life of the equipment, improve production efficiency, reduce failure rates, and ensure the normal operation of the production process and the economic benefits of the enterprise.

Most ASU Shutdown operations are highly dependent on the participation of operators, and the existing automation systems cannot completely replace manual operations. Operators must follow the guidance on the shutdown operation tickets to perform a series of complex shutdown steps. Although in some cases, the flexibility of manual shutdowns does not appear to have a significant impact on the shutdown results on the surface, there are still risks and uncertainties from a deeper perspective in terms of operational safety and equipment stability. In order to improve the efficiency and reliability of ASU Shutdown, reduce the potential safety risks caused by human errors, it is particularly necessary to adopt a more efficient and reliable auxiliary shutdown strategy. In this article, we propose a new method for identifying and evaluating the operation flow of ASU Shutdown processes, based on the operational data of the unit, technical platforms and logical models, in response to this practical need [5]. This method aims to assist operators in performing standardized and safe shutdown operations through precise operation flow identification and evaluation, while also enhancing their skills and ability to respond to emergency situations, reducing human errors to prevent potential accidents, and thereby improving the safety standards and operational level of the entire air separation industry.

2 Air Separation Unit Shutdown - Externally Compressed Air Separation Process

2.1 Externally Compressed Air Separation Process

A typical external compressed cryogenic air separation process mainly includes air filter (AF), main air compressor (MAC), air cooling tower(ACT), molecular sieves absorbers(MSA), booster expander (BE), main heat exchanger (MHE), high pressure column(HPC), low pressure column(LPC), crude argon column 1 (CAC-I), crude argon column 2 (CAC-II) and pure argon column (PAC), shown as Fig. 1. Feed air is firstly filtered by the AF, compressed by the MAC, then cooled by the ACT, and subsequently purified by the MSA to remove impurities,water vapor, and carbon dioxide. The purified air is divided into two streams.The majority of the air exchanges heat with the reflux gas (pure oxygen, pure nitrogen, waste nitrogen, etc.) in the MHE and enters the HPC, while a smaller portion of the air is compressed and expanded by the BE to the liquefaction temperature and enters the LPC after exchanging heat in the MHE. In LPC, the air is initially separated into liquid nitrogen(LIN) and oxygen-enriched liquid air, with a portion of liquid nitrogen sent back to HPC for reflux,, a portion sent to the top of the LPC through a sub-cooler for reflux, and a portion sent as liquid products to the storage tank. After passing through the sub-cooler, a portion of the oxygen-enrich liquid air is sent to the middle of the LPC for reflux, and another portion is sent to the upper part of the CAC-II. Gaseous nitrogen(GAN) is produced by the gaseous nitrogen in the top of the LPC after heat exchange in the MHE. in the bottom of the LPC, liquid oxygen is produced, with a portion used as liquid oxygen(LOX) and another portion used to generate gaseous oxygen(GOX), which are respectively sent to storage tanks and user pipelines. A side flow extracted from LPC is sent to CAC-I for further separation to produce argon products. The bottom product of CAC-I is sent back to LPC, and the crude argon in the top is sent to CAC-II. The bottom component of CAC-II is sent to CAC-I, and the top component is sent to PAC. Cruse argon is denitrogenated in PAC, and liquid argon(LAR) is produced at the bottom of PAC, and part of it is directly used as the product, while the other part is sent into MHE to produce gaseous argon(GAR).

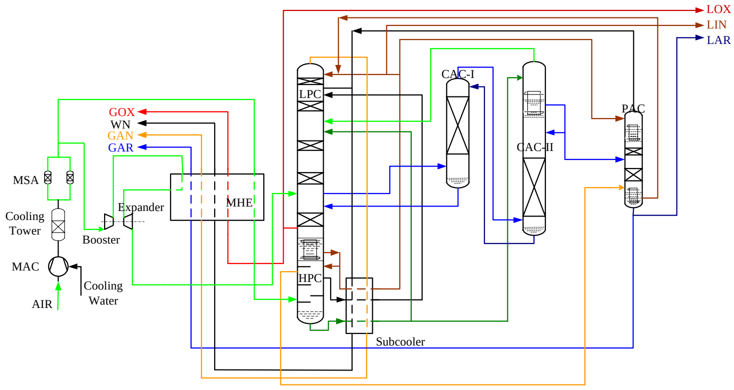

Fig. 1. A diagram of externally compressed air separation process

2.2 Air Separation Shutdown Process

The ASU Shutdown requires following a set of standard operating procedures, which can be divided into multiple processes in sequence according to the operating logic, including shutting down the oxygen compressor, the nitrogen compressor, the storage tank inlet, the argon system, the main distillation system, the BE, the MSA, the pre cooling system(mainly ACT), and the MAC, and finally replacing the sealing gas source, as shown in Fig. 2. There are many problems with ASU Shutdown in practical operation. The operation ticket referred to in ASU Shutdown does not follow a fixed and unchanging sequence, but is flexibly executed based on the actual situation and the operator's judgment, resulting in strong subjectivity in operators' operation. For example, when shutting down the BE， the operator will decide based on personal experience and operating habits whether to pre reduce the speed of the BE to to below a specific value. In addition, ASU Shutdown often require multiple operators to collaborate and coordinate actions by observing variables on the DCS interface and communicating over the phone. However, this approach may lead to parallel or chaotic sequence of operation steps. The above-mentioned differentiated shutdown operations can sometimes cause serious accidents. In 2006, a temporary ASU Shutdown was carried out in the air separation workshop of a fertilizer plant. Due to negligence, the operator opened the liquid oxygen discharge valve in the acetylene separator, causing the liquid oxygen to flow into the indoor trench and evaporate rapidly, ultimately leading to a gas explosion accident [6]. In addition to the uncertainty caused by human factors, emergency situations may also be encountered during the operation of ASU. In an ASU workshop of a certain steel company, the malfunction of the liquid level gauge caused an abnormality in the I/O module, resulting in fluctuations in the simulated input signal, Subsequently, the outlet pressure of the air compressor exceeded the pressure, triggering an interlock, causing the air compressor to dissipate and the ASU to shut down [7]. On a night in 2013, due to a sudden increase in atmospheric carbon dioxide content at the inlet of the air compressor, carbon dioxide broke through the molecular sieves absorbers and blocked the main heat exchanger, causing the ASU to shut down [8]. These unexpected situations require operators to maintain high operational proficiency and adaptability to perform emergency shutdown or cooperate with ASU interlocking shutdown.

In response to the above issues, we have established a detailed ASU Shutdown logical model based on shutdown operation tickets and on-site operator experience. Based on the logical model, we propose a method for identifying and quantitatively evaluating the ASU Shutdown operation flow.

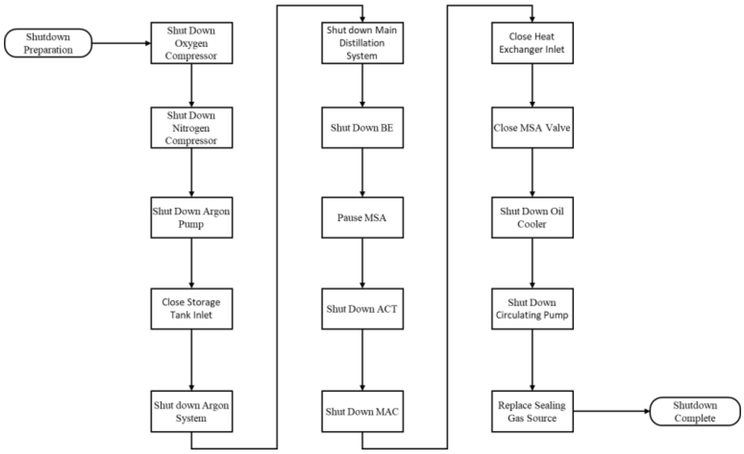

Fig. 2. Main flow chart of ASU Shutdown

3 ASU Shutdown operation flow assistance system(SOFAS)

The core of SOFAS is as follows.

Logical model: Based on the operation ticket and the ASU operators' practical experience, a shutdown logical model was constructed. This model provides a detailed description of the entire shutdown process, including changes in unit status, operator actions, expected sequence and state transition conditions. The model is the underlying logic of the identification algorithm and serves as a reference for evaluating the algorithm. The main part is shown in Fig. 2.

Operation flow identification algorithm: The identification algorithm analyzes the data collected by the DCS, which involves analyzing the actions of operators and changes in unit status to identify various key stages in the shutdown process.

Operation flow evaluation algorithm: The evaluation algorithm quantitatively analyzes the identified shutdown operation flow to evaluate its consistency and efficiency compared to standard operating procedures.

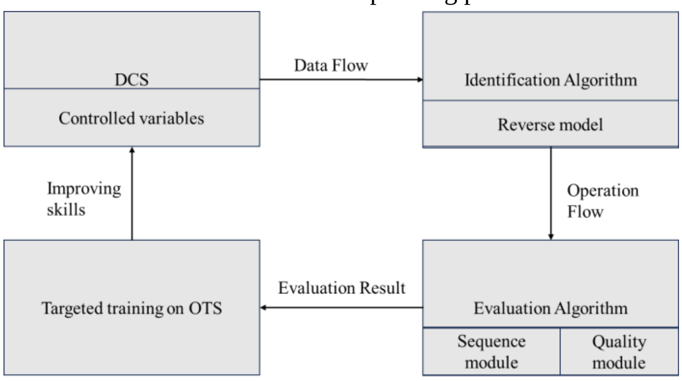

Fig. 3. Operational flow shutdown assistance system framework

3.1 Operation flow identification algorithm

The operation flow identification algorithm, based on the logical model, includes multiple independent modules, each designed to scan the operation of the corresponding subprocess in the ASU Shutdown process. Due to some on-site manual operation information not being recorded by DCS, a total of 7 typical shutdown sub processes modules were designed, including shutting down the oxygen compressor, nitrogen compressor, argon system, main distillation system, BE, MAC and MHE intake, covering the main operations of ASU Shutdown. State update functions were written based on their respective logical models. These modules get operational data such as pressure, temperature, valve opening value, and operation switch values from DCS, predict possible operating variables through a set of pre established reverse transfer function models from the controlled variables to the corresponding control variables, and independently identify the current status of each subprocess based on experience preset parameters and thresholds. For example, the status update function of the oxygen compressor checks the sensor readings, status switch values, and operating variables related to the oxygen compressor, such as outlet pressure, operation switch values, and oxygen compressor vent valve opening. Based on these data, the oxygen compressor module determines whether the oxygen compressor is running normally, closing a certain valve, or has already stopped. If the oxygen compressor vent valve is detected to be open at any time, the current timestamp and the corresponding subsystem's new status will be recorded.

In addition, to improve the flexibility of the algorithm, parameterized configurations have been introduced, which allow for adjusting key thresholds and conversion conditions based on different parking needs and device characteristics without modifying the source code itself. By updating an external configuration file, these parameters can be easily updated and maintained, thereby achieving adaptability and scalability for different air separation devices.

3.2 Operation flow evaluation algorithm

In previous algorithmic research on operational evaluation, most studies have employed strictly sequential evaluation methods, where operators must follow specific steps and transition conditions to perform operations [9,10]. This is effective for training in standardized process tasks, however, for tasks such as ASU shutdown, this approach greatly limits the flexibility of operation, leading to operation rigidity.

In this study, we adopt a sequential evaluation module with a certain degree of flexibility, combined with a quality evaluation module, to provide a comprehensive and complete operational evaluation. two key evaluation indicators were selected as follows.

(a) Completion Time(CT)

CT directly reflects the efficiency of shutdown operation. Shorter completion time helps to reduce product release rate and lower energy consumption costs. The score of CT can be calculated as follows:

$$S_1 = \frac{T_{standard}}{T_{Operator}} \times 100 \tag{1}$$

where $T_{Operator}$ represents the actual time spent by the operator to complete the shutdown operation, while $T_{standard}$ is a benchmark time for comparison, which can be the theoretical parking time simulated by the parking model according to the standard parking process. ω_1 is the weighing factor of S_1.

(b) Deviation Degree(DD)

DD reflects the difference between the actual shutdown operation flow and the standard process, which is an important indicator for measuring the consistency of operation and the degree of standardization. To quantify DD, the following steps need to be taken.

Identify operation flow from raw data. Using identification algorithm to scan DCS data and OTS standard shutdown model simulated data separately to obtain the actual operation flow and standard operation flow, including each operator action, unit status change, and timestamp.

Operation flow match. Match the actual operation flow with the standard operation flow.

Deviation Identification. Identify the differences between the actual operation flow and the standard operation flow, and classify them as a type of deviation, such as additional operations, missed operations, errors in operation sequence, and deviations in operation conditions.

Deviation quantification. Specify the types of deviation as shown in Table 1. Quantify deviation using the deviation index. 0 is the minimum deviation index, indicating that a single actual operation fully complies with the standard process; 4 is the maximum deviation index. Assign values to different types of deviations in each sub process based on the degree of impact of actual deviations on the shutdown process, as shown in Table 2.

In the context of our research, we have implemented a Dynamic Time Warping (DTW) algorithm to match the shutdown operation sequences, where each operation is assigned a weight reflecting its significance in the process. The DTW algorithm is adept at aligning two temporal sequences, which in our case are the actual and standard shutdown sequences, by stretching or compressing the time axis to find an optimal match. To account for the varying importance of operations, we introduce a weighting factor wo for each operation oo in the sequence. This weight is determined by expert knowledge and reflects the operation's impact on safety, efficiency, or regulatory compliance. The local distance measure d(ta,ts) between two operations ta from the actual sequence and ts from the standard sequence is then modified as follows:

$$d'(t_a, t_s) = \omega_a \cdot \omega_s \cdot d(t_a, t_s) \tag{2}$$

where ω_a and ω_s are the weights of the respective operations. The cumulative cost $C(i, j)$ at each step (i, j) in the DTW matrix is updated to incorporate these weights, calculated as:

$$C(i, j) = \min\left(C(i-1, j), C(i, j-1), C(i-1, j-1) + d'(t_{a_i}, t_{s_j})\right) \tag{3}$$

where t_{a_i} and t_{s_j} are the operations from the actual and standard sequences at indices i and j, respectively. The total deviation TD is then the sum of the weighted distances along the optimal warping path, given by:

$$DD = \sum_{(i,j)\epsilon path} d'(t_{a_i}, t_{s_j}) \tag{4}$$

This approach allows us to quantify the deviation between the actual and standard shutdown sequences with a sensitivity to the criticality of each operation, providing a more nuanced evaluation of the shutdown process.

The evaluation algorithm calculates the DD for each sub process according to the rules in Table 2, and calculates S_2 as follows:

$$S_2 = 100 - \frac{TD}{TD_{max}} \times 100 \tag{5}$$

TD_{max} is the maximum theoretical deviation value of the entire process, calculated as 85 in our process case.

The final score is weighted by the scores of two indicators:

$$S_{final} = \sum_i^2 \omega_i S_i \tag{6}$$

where ω_i is the indicator weight. When evaluating the operation flow, we place greater emphasis on the level of process standards, hence we set $\omega_1 = 0.3$, $\omega_2 = 0.7$. The higher the S_{final}, the closer the actual operation process is to the standard process.

Table 1. Deviation type and corresponding description

Deviation Type	Description	Deviation Index
No deviation	Completely identical to the standard operation flow	0
Additional peration	Actual execution of steps that do not exist in the standard process	0~4
Missed operation	The steps that exist in the standard process were not actually executed.	1~4
Disordered operation	The steps were executed, but the order of execution is different from the standard process.	0~4
Operation of numerical deviation	The steps were executed, but there was a deviation in the operating values	1~4

Table 2. Deviation index of different sub processes for each deviation type

	Oxygen Compressor	Assist Oxygen Compressor	Nitrogen Compressor	Argon System	Main Distillation System	Expander	Air Compressor	Heat Exchanger
Missed, additional, disorered operation within the sub process	4	1	2	2	1	4	4	3
Disordered operation between sub processes	2	2	2	2	2	2	2	2

4 Experimental Analysis

We validate the effectiveness of the proposed ASU Shutdown operation flow identification and evaluation algorithm in this section. Using the operating data of an externally compressed ASU with nominal capacity of 20,000 Nm^3/h at the Gas Supply Company of Nanjing Iron Steel United Co., Ltd.

4.1 Operation flow identification and analysis

Scan the DCS data and the theoretical shutdown data simulated by the OTS standard shutdown model using identification algorithms, and obtain the actual operation flow and theoretical operation flow respectively, with the latter used as the standard operation flow.
Fig. 4 shows the output standard operating flow, where the standard shutdown process takes 318 seconds from 'starting the OC shutdown program' to 'MHE in shutdown'.

Fig. 5 shows the flow of the first shutdown operation. After comparing with the standard operation flow, it can be found that there were no missed or additional operations in this operation flow, but the nitrogen compressor was stopped about four hours earlier than the oxygen compressor. After analysis, it was found that due to the relatively small demand for nitrogen as a subsidiary product, the nitrogen supply is often adjusted based on real-time demand. Even during normal operation of the ASU, the nitrogen compressor frequently starts up and shuts down. Therefore, when the ASU begins to stop, the nitrogen compressor is often already shut down in advance. In addition, the sub processes of stopping the argon system, MAC, MHE inlets, can be seen from the operation flow that there are interspersed operations, which is caused by the collaborative operation of multiple operators.

Fig. 6 shows the second shutdown operation flow. When scanning the initial timestamp, the nitrogen compressor was already in a shutdown state. After further exploration, it was found that the nitrogen compressor had stopped early two days ago to balance the downstream nitrogen supply and demand. At the same time, this shutdown also has the same problem of multiple sub processes interspersed operations as the first shutdown. In addition, the valves of the argon system have not been fully adjusted in place. Among them, V751 valve is the exhaust gas discharge valve of PAC, which should have been fully closed in the standard process to prevent negative pressure from entering the tower. However, the actual process maintains a 40% opening throughout the entire process; The V757 valve should have been fully open in the standard process to transfer the liquid argon from the kettle of PAC to the CAC-I, so that the argon system can quickly accumulate cold energy during the next startup. However, in this shutdown process, it was fully closed instead. In addition, the algorithm detected unconventional shutdown operations when shutting down the MAC. After fully opening the air compressor vent valve, the operator did not first close the guide vanes to 15%, but directly pressed the stop MAC button. During the shutdown process, excessive guide vanes may cause the MAC to experience surging, seriously affecting its lifespan, which is a very non compliant operation.

From the above analysis, it can be seen that due to differences in production conditions before shutdown, difficulty in coordinating with multiple operators, and non-standard shutdown operations, the actual operation process time of the two times is much longer than the standard operation flow, and the operation sequence is significantly different from the standard process. Relatively speaking, the first shutdown process is more standardized. In the following section, a quantitative evaluation will be conducted on five stops, including the two mentioned above.

Timestamp	Oxygen Compressor	Assist Oxygen Compressor	Nitrogen Compressor	Argon System	Main Distillation System	Expander	Main Air Compressor	Main Heat Exchanger
2024/4/23 7:50:00	OC in operation		NC in operation	Argon System in operation	MDS in operation	BE in operation	MAC in operation	MHE in operation
2024/4/23 8:00:06	Start the OC shutdown program							
2024/4/23 8:00:18	Valve V3304 fully open							
2024/4/23 8:00:25	Valve V3303 fully open							
2024/4/23 8:00:34	Valve V3306 powered off							
2024/4/23 8:00:39	OC in shutdown							
2024/4/23 8:00:53		Vent valve V103 fully open						
2024/4/23 8:01:16			NC in shutdown					
2024/4/23 8:01:47			Vent valve V105 fully open					
2024/4/23 8:02:09				Valve adjustment in progress(V701,V706,V707,V711,V751,V757)				
2024/4/23 8:02:11				Valve adjustment in progress(V701,V706,V707,V711,V751,V757)				
2024/4/23 8:02:12				Valve adjustment in progress(V701,V706,V707,V711,V751,V757)				
2024/4/23 8:02:15				Valve adjustment in progress(V701,V706,V707,V711,V751,V757)				
2024/4/23 8:02:16				Valve adjustment in progress(V701,V706,V707,V711,V751,V757)				
2024/4/23 8:02:19				Valve adjustment in progress(V701,V706,V707,V711,V751,V757)				
2024/4/23 8:02:24				Valve adjustment in progress(V701,V706,V707,V711,V751,V757)				
2024/4/23 8:03:13					Valve V1 and V3 closed			
2024/4/23 8:03:32						Return valve fully open		
2024/4/23 8:03:46						Turn nozzle down		
2024/4/23 8:03:49						Press the manual stop button		
2024/4/23 8:04:04							Vent valve fully open	
2024/4/23 8:04:22							Turn guide vane down	
2024/4/23 8:05:06							MAC in shutdown	
2024/4/23 8:05:10								MHE intake closed(V111,V112,V113,V11
2024/4/23 8:05:14								MHE intake closed(V111,V112,V113,V11
2024/4/23 8:05:19								MHE intake closed(V111,V112,V113,V11
2024/4/23 8:05:24								MHE in shutdown

Fig. 4. The Standard shutdown operation flow

Timestamp	Oxygen Compressor	Assist Oxygen Compressor	Nitrogen Compressor	Argon System	Main Distillation System	Expander	Air Compressor	Heat Exchanger
2024/3/12 8:00:01	OC in operation		NC in operation	Argon System in operation	MDS in operation	BE in operation	MAC in operation	MHE in operation
2024/3/12 8:01:50			NC in shutdown					
2024/3/12 8:02:19			Vent valve V105 fully open					
2024/3/12 11:59:07	Start the OC shutdown program							
2024/3/12 12:00:03	Valve V3304 fully open							
2024/3/12 12:00:47	Valve V3303 fully open							
2024/3/12 12:00:48	Valve V3306 powered off							
2024/3/12 12:00:53	OC in shutdown							
2024/3/12 12:00:54		Vent valve V103 fully open						
2024/3/12 12:01:27				Valve adjustment in progress(V701,V706,V707,V711,V751,V757)				
2024/3/12 12:01:52				Valve adjustment in progress(V701,V706,V707,V711,V751,V757)				
2024/3/12 12:02:00				Valve adjustment in progress(V701,V706,V707,V711,V751,V757)				
2024/3/12 12:02:08				Valve adjustment in progress(V701,V706,V707,V711,V751,V757)				
2024/3/12 12:02:15				Valve adjustment in progress(V701,V706,V707,V711,V751,V757)				
2024/3/12 12:03:26						Return valve fully open		
2024/3/12 12:03:34						Turn nozzle down		
2024/3/12 12:03:42						Press the manual stop button		
2024/3/12 12:05:39							Vent valve fully open	
2024/3/12 12:06:25								MHE intake closed(V111,
2024/3/12 12:06:27							Turn guide vane down	
2024/3/12 12:06:34								MHE intake closed(V111,
2024/3/12 12:06:40								MHE intake closed(V111,
2024/3/12 12:06:47								MHE in shutdown
2024/3/12 12:06:59							MAC in shutdown	
2024/3/12 12:09:23				Valve adjustment in progress(V701,V706,V707,V711,V751,V757)				
2024/3/12 12:09:55				Valve adjustment in progress(V701,V706,V707,V711,V751,V757)				
2024/3/12 12:10:25					Valve V1 and V3 closed			

Fig. 5. The first shutdown operation flow

Timestamp	Oxygen Compressor	Assist Oxygen Compress	Nitrogen Compressor	Argon System	Main Distillation System	Expander	Air Compressor	Heat Exchanger
2024/4/7 15:00:01	OC in operation		NC in shutdown	Argon System in operation	MDS in operation	BE in operation	MAC in operation	MHE in operation
2024/4/7 15:09:11	Start the OC shutdown program							
2024/4/7 15:15:40	Valve V3304 fully open							
2024/4/7 15:18:01		Vent valve V103 fully open						
2024/4/7 15:18:27	Valve V3303 fully open							
2024/4/7 15:18:28	Valve V3306 powered off							
2024/4/7 15:18:46	OC in shutdown							
2024/4/7 15:20:45				Valve adjustment in progress(V701,V706,V707,V711,V751,V757)		Return valve fully open		
2024/4/7 15:20:54				Valve adjustment in progress(V701,V706,V707,V711,V751,V757)				
2024/4/7 15:21:02				Valve adjustment in progress(V701,V706,V707,V711,V751,V757)		Turn nozzle down		
2024/4/7 15:21:09				Valve adjustment in progress(V701,V706,V707,V711,V751,V757)				
2024/4/7 15:21:11						Press the manual stop button		
2024/4/7 15:23:16							Vent valve fully open	
2024/4/7 15:23:40							MAC shutdown in disorder	MHE intake closed(V
2024/4/7 15:23:46								MHE intake closed(V
2024/4/7 15:23:51							MAC in shutdown	
2024/4/7 15:23:52								MHE intake closed(V
2024/4/7 15:23:59								MHE in shutdown
2024/4/7 15:24:57					Valve V1 and V3 closed			
2024/4/7 15:25:42				Valve adjustment in progress(V701,V706,V707,V711,V751,V757)				

Fig. 6. The second shutdown operation flow

4.2 Operation flow evaluation and analysis

On the basis of identifying and analyzing the operation flow, quantitatively evaluate and analyze the operation flow.

The indicators for evaluating the operation flow include CT(Completion Time) and DD(Deviation Degree), and the benchmark used is the standard operation flow.

In the first shutdown process, the nitrogen compressor was stopped 4 hours at 08:01:50 before the oxygen compressor was stopped. If the nitrogen compressor is considered as the starting point and the entire stop time is calculated to reach 14915 seconds, the completion time index s1 for the first stop will be only 2.13 points(out of 100 points). For the convenience of comparing multiple shutdown processes with each other, intercept the first shutdown data and considering the time starting point as 11:59:07, though resulting in missing nitrogen compressor shutdown operations and a decrease in S_2 score. The completion time is 678 seconds and the score for S_1 is 47 points. The valve of the argon system was not fully adjusted during the second shutdown, and the final operation was considered as the end point of the stop. Therefore, the completion time is 991 seconds, and the score for S_1 is 32 points.

Evaluate the DD, with a deviation index of 18 and a score of 79 for the first shutdown as shown in Table 3, and a deviation index of 28 and a score of 67 for the second shutdown as shown in Table 4. Taking Table 3 as an example, the table shows the times of deviation and total deviation values involved in each sub process during the first shutdown.

In addition to the first two stops, we continued to test the parking data for three more times and summarized the scoring results in Fig. 7.

After investigation, the first shutdown was planned and notified three days in advance. The workshop arranged five skilled operators. The fourth shutdown was temporary and only notified three hours in advance. Among the five operators, two had less parking experience. It can be seen that temporary shutdown is more prone to operational errors and non-standard operations due to its suddenness.

Table 3. Deviation degree indicator for the first shutdown

	Oxygen Compressor	Assist Oxygen Compressor	Nitrogen Compressor	Argon System	Main Distillation System	Expander	Air Compressor	Heat Exchanger	TD(Total Deviation)	S2
Missed, additional, disorered operation within the sub process	0	0	0	0	0	0	0	0		
Disordered operation between sub processes	1	1	0	3	3	0	1	0		
Deviation index	2	2	0	6	6	0	2	0	18	79

Table 4. Deviation degree indicator for the second shutdown

	Oxygen Compressor	Assist Oxygen Compressor	Nitrogen Compressor	Argon System	Main Distillation System	Expander	Air Compressor	Heat Exchanger	TD(Total Deviation)	S2
Missed, additional, disorered operation within the sub process	0	0	0	1	0	1	0	0		
Disordered operation between sub processes	2	1	0	4	3	0	1	0		
Deviation index	4	2	0	10	6	4	2	0	28	67

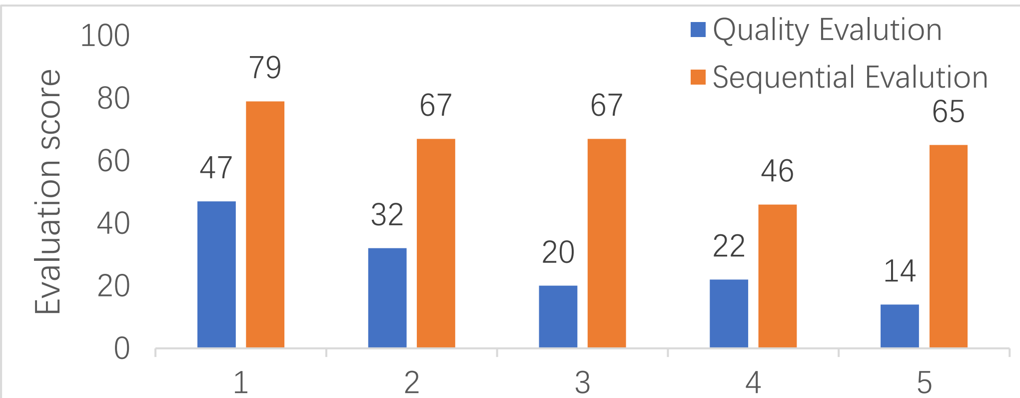

Fig. 7. Evaluation results for five shutdown operations

5 Conclusion

In this article, we propose a shutdown operation flow identification and evaluation method for the ASU Shutdown. A detailed logical model was established by combining the operational data of the ASU, and algorithms were developed to assist operators in establishing standardized and safe shutdown operations.

we first collected data of the ASU and operator operations through the DCS, and then analyzed these data using the shutdown operation flow identification algorithm to identify key operation flow. Subsequently, we designed a quantitative evaluation algorithm and selected multiple key evaluation indicators to comprehensively evaluate the efficiency and safety of operation flow, and generated a comprehensive score. The experimental result shows that the proposed method can effectively identify the actual shutdown operation flow and compare it with the standard shutdown process, revealing deviations in the operation. Through the case analysis of two shutdown processes, we found that the operators' experience, preparation time, standardization of the operation process, and the execution of key operation steps have a significant impact on the efficiency and safety of shutdown processes.

In future research, we plan to calibrate the evaluation rules and parameters more finely to ensure that the evaluation results are more realistic. We will also explore deeper integration methods between technological systems and manual operations, and develop a set of intelligent shutdown systems that can assist operators or be fully automated. Finally, we plan to apply the method of this study to different types of air separation units to verify their applicability across different units.

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