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Research Article

Robust Multicriteria Selection of Process-Air Redistribution Strategies in A Medium-Pressure Nitric Acid Plant: An Ak-72m Case Study

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ABSTRACT

Air compression, ammonia oxidation, heat recovery, nitrogen-oxide absorption and product-acid bleaching are strongly coupled in medium-pressure nitric acid plants. This study formulates the redistribution of process air in an AK-72M unit as a multicriteria retrofit-selection problem. Five alternatives were compared against seven criteria covering production potential, energy performance, capital demand, implementability, process safety, environmental performance and controllability. A normalized weighted-sum model identified partial replacement of the T-5–K-47 bleaching-air stream by filtered ambient air, with the released M-10A compressor air redirected to the R-12/1,2 contact section, as the leading concept (score 7.49/9). Control-only optimization ranked second (7.18/9). Robustness was evaluated by 200,000 Monte Carlo samples in which all criterion weights were perturbed independently by ±20% and renormalized. The preferred concept ranked first in 99.9895% of samples; its 95% score interval was 7.444–7.535 and the 95% score gap over the second-ranked alternative was 0.102–0.515. The result is robust to the stated weight uncertainty but remains conditional on the expert ratings and on hard technical

constraints. A front-end engineering and validation framework is therefore proposed instead of claiming an implemented industrial improvement.

Keywords

Nitric acid, process integration, airflow redistribution, multicriteria decision analysis, sensitivity analysis, retrofit selection, AK-72M.

Introduction

Weak nitric acid is produced industrially through catalytic ammonia oxidation, gas-phase oxidation of NO and reactive absorption of NOx in water. These stages are integrated with compression, expansion and heat recovery; consequently, a local change in an air branch can affect catalyst loading, steam generation, absorber hydraulics, tail-gas emissions and shaft power simultaneously [1–4]. Reactive-flow modelling has further shown that local velocity and surface chemistry jointly influence N2O selectivity over industrial platinum gauzes [4]. A retrofit decision should therefore be evaluated at plant level rather than by considering only the modified pipe or apparatus.

The AK-72M case considered here contains two functional process-air branches supplied by the M-10A compressor. The major branch, 162,800–202,400 $Nm^3\ h^{-1}$, feeds the R-12/1,2 contact reactors. A second branch of 17,000–35,000 $Nm^3\ h^{-1}$ transfers heat in T-5 and subsequently bleaches product acid in K-47 [13,14]. The latter stream is not redundant: it provides both thermal duty and oxygen-containing gas to the downstream process. Nevertheless, replacing part of its bleaching function with a separate ambient-air stream could release already-compressed M-10A air for the contact section without a major increase in total compressor load.

Previous studies provide detailed models for catalytic oxidation, NOx absorption, process synthesis and energy integration [4–8], but they do not resolve the specific decision of how existing process air should be redistributed between the contact and bleaching branches of an AK-72M unit. The objective of this paper is therefore to:

- define a plant-wide decision boundary;
- compare technically distinct retrofit alternatives using a transparent multicriteria model;
- quantify ranking robustness to criterion-weight uncertainty;
- identify the technical evidence required before industrial use.

Industrial case and decision alternatives

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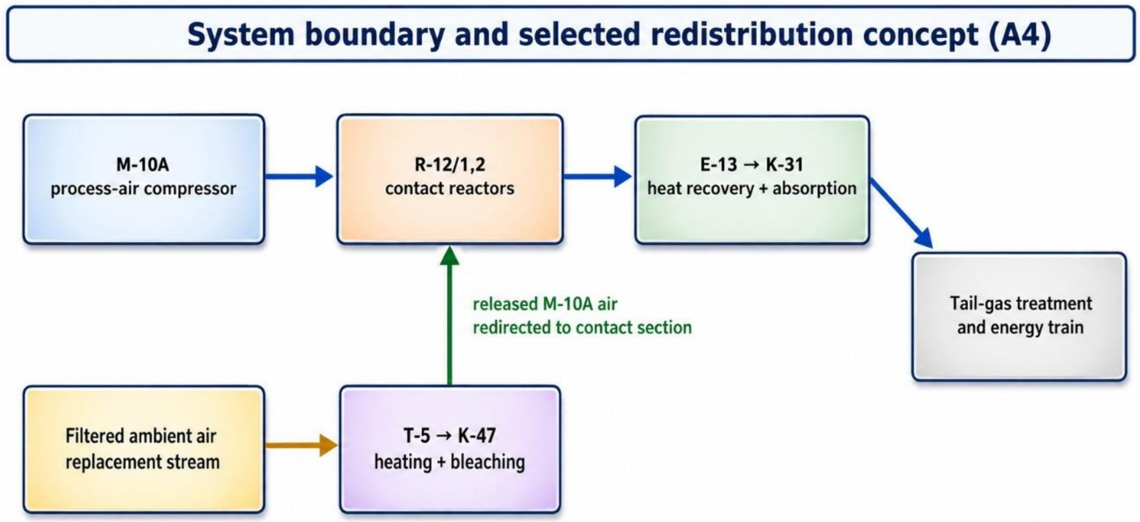

Figure 1. Plant-wide system boundary and the selected process-air redistribution concept.

Table 1. Case-study operating ranges used to define the decision problem.

Parameter	Range	Unit	Decision relevance
Contact-section air	162,800–202,400	$Nm^3\ h^{-1}$	M-10A → R-12/1,2
Heating/bleaching air	17,000–35,000	$Nm^3\ h^{-1}$	M-10A → T-5 → K-47
M-10A discharge pressure	0.23–0.35	MPa(g)	Season- and load-dependent
M-10A discharge temperature	130–216	°C	Heat source for T-5
Air after T-5	75–85	°C	K-47 bleaching service
NH_3 in reactor feed	9.2–10.6	vol.%	Specified operating range

Five alternatives were retained because they represent materially different ways to obtain additional contact-section air. A1 increases M-10A loading; A2 adds a dedicated compressor; A3 injects a separate air stream directly into the contact section; A4 replaces part of the K-47 branch with external air and redirects released M-10A air to R-12/1,2; and A5 relies on control optimization without a major flow-path change. The analysis is a concept-selection study, not a detailed design or operating procedure.

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Table 2. Retrofit alternatives and principal screening constraints.

Code	Concept	Main advantage	Primary constraint
A1	Increase M-10A load	Low new-equipment demand	Surge, mechanical and driver margins
A2	Install an additional compressor	Large independent air capacity	High CAPEX and power demand
A3	Feed external air directly to R-12	Independent of M-10A split	Pressure, temperature and cleanliness compatibility
A4	External air to K-47; released M-10A air to R-12	Uses existing compressed air more effectively	T-5 heat balance and coupled control
A5	Control-system optimization only	Low capital demand and high implementability	Limited production potential

Methods

1. Multicriteria model

The alternatives were scored on a common 1–9 scale, where 9 denotes the most desirable outcome. For capital cost, a high score means lower expenditure; for safety, it means lower residual risk after standard safeguards. Seven normalized weights sum to unity. The aggregate score of alternative i is:

$$S_i = \Sigma_j \ w_j \ x_{ij} \qquad (1)$$

where wj is the weight of criterion j and xij is the corresponding alternative score. Weighted-sum models provide an auditable first screen, while more elaborate methods such as AHP and TOPSIS are appropriate when a structured expert panel and pairwise-judgment data are available [9–11]. Because no expert-panel dataset was supplied, the present paper does not fabricate agreement statistics or AHP consistency ratios.

Table 3. Criteria, weights and alternative ratings used in the baseline model.

Criterion	w_j	A1	A2	A3	A4	A5
C1 Production potential	0.22	7	9	8	8	4
C2 Energy performance	0.20	5	4	4	8	7
C3 Capital demand	0.15	8	2	6	7	9
C4 Implementability	0.12	7	3	5	7	9
C5 Process safety	0.16	5	7	5	7	8

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C6 Environmental performance	0.08	5	5	5	7	7
C7 Controllability	0.07	6	8	6	8	9

2. Robustness analysis

Two deterministic checks were applied. First, each weight was varied individually by ±20%, after which all weights were renormalized. Second, 200,000 Monte Carlo weight vectors were generated with a fixed random seed (20260731). Each baseline weight was multiplied by an independent uniform factor U(0.8,1.2) and the vector was then normalized to sum to one. Ratings were held fixed in the primary experiment so that weight uncertainty could be isolated. Ranking frequency, score quantiles and the A4–A5 score gap were calculated. This experiment tests stability of the stated preference model; it does not validate the underlying technical ratings.

3. Hard-constraint screen

A high multicriteria score is admissible only if the candidate can satisfy non-compensatory limits. The screen includes the specified NH3 fraction at the contact-reactor inlet, catalyst temperature and pressure drop, heat-recovery capacity, absorber hydraulic margin, tail-gas NOx/N2O performance, turbomachinery maps, K-47 product quality and process-safety interlocks. Failure of any limit rejects the concept irrespective of its aggregate score.

Results and Discussion

1. Baseline ranking

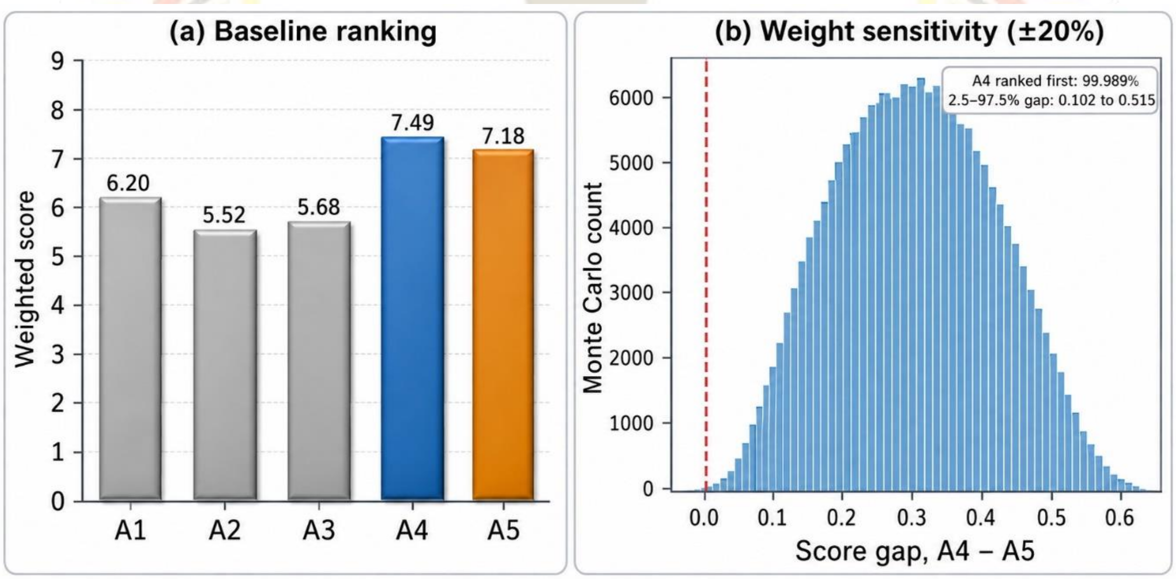

Figure 2. Baseline weighted scores and Monte Carlo sensitivity of the A4–A5 score gap.

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The baseline scores were 6.20 (A1), 5.52 (A2), 5.68 (A3), 7.49 (A4) and 7.18 (A5). A4 leads because it combines high production and energy scores without requiring a new large compressor. The concept also retains the pressure–temperature characteristics of M-10A air at the contact section; the separate external stream is assigned to the less pressure-intensive bleaching function. A5 ranks second and is complementary rather than mutually exclusive: improved split control, analytical monitoring and constraint management would be required if A4 advances to engineering design.

A2 has the highest production rating but is penalized by capital and power demand. A3 avoids dependence on the existing air split, yet direct contact-section injection creates a more difficult compatibility problem. A1 is comparatively simple but is constrained by the available compressor and driver margins. These outcomes illustrate why a single-objective production comparison would be incomplete.

2. Weight sensitivity

The one-at-a-time ±20% tests did not change the leading alternative for any criterion. In the Monte Carlo experiment, A4 ranked first in 199,979 of 200,000 samples (99.9895%); A5 ranked first in the remaining 21 samples. The median A4 score was 7.490, and the 2.5th–97.5th percentile interval was 7.444–7.535. The corresponding A4–A5 gap interval was 0.102–0.515, remaining positive throughout the central 95% of samples. Thus, the preference is not an artefact of small perturbations in the stated criterion weights.

This robustness result should be interpreted narrowly. The baseline ratings originate from an engineering assessment rather than a documented multi-expert elicitation. If ratings are allowed to move substantially, particularly for thermal feasibility, safety or implementability, A5 can overtake A4. Accordingly, the next decision cycle should recruit plant operations, process engineering, maintenance, instrumentation, energy and environmental specialists; record rating rationales; and report inter-rater agreement. AHP or TOPSIS may then be used as a cross-method check rather than as a cosmetic replacement for missing evidence.

3. Engineering interpretation of A4

The selected concept changes the allocation of already-compressed air rather than simply increasing total compression. Its principal benefit is therefore systemic: M-10A air released from the heating/bleaching branch can be used where pressure and temperature compatibility are already established. The critical trade-off is the heat duty of T-5. If external air is introduced downstream of T-5, it replaces bleaching gas but not ammonia-heating duty; supplementary T-202 steam or another heat source may be required. If it is introduced upstream, pressure, cleanliness and thermal compatibility must be demonstrated. The gross benefit cannot be treated as a net energy saving until this penalty is quantified.

The external-air scenario of 10,000 Nm^3 h^{-1} represents 28.6–58.8% of the documented K-47 branch range, so it is a material process change rather than a minor trim. The concept must therefore be evaluated against the complete R-12–E-13–K-27–M-10V–K-31–K-47–tail-gas train. The present paper intentionally does not provide setpoints, start-up sequences or construction instructions.

Validation and decision-gate framework

The concept should move forward only through formal engineering decision gates. Gate 1 confirms data quality and recalculates ratings from plant evidence. Gate 2 closes steady-state mass, heat and shaft-power balances and verifies equipment maps. Gate 3 performs process-hazard analysis and an independent design review. Gate 4 validates the model against a representative operating-history dataset, including flow, pressure, temperature, product quality, steam and emission measurements. Only after these gates should a qualified plant owner consider a controlled industrial trial under approved procedures.

For statistical validation, predicted and measured responses should be compared using parity plots, confidence intervals, RMSE, MAE and mean absolute percentage error, with instrument uncertainty propagated to the reported outcome [12]. A claimed production or energy improvement must be estimated from observed data; it should not be fixed in advance as an acceptance target.

Conclusions

A plant-wide multicriteria formulation was developed for five process-air retrofit alternatives in an AK-72M nitric acid unit.

Partial replacement of the T-5–K-47 branch by external air, with released M-10A air redirected to R-12/1,2 (A4), achieved the highest baseline score of 7.49/9.

A4 remained first in 99.9895% of 200,000 ±20% weight-perturbation samples, indicating strong weight robustness within the defined model.

The result is not yet an industrial performance claim: rating validation, complete thermal/hydraulic/shaft balances, emissions assessment and formal process-safety review remain mandatory.

A4 and control optimization (A5) should be studied as a combined front-end engineering package because controllability is essential to realizing any physical redistribution benefit.

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