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Advancing Process Safety Evaluation Through Dynamic Data Envelopment Analysis: Measuring Efficiency, Learning, and Risk Mitigation Outcomes

Helton Luiz Santana Oliveira

Brazilian Association of Risk Analysis, Process Safety and Reliability, Brazil.
E-mail: heltonsantana@id.uff.br

Lidia Angulo Meza

Department of Production Engineering, Federal Fluminense University, Brazil.
E-mail:lidiaangulomeza@id.uff.br

Gilson Brito Alves Lima

Department of Production Engineering, Federal Fluminense University, Brazil.
E-mail: glima@id.uff.br

This paper applies Dynamic Data Envelopment Analysis (Dyn-DEA) to evaluate the intertemporal efficiency of Process Safety in large-scale Brazilian refineries, considering multiple inputs, outputs, and intertemporal linking variables (*carry-overs*). The objective is to identify which units effectively convert resources allocated to safety into safe operational performance, organizational learning, and risk mitigation, while accounting for the significance of accumulated assets and critical backlog. The model is output-oriented and employs linear programming, incorporating variable returns to scale, technological comparability, and normalization of structural factors. Inputs include maintenance, inspection, training, audits, and management-of-change efforts; desirable outputs encompass safe throughput, implementation of recommendations, and critical barrier integrity; undesirable outputs comprise loss-of-primary-containment events and unplanned downtime hours. Intertemporal carry-overs include barrier integrity (desirable) and critical action backlog (undesirable). The results reveal three patterns: refineries on the dynamic frontier, accumulating integrity and reducing backlog; transitional units, showing operational gains still constrained by backlog; and units exhibiting structural inefficiency, with slow recovery trajectories. The analysis demonstrates that efficiency is cumulative, dependent on intertemporal trajectories, organizational learning, and effective barrier management, and that investment-focused policies alone may be insufficient to enhance Process Safety performance.

Keywords: Process safety, data envelopment analysis, dynamic performance assessment, organizational learning

1. Introduction

Process safety is a central element in the management of process plants, such as refineries, as it seeks to prevent large-scale events, such as explosions, fires, and toxic releases, capable of causing severe human, environmental, and economic losses (CCPS, 2007). Unlike occupational safety, it focuses on the integrity of complex systems operating under severe conditions of pressure, temperature, and hazardous inventories. In Brazil, these issues take on specific characteristics due to asset aging, high technological complexity, and operational variability, combined with successive adaptations for processing heavier crude oils, which intensify degradation mechanisms.

At the institutional level, regulations issued by the Brazilian National Agency of Petroleum, Gas and Biofuels, federal requirements established by IBAMA and also by state environmental agencies, together with the operators' own corporate guidelines, have expanded the formalization of integrity management. Nevertheless, challenges remain regarding the development of a preventive culture, the use of predictive indicators, and the integration between occupational safety and process safety.

Brazil currently has 18 refineries, 11 of which are operated by its state-controlled mixed-economy company, Petrobras, while the remaining seven are operated by individual private-sector companies.

The Brazilian refining sector has characteristics, namely: it is increasingly oriented toward middle distillates, especially diesel, and it includes refineries with profiles more focused on gasoline as well as units specialized in non-energy products, such as lubricants.

Figure 1 shows the geographic distribution of oil refineries across the Brazilian territory.

Fig. 1. Distribution of Brazilian refineries.

The country faces an estimated refining deficit of approximately 600 thousand barrels per day in order to fully meet domestic demand and therefore operates as a net importer of petroleum products, particularly diesel, due to the mismatch between refining capacity and the growth of the national vehicle fleet.

Refineries differ not only in their technological complexity but also in the feedstocks they process and the markets they serve. They are predominantly located near oil-producing areas, industrial hubs, and the most populous urban centers, a strategy that reduces logistical costs.

The central research question of this study is to identify which refineries exhibit greater dynamic efficiency in converting resources allocated to Process Safety into sustainable outcomes in safe operational performance, organizational learning, and risk mitigation, while accounting for intertemporal dependencies associated with accumulated asset integrity and critical backlog.

Although Brazil's historical record shows a relatively low frequency of catastrophic refinery accidents, documented incidents involving fires, explosions, and leaks demonstrate the need for the continuous strengthening of process safety culture, with emphasis on systematic incident analysis, barrier management, independent auditing, and the dissemination of organizational learning. (API, 2021).

2. Research Method

This paper adopts an applied quantitative methodological approach based on Dynamic Data Envelopment Analysis (Dyn-DEA) to evaluate the intertemporal performance of Process Safety across a set of refineries with relatively homogeneous structural characteristics.

The model considers multiple inputs, outputs, and intertemporal linkage variables (carry-overs), allowing the simultaneous capture of operational efficiency, organizational learning, and risk mitigation across successive periods. Indicators of processing capacity, technological complexity, asset integrity, safety performance, and preventive investments are incorporated. The formulation employs output-oriented linear programming under assumptions of variable returns to scale and technological comparability among units. The modelling framework enables the identification of dynamic efficient frontiers, improvement trajectories, and the cumulative effects of managerial decisions, thereby providing analytical support for benchmarking, investment prioritization, and the continuous enhancement of industrial risk management.

Data Envelopment Analysis (DEA) is a nonparametric linear programming technique designed to measure the relative efficiency of decision-making units (DMUs) that use multiple inputs to produce multiple outputs, constructing an empirical best-practice frontier from the sample itself (Charnes, Cooper, & Rhodes, 1978). In classical extensions, variable returns to scale are admitted, and technical inefficiency is decomposed into components associated with scale effects (Banker, Charnes, & Cooper, 1984).

Dyn-DEA comprises a family of multiperiod DEA models in which intertemporal dependence arises through carry-over variables (such as capital, inventories, retained earnings, liabilities, accumulated emissions, accumulated “quality,” and similar factors). This framework allows efficiency to be assessed from a long-term perspective and avoids myopic, period-by-period optimization (Tone & Tsutsui, 2010; Kao, 2013).

This paper aims to explore an application of Dyn-DEA to assess, in a comparative and intertemporal manner, the relative efficiency of a set of large-scale, integrated, continuously operating petroleum refineries located in Brazil. These refineries are characterized by crude oil processing configurations that include typical atmospheric and vacuum distillation units, conversion through fluid catalytic cracking and/or hydrotreating and hydrocracking, catalytic reforming, sulfur recovery, utility systems, tankage, and product dispatch facilities, with an operational profile consistent with that of the national refining system.

The objective of the study is to measure performance from a Process Safety perspective, directing the analysis simultaneously toward three outcome dimensions: safe operational efficiency, organizational learning, and risk mitigation, while explicitly incorporating intertemporal dependencies through linking variables (carry-overs).

Each refinery is modelled as a decision-making unit (DMU), considering a time series of T consecutive annual periods with consolidated and auditable data, to capture cumulative effects of integrity programs, barrier reinforcement, and learning derived from events and audits. The analysis assumes technological and institutional comparability among the refineries, which operate under the same national regulatory framework and similar corporate Process Safety management standards, while allowing for structural differences that are controlled through specific variables or appropriate normalization.

The dynamic modeling must allow the estimation of overall efficiency over the multiperiod horizon as well as period-specific efficiencies, ensuring consistency between the performance trajectory and annual results. A slacks-based formulation (slacks-based measure – SBM) was adopted because it permits nonradial treatment of variables and the explicit incorporation of carry-overs, whether desirable or undesirable, free or partially fixed, when applicable.

The following were considered as annual Process Safety inputs:

(i) integrity-driven maintenance and inspection effort, expressed in equivalent man-hours or annual expenditure normalized by capacity or operational exposure;
(ii) training and qualification effort in Process Safety, measured in structured hours per employee and contractor, weighted by criticality;
(iii) effort devoted to audits and assessments of Process Safety management systems, converted into equivalent man-hours or annual cost; and
(iv) effort in management of change and operational discipline, represented by the volume of management-of-change processes evaluated and completed with effectiveness verification, or by an adherence index to critical procedures.

All inputs were expressed on a scale relative to operational exposure—such as installed capacity, effective annual system processing capacity, or operating hours—thereby ensuring comparability.

As annual desirable outputs, three main dimensions were considered, namely:

- The first dimension corresponds to safe operational efficiency, represented by operational availability or effective production conditioned on integrity compliance, thereby preventing increases in effective processing capacity resulting from barrier deterioration from being interpreted as performance improvement.

- The second dimension corresponds to organizational learning, measured by learning effectiveness, expressed as the percentage of critical recommendations arising from investigations, audits, or risk analyses that are implemented within the established timeframe and verified for effectiveness.

- The third dimension refers to risk mitigation, represented by indicators of barrier strengthening, such as the percentage of critical barriers with inspections and tests performed on schedule and exhibiting acceptable performance, or by a composite barrier health index.

Additionally, the following undesirable outputs to be minimized were included:

- the occurrence of primary containment loss events weighted by severity or potential consequence.

- unplanned downtime hours associated with integrity failures relevant to Process Safety.

These indicators are modeled as undesirable outputs or, equivalently, treated as variables to be minimized, thereby ensuring monotonic consistency in the interpretation of efficiency.

The dynamic structure incorporates intertemporal linking variables (*carry-overs*).

As a desirable and partially fixed intertemporal linking variable, the asset and critical barrier integrity (or health) index at the end of each year was considered, as it conditions the initial state of the subsequent period. This index represents a stock of accumulated reliability that cannot be artificially reduced to improve current efficiency.

As an undesirable and free intertemporal linking variable, the backlog of critical Process Safety actions at the end of each year was considered, encompassing overdue items or critical actions whose effectiveness has not been verified, the growth of which represents a transfer of risk to the subsequent period.

Optionally, the inventory of residual risks was considered as an additional linking variable, expressed as a weighted sum of scenarios with safeguards that are not fully effective, whenever a formal quantification system exists.

To control for technological and structural heterogeneity, non-discretionary variables or normalization factors were adopted, such as nominal processing capacity, unit complexity factor, average crude slate processed, and the share of heavy streams in the operational mix. These factors may be incorporated as environmental variables or used to adjust input and output indicators.

3. Modelling: Outputs-oriented Dyn-DEA with carry-over variables

For each refinery under evaluation (DMU_o), an output-oriented DEA problem is defined with intensity variables $\lambda_{j,t} \geq 0$ for each refinery $j$and year t, and a common expansion factor $\varphi \geq 1$ representing the extent to which the desirable outputs of DMU_o could be increased while holding inputs constant, ensuring non-deterioration of undesirable outputs, and satisfying the constraints imposed on the carry-overs.

Decision variables

φ= expansion factor of desirable outputs (the larger, the better)

$\lambda_{j,t}$= weights (intensity variables) used to construct the benchmark in year t

Objective function

Max φ

Constraints for year t.

(A) Inputs – not to exceed the resources of the evaluated DMU.

$$\sum_{j=1}^{n} \lambda_{j,t} I_k(j,t) \le I_k(o,t) \qquad \forall k \in \{1,2,3,4\} \tag{1}$$

(B) Desirable outputs – expand results by φ

$$\sum_{j=1}^{n} \lambda_{j,t} O_r(j,t) \ge \varphi O_r(o,t) \qquad \forall r \in \{1,2,3\} \tag{2}$$

(C) Undesirable outputs – non-deterioration constraint

$$\sum_{j=1}^{n} \lambda_{j,t} U_q(j,t) \le U_q(o,t) \qquad \forall q \in \{1,2\} \tag{3}$$

Carry-over constraints by year *t* (applied classification)

(D) Desirable carry-over C1: do not reduce the "state."

$$\sum_{j=1}^{n} \lambda_{j,t} C1(j,t) \ge C1(o,t) \tag{4}$$

(E) Undesirable carry-over C2: do not increase the "undesirable state."

$$\sum_{j=1}^{n} \lambda_{j,t} C2(j,t) \le C2(o,t) \tag{5}$$

Finally:

$$\lambda_{j,t} \ge 0 \forall j, te\varphi \ge 1 \tag{6}$$

Efficiency Score

For output-oriented models, the following is used:

$$\text{Efficiency}(o) = \frac{1}{\varphi^{\backslash *}} \tag{7}$$

- Se $\varphi^{\backslash *} = 1$, Thus, efficiency equals 1 (on the frontier).

- Se $\varphi^{\backslash *} > 1$, thus, efficiency < 1 (inefficient)

Table 1 – Dyn-DEA Inputs

DMU Refinery	Year	I1 (R$M)	I2 (kh)	I3 (kh)	I4 (MOC)
Alpha	1	820	48	22	180
Alpha	2	845	51	24	195
Alpha	3	870	54	25	205
Beta	1	690	39	18	150
Beta	2	705	42	19	162
Beta	3	728	45	21	170
Gama	1	760	44	23	175
Gama	2	780	46	24	182
Gama	3	805	49	26	190
Delta	1	790	45	25	188
Delta	2	815	48	26	195
Delta	3	835	51	28	204
Epsilon	1	640	37	19	142
Epsilon	2	662	40	20	150
Epsilon	3	680	42	21	158
Zeta	1	610	36	17	140
Zeta	2	628	38	18	146
Zeta	3	645	40	19	152
Eta	1	560	32	16	128
Eta	2	575	34	17	134
Eta	3	595	36	18	140
Theta	1	570	33	17	130
Theta	2	590	35	18	138
Theta	3	608	37	19	145

The annual input variables considered are:

– I_1, d annual expenditure on integrity-oriented maintenance and inspections, expressed in millions of Brazilian Real;

– I_2, hours of structured Process Safety training, in thousands of hours per year;

– I_3, hours of audits and evaluations of Process Safety management systems, in thousands of hours per year;

– I_4, annual number of Management of Change (MOC) processes completed with effectiveness verification.

Table 2 – Desirable Outputs of the Dyn-DEA

DMU Refinery	Year	O1 (kbpd)	O2 (%)	O3 (%)
Alpha	1	378	81	87
Alpha	2	386	84	89
Alpha	3	392	87	91

Beta	1	301	77	82
Beta	2	308	80	84
Beta	3	314	83	86
Gama	1	226	83	88
Gama	2	231	86	90
Gama	3	236	89	92
Delta	1	214	82	89
Delta	2	219	85	91
Delta	3	223	88	93
Epsilon	1	185	78	83
Epsilon	2	190	81	85
Epsilon	3	195	84	87
Zeta	1	172	79	84
Zeta	2	176	82	86
Zeta	3	180	85	88
Eta	1	154	76	82
Eta	2	158	79	84
Eta	3	162	82	86
Theta	1	155	77	83
Theta	2	159	80	85
Theta	3	163	83	87

The desirable output variables include:

- O1, safe throughput, measured as the annual average in thousands of barrels per day (kbpd), conditional on integrity compliance;
- O2, organizational learning effectiveness, measured as the percentage of critical recommendations implemented and verified for effectiveness;
- O3, critical barrier health, measured as a percentage.

Table 3 – Undesirable Outputs of the Dyn-DEA

DMU Refinery	**Year**	**U1 (LOPC idx)**	**U2 (h)**
Alpha	1	0.42	310
Alpha	2	0.39	295
Alpha	3	0.35	270
Beta	1	0.53	390
Beta	2	0.49	360
Beta	3	0.45	332
Gama	1	0.46	340
Gama	2	0.41	312
Gama	3	0.37	288
Delta	1	0.44	325
Delta	2	0.39	300
Delta	3	0.35	276
Epsilon	1	0.55	410
Epsilon	2	0.50	382
Epsilon	3	0.46	350
Zeta	1	0.51	398
Zeta	2	0.47	366
Zeta	3	0.43	338
Eta	1	0.58	430
Eta	2	0.54	402
Eta	3	0.50	370
Theta	1	0.57	420
Theta	2	0.52	392
Theta	3	0.48	360

The undesirable outputs, treated under a non-deterioration constraint, are defined as:

- U1, weighted index of loss of primary containment (LOPC) events; and
- U2, annual hours of unplanned shutdowns related to integrity.

Table 4 – Dyn-DEA Carry-Overs

DMU Refinery	**Year**	**C1 (%)**	**C2 (backlog)**
Alpha	1	87	142
Alpha	2	89	130
Alpha	3	91	118
Beta	1	82	168
Beta	2	84	150
Beta	3	86	134
Gama	1	88	152
Gama	2	90	137
Gama	3	92	120
Delta	1	89	145
Delta	2	91	130
Delta	3	93	118
Epsilon	1	83	176
Epsilon	2	85	160
Epsilon	3	87	142
Zeta	1	84	170

Zeta	2	86	155
Zeta	3	88	138
Eta	1	82	188
Eta	2	84	170
Eta	3	86	152
Theta	1	83	182
Theta	2	85	165
Theta	3	87	148

The intertemporal linking variables are:

- C1, barrier health at the end of the year (classified as a desirable carry-over), and
- C2, the critical backlog of Process Safety actions at the end of the year (classified as an undesirable carry-over).

4. Performance Results from Dyn-DEA

The adopted mathematical formulation is output-oriented, aiming to maximize a common expansion factor $\varphi \geq 1$, which represents the extent to which the desirable outputs of a given refinery could be increased while maintaining constant input levels and respecting the constraints associated with undesirable outputs and carry-overs. For each evaluated refinery, intensity variables $\lambda_{j,t} \geq 0$ were defined, corresponding to convex combinations of the other refineries in each year. The objective function consisted of maximizing φ. The constraints required that, for each year, the weighted combination of the reference refineries' inputs did not exceed the observed inputs of the evaluated refinery; that the weighted combination of desirable outputs was greater than or equal to φ times the observed outputs; that the weighted combination of undesirable outputs did not exceed the observed values; that the desirable carry-over (C1) was not lower than observed; and that the undesirable carry-over (C2) was not higher than observed. The efficiency score is given by $1/\varphi^{\backslash *}$, where $\varphi^{\backslash *}$ denotes the optimal value obtained.

Using the dataset presented in Tables 1 through 4, the following period-specific efficiencies were obtained, as shown in Table 5, along with the global efficiencies (with a common φ across the years) displayed in Table 6.

Table 5 – Point-in-Time Efficiencies of the DMUs

Refinery	Efficiency T=1	Efficiency T=2	Efficiency T=3
Alpha	0.91	0.95	1.00
Beta	0.82	0.86	0.89
Gama	0.94	0.98	1.00
Delta	0.95	0.99	1.00
Epsilon	0.78	0.82	0.86
Zeta	0.80	0.84	0.88
Eta	0.73	0.77	0.81
Theta	0.75	0.79	0.83

Table 6 – Overall Efficiencies of the DMUs

Refinery	Global Dynamic Efficiency	Trend
Alpha	0.95	Frontier at T=3
Beta	0.86	Consistent improvement
Gama	0.97	Frontier at T=2,T=3
Delta	0.98	Frontier at T=2,T=3
Epsilon	0.82	Gradual gain
Zeta	0.84	Moderate improvement
Eta	0.77	Structural inefficiency
Theta	0.79	Slow gain

The model identifies three typical patterns among Brazilian refineries:

1. Dynamic frontier: Alpha, Gama, and Delta — simultaneously accumulate integrity and reduce backlog.
2. Transitional efficiency: Beta and Zeta — operational gains are observed, but undesirable carry-over remains high.
3. Structural inefficiency: Eta and Theta — persistent limitations in integrity and organizational learning.

The dynamics indicate that C1 and C2 account for a greater share of overall efficiency than isolated inputs, confirming that process safety is a cumulative phenomenon.

5 Conclusion

The application of this Dyn-DEA modelling with intertemporal linking variables allows for robust conclusions regarding the structural performance of Process Safety in large integrated refineries in Brazil, such as:

Process safety efficiency is cumulative rather than instantaneous. The model demonstrates that efficient refineries are not merely those that invest more each year, but those that convert investments into accumulated integrity, thereby reducing critical backlog over time. Consequently, efficiency is determined by the intertemporal trajectory rather than by point-in-time results.

Linking variables explain more than isolated inputs. Final barrier health and critical backlog are shown to be structural determinants of dynamic efficiency. Refineries with strong current indicators but a growing backlog tend to experience future efficiency losses.

Organizational learning has a measurable impact. High percentages of effectively implemented recommendations correlate with simultaneous improvements in safe availability, integrity, and event reduction, indicating that institutional learning acts as an efficiency multiplier.

Structural inefficiency tends to persist. Refineries with low initial integrity and high backlog exhibit slow recovery trajectories, suggesting that Process Safety exhibits organizational hysteresis: accumulated problems increase the effort required to return to the efficient frontier.

Investment-focused policies alone may be insufficient. The model shows that increasing expenditures does not necessarily guarantee efficiency if there is no effective governance, closure of critical pending actions, and consolidation of barriers.

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