
COPA: Comparing the incomparable in multi-objective model evaluation

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Abstract

As machine learning (ML) practitioners, we often have hundreds of (trained) ML models at hand from which we need to choose one, based on various objectives such as accuracy, robustness, fairness, scalability, etc. However, how to *compare*, *aggregate* and, ultimately, *trade-off* these objectives is usually a time-consuming task that requires expert knowledge, as they may be measured in different units or scales. In this work, we investigate *how* objectives can be automatically normalized and aggregated to systematically navigate their Pareto front. To do so, we make incomparable objectives comparable using their CDFs, approximated by their relative rankings. As a result, we can aggregate them while matching user-specific preferences, allowing practitioners to meaningfully navigate and search for models in the Pareto front. We demonstrate the potential impact of our approach, named COPA, in both model selection and benchmarking tasks across diverse ML areas such as fair ML, domain generalization, AutoML and foundation models, where classical ways to normalize and aggregate objectives fall short.

1 Introduction

In many phases of machine learning (ML), from model development to deployment, we often need to *compare and select among a population of trained models according to multiple objectives*. For example, even in the simple scenario of a single classification task, model selection involves comparing and selecting among a population of trained classifiers with different hyperparameters to find a specific compromise among objectives such as accuracy, sensitivity, or specificity [24]. A common and more complex scenario these days involves benchmarking a large number of large deep learning models in terms of how they perform with respect to many and diverse objectives that go beyond accuracy, such as robustness [61], fairness [21], and CO₂ footprint [9, 35]. In both examples, we encounter the following challenge: *how do we systematically compare and select among a large number of ML models in terms of multiple objectives?*

Moreover, *different users and applications often have different needs and preferences*. For example, a user may want to download a subset of trained large language models (LLMs) from the *Open LLM Leaderboard* [12] to compare different prompt engineering approaches for a new task. The user requires LLMs that perform relatively well without leaving unnecessarily large CO₂ footprints. To this end, they need to compare the 2148 submitted LLMs in terms of 7 objectives, i.e., their performance across 6 benchmarks and inference CO₂ cost. Among these models, 487 present non-trivial trade-offs, i.e., for every pair, one is better in an objective but worse in another (see Fig. 1). How should they compare the hundreds of models to decide what are acceptable performance-emission trade-offs? Should they manually inspect all 487 LLMs? And what if another user required the most robust model, rather than the most performant? Should they start from scratch?

Similar challenges can be easily found in the literature related to, e.g., multitask learning or domain generalization [43, 48], where the selected model is expected to work ‘well’ on several tasks/domains;

fair classification [62], where it is often unclear what is an acceptable fairness-accuracy trade-off for deployment; or AutoML [15], where tens of frameworks are compared on hundreds of objectives. Crucially, all these works highlight two important limitations in multi-objective ML evaluation:

- L1. Objectives with different semantics and domains, such as average performance score and CO₂ cost in Fig. 1, are not directly *comparable*, and thus cannot be properly aggregated nor traded-off. In physics, this would be akin to comparing meters and grams.
- L2. When dealing with many objectives (7 in our LLM example), it is challenging for humans to translate their preferences into a concrete decision, as the number of plausible trade-offs quickly becomes overwhelming (487 in our example).

These challenges reinforce the idea that we need automatic tools to navigate the Pareto front (i.e., the set of optimal trade-offs) in high dimensions, tuning their parameters according to the user preferences. The most common approach would be to perform a weighted combination of either the raw (Naive) or normalized objectives (Norm. and Delta, see §2 for their definitions). However, as we show in Fig. 1, both fail to address L1 and, thus, to evenly explore the Pareto front. In other words, they map most CO₂ importance values, α , to a small region of the front. To overcome these issues, prior works had to devise heuristic approaches tailored to their specific cases [5, 44]. For example, the authors of DecodingTrust [57] had to provide 8 ad hoc rules to normalize their objectives, one per objective. To date, we lack grounded approaches to compare, aggregate and, ultimately, trade-off objectives according to user preferences, that can be used out-of-the-box in multi-objective ML evaluation.

Contributions. We first motivate and *establish* the incomparability problem in multi-objective ML evaluation, shedding light on why previous approaches fail (§2). Next, we introduce **COPA** , a novel approach to allow practitioners to *meaningfully navigate the Pareto front*, and thus compare and select models that reflect their preferences (§3). COPA accomplishes this goal with two components: **i)** a normalization function that *universally* makes all objectives comparable via their cumulative distribution functions, which we approximate using relative rankings; and **ii)** a criterion function with two easily interpretable parameters controlling the aggregation and importance of each objective. We then place COPA in the context of related work (§4), and finally demonstrate its potential impact (§5) in diverse and timely applications such as domain generalization, multitask learning, fair ML, AutoML benchmarking, and LLM selection. As we illustrate in Fig. 1, COPA enables thoroughly exploring the Pareto front as a function of the user preferences, here controlled by α . For instance, a deployer equally interested in the performance and CO₂ emissions of the LLM, could use COPA with $\alpha = 1/2$ to pick the model in the middle of the Pareto front (last row in Fig. 1), ranked top-18 % for both objectives.

2 Problem statement

We are given a population of already-trained models $\mathcal{H}$, typically obtained by changing hyperparameters, where each model $h \in \mathcal{H}$ is associated to a vector of K metrics assessing its performance with respect to different evaluation objectives. In addition, we assume each objective to be a continuous random variable for which we have sampled observations in $\mathcal{H}$.

Without loss of generality, we assume that each individual objective has to be *minimized*, and we can thus frame the problem as a multi-objective optimization (MOO) problem of the following form:

$$\min_{h \in \mathcal{H}} \mathbf{y}(h) := [y_1(h), y_2(h), \dots, y_K(h)], \quad (1)$$

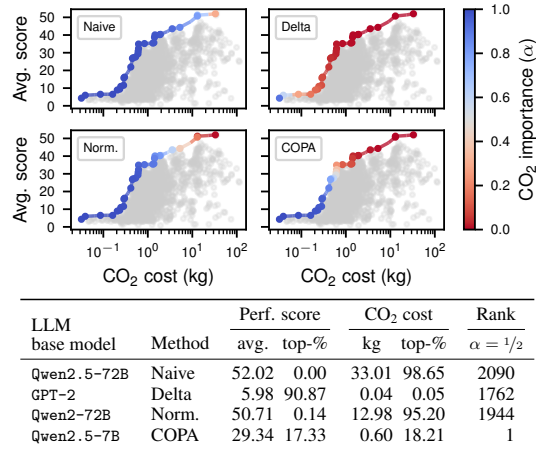


Figure 1: **COPA meaningfully navigates the performance-emissions trade-off of the Open LLM Leaderboard [12]**, evenly mapping the importance of CO₂ cost to the Pareto front. In contrast, existing approaches are biased toward one of the objectives. This is reflected in the retrieved LLMs where, e.g., COPA maps $\alpha = 1/2$ to a top-18 % model for both objectives, and all other approaches select either a high-performing but CO₂-demanding model, or vice versa.

where $\mathbf{y}(h)$ is the objective vector of model h , and $y_k(h)$ its performance on the k -th objective. When it is clear from the context, we will omit the argument and write $\mathbf{y}$ and y_k directly.

How can we minimize a vector? A fundamental problem of Eq. 1 is that *minimizing the vector* $\mathbf{y}$ is *not well-defined*, as there is no canonical total order in high dimensions. Therefore, two models could yield objective vectors where one is not always better than the other for all objectives. In the MOO literature, the set of optimal trade-off solutions is known as the *Pareto front* and, more formally, an objective vector $\mathbf{y}^*$ is in the Pareto front (and called *Pareto-optimal*) if there exists no other feasible vector $\mathbf{y}$ such that $y_k \leq y_k^*$ for all $k \in \{1, 2, \dots, K\}$, and $y_k < y_k^*$ for at least one of the objectives.

While the Pareto front is theoretically appealing, in practice, the **decision maker** (DM) needs to navigate the Pareto front and, eventually, select one single model.¹ In other words, the DM needs to specify a total order in Eq. 1 which implies: **i)** taking a total order directly in $\mathbb{R}^K$, e.g., the lexicographic order where $\mathbf{y} < \mathbf{y}^*$ iff $y_k < y_k^*$ and $y_i = y_i^* \forall i < k$; or **ii)** defining a **criterion function** $C: \mathbb{R}^K \rightarrow \mathbb{R}$ to rewrite Eq. 1 as a scalar-valued problem:

$$\min_{h \in \mathcal{H}} C(\mathbf{y}(h)). \quad (2)$$

One remarkable example of the latter is the *global-criterion method* [63] which maps DM preferences to the problem geometry by interpreting Eq. 2 as selecting the model closest to the *ideal* one, i.e.,

$$\min_{h \in \mathcal{H}} \|\mathbf{y}(h) - \mathbf{y}^{\text{ideal}}\|_*, \quad (3)$$

where $\mathbf{y}^{\text{ideal}}$ is the ideal solution, $\mathbf{y}^{\text{ideal}} := [\min_h y_1, \min_h y_2, \dots, \min_h y_K]$, and $\|\cdot\|_*$ is typically a p -norm. However, naively solving Eq. 3 (and, more generally, Eq. 2) is well-known in the MOO literature to be sensitive to the scaling of the objectives [4] (recall **L1** in §1), and thus prevents us from properly accounting for any DM preferences (**L2**). In this work, we argue that the criterion function C should fulfill the following desiderata:

D1. Reflect the DM preferences, translating their model expectations into an optimization problem.

D2. Provide a simple way to tune its parameters to meaningfully explore the Pareto front.

When are objectives incomparable? Similar to dimensional analysis in physics [2]—which argues that we cannot combine incommensurable quantities, e.g., kilograms and meters—we argue that a second fundamental issue that we face in Eq. 2 is **semantic incomparability**, i.e., whether it is sensible to compare (and thus aggregate) the values of two different objectives.

For example, if objectives differ in their semantics they are hardly comparable in general, e.g.: despite both accuracy and ROC AUC lying in the unit interval, it does not make immediate sense to compare their values. There are, however, other aspects that are more subtle. To illustrate these, Fig. 2 presents a synthetic Pareto front from §5.1 where both objectives quantify prediction error in significantly different domains, namely, within the intervals $[0, 0.2]$ and $[0.5, 3.0]$. We navigate the Pareto front solving a weighted Tchebycheff problem [3] of the form

$$\min_{h \in \mathcal{H}} \max \{ \alpha |y_1|, (1 - \alpha) |y_2| \}, \quad (4)$$

which solves Eq. 3 with C as the ∞ -norm weighted by $\alpha \in [0, 1]$. Intuitively, Eq. 4 looks for robust solutions that account for the importance of solving one objective over the other, seemingly satisfying our desiderata, **D1-2**. However, its naive application over the original objectives clearly shows how we can bias model selection in favor of Objective 2, as it can be seen in Fig. 2: for any given preference α smaller than 0.75, Eq. 4 yields a solution which *completely ignores Objective 1 performance*.

How can we make objectives comparable? As we just discussed, *even if we use a well-designed criterion function*, semantic incomparability can hinder our goal to meaningfully explore the Pareto

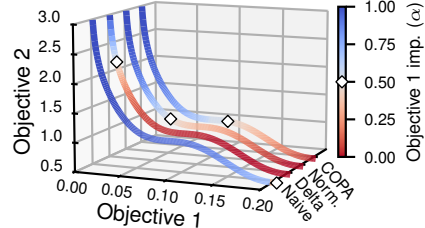


Figure 2: As we explore a synthetic Pareto front with different normalization functions to solve Eq. 3, only COPA meaningfully navigates it as we change α , and its min-max solution agrees with our expectations of a robust solution.

¹Note that, when we plot the Pareto front in 2D, e.g., in Fig. 1, the linear interpolation between models (dots) only serves visualization purposes, i.e., we cannot interpolate between models.

front. Historically, this has been addressed in the MOO literature by applying **component-wise transformations** to the objectives to normalize them [40], turning Eq. 2 into

$$\min_{h \in \mathcal{H}} C(\phi(\mathbf{y})) := C([\phi_1(y_1), \dots, \phi_K(y_K)]) . \quad (5)$$

Two classic examples of these transformations are

$$\Delta_k(y_k) := \frac{y_k - y_k^{\text{ideal}}}{y_k^{\text{ideal}}} \quad \text{and} \quad \text{norm}_k(y_k) := \frac{y_k - y_k^{\text{ideal}}}{y_k^{\text{nadir}} - y_k^{\text{ideal}}} , \quad (6)$$

where $y_k^{\text{nadir}} := [\max_h y_1, \max_h y_2, \dots, \max_h y_K]$ is the worst possible solution. Intuitively, Δ_k represents the difference relative to the ideal solution, and norm_k reweighs the objective to lie in the unit interval. Prior works have extensively used Δ_k , often replacing y_k^{ideal} with a reference vector, as computing it can be challenging [33, 38, 40]. Back to our synthetic case, we now want to solve

$$\min_{h \in \mathcal{H}} \max \{ \alpha |\phi_1(y_1)|, (1 - \alpha) |\phi_2(y_2)| \} . \quad (7)$$

By testing different ϕ_k , we can understand why classic approaches fail to make objectives comparable. More specifically: **i)** using Δ_k now biases the problem toward the first objective, since $\min_h y_1 \approx 0$; and **ii)** using norm_k alleviates these problems, as the denominator is now bigger than the numerator, yet the differences between distributions (that of y_2 being heavy-tailed) still bias the optimization towards the first objective. Instead, we seek to explore the Pareto front making a more meaningful use of α , spreading it uniformly along the curve.

The *main goal* of the functions $\phi_k: \mathbb{R} \rightarrow \mathbb{R}$ is thus to make the objectives semantically comparable, so that we can seamlessly aggregate them with the criterion function C . To this end, we argue that the functions ϕ_k should be:

D3. Objective-agnostic, so that we can normalize any objective irrespectively of its specific nature.

D4. Order-preserving (i.e., strictly increasing), so that it preserves Pareto-optimality.

In summary, to meaningfully explore the Pareto front, it is important to design a criterion function C that translates well DM preferences into an optimization problem (**D1-2**), and a normalization function ϕ that makes objectives semantically comparable (**D3-4**). These desiderata will blend in COPA, discussed in the next section. In the synthetic experiment above, COPA maps the value $\alpha = 1/2$, which turns Eq. 7 into a robust min-max problem [56], to the flat region of the curve in Fig. 2, matching the intuition of what a robust solution should represent.

3 Methodology

Next, we introduce the proposed normalization and criterion functions fulfilling the desiderata **D1-4** described in §2. We refer to the problem resulting of solving Eq. 5 with the proposed functions as **cumulative-based optimization of the Pareto front** or, in short, **COPA** 🍷.

3.1 Designing a universal normalization function

We argued in §2 that the function ϕ should fulfill desiderata **D3-4**, i.e., it should make any objectives semantically comparable while preserving their Pareto-optimality. Taking advantage of our probabilistic perspective (recall that y_k is a continuous random variable), we propose to design ϕ such that the resulting variables are all equally distributed and, w.l.o.g., uniformly distributed in the unit interval. That is, we propose to use $\mathbf{u} := [u_1, u_2, \dots, u_K]$ instead of $\mathbf{y}$, where

$$u_k := F_k(y_k) \sim \mathcal{U}(0, 1) \quad \forall k \in \{1, 2, \dots, K\} , \quad (8)$$

and $\phi_k = F_k$ is the marginal cumulative distribution function (CDF) of the k -th objective. Indeed, this transformation is known in statistics as the probability integral transform [6, Example 5.6.3], and u_k is guaranteed to follow a standard uniform distribution if y_k is continuous.

Remarkably, Eq. 8 makes all criterion functions *marginal-distribution-free* in the sense of Kendall and Sundrum [29], i.e., it strips away all individual properties of the marginal distributions (e.g., the domain) of any given objective (**D3**). We note that normalizing random variables this way is one of the fundamental building stones of copulae in statistics [14, 51], ensuring that copula functions exclusively learn the relationship across random variables.

178 **How can we interpret the values of $\mathbf{u}$?** One important advantage of using $\mathbf{u}$ in place of $\mathbf{y}$ in Eq. 5
 179 is that it provides a common framework to think about all objectives, since all their values are now
 180 framed as *elements within a population*. In practice, this means that the DM has a common language
 181 to express their expectations on the model. For example, $\mathbf{u} = 1/2$ corresponds for all objectives to the
 182 *the median value*, which divides $\mathcal{H}$ into two *halves* comprising the best and worst performing models.
 183 However, there is still one caveat we need yet to address: we have no access to the marginal CDF of
 184 each objective, but only to samples of the joint distribution in $\mathcal{H}$.

185 3.2 Rankings as finite-sample approximations

186 As mentioned above, while we have no access to the CDFs themselves, we have samples from the
 187 joint distribution over the objectives, i.e., over, $p([y_1, y_2, \dots, y_K])$. Namely, we can consider each
 188 model $h \in \mathcal{H}$ as a sample from the joint distribution and, by looking at each objective individually,
 189 as a sample from the marginal distributions.

190 Let us now focus on the k -th objective, y_k , and drop the subindex in the following to ease notation. Say
 191 that we have $|\mathcal{H}| = N$ i.i.d. realizations of the objective, i.e., $\{y_1, y_2, \dots, y_N\} \stackrel{\text{i.i.d.}}{\sim} P_k$. Then, we can
 192 approximate Eq. 8 for the i -th sample, $u_i = F(y_i)$, by computing its order statistic, i.e., the random
 193 variable representing its relative ranking within the population, $R(i) := \sum_{j=1}^N [y_j < y_i]$, where
 194 Iverson brackets denote the indicator function, such that $y_{R(1)} \leq y_{R(2)} \leq \dots \leq y_{R(N)}$. Specifically,
 195 since the *empirical CDF* is the fraction of samples smaller than the input, it is direct to show that

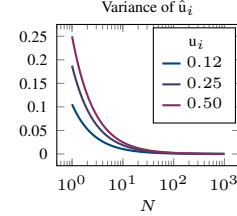
$$\hat{u}_i = \hat{F}(i) := \frac{1}{N} \sum_{j=1}^N [y_j < y_i] = \frac{1}{N} R(i) \quad (9)$$

196 enjoys the following properties [6]:

197 **Proposition 3.1.** $\hat{u}_i$ is an unbiased estimator of the CDF at y_i , u_i , with variance $u_i(1 - u_i)/N$. The
 198 variance of $\hat{u}_i$ decreases linearly with N , and has a maximum value of $0.25/N$ at the median.

199 *Proof.* First, note that $[y_j < y_i] \sim \text{Bern}(u_i)$. Then, we have $R(i) \sim \text{Bin}(N, u_i)$ with mean Nu_i
 200 and variance $Nu_i(1 - u_i)$. Hence, $\hat{u}_i$ has mean $\frac{1}{N} \mathbb{E}[R(i)] = u_i$, and variance $\frac{1}{N^2} \mathbb{V}[R(i)] =$
 201 $u_i(1 - u_i)/N$ which, by taking derivatives w.r.t. u_i , $\partial_{u_i} \mathbb{V}[\hat{u}_i] = 1 - 2u_i = 0 \Rightarrow u_i = 1/2$, which is a
 202 maximum since $\partial_{u_i}^2 \mathbb{V}[1/2] < 0$. $\square$

203 In other words, we can use the relative rankings of each objective to build
 204 an unbiased² estimator of the CDF, $\hat{u}_i$, whose variance rapidly decreases as
 205 we increase the size of $\mathcal{H}$, i.e., $\mathbb{V}[\hat{u}_i] \rightarrow 0$ as $N \rightarrow \infty$. Indeed, the inset
 206 figure shows the variance of $\hat{u}_i$ as a function of the sample size for three
 207 different values of u_i . Note that the relative ranking is strictly increasing:
 208 if $y_i < y_j$, then $\hat{F}(y_i) < \hat{F}(y_j)$ for any $\mathcal{H}$ containing both samples (D4).
 209 While this is an approximation of the true CDF, which would retain instead
 210 all the information about the joint distribution, it works egregiously well in our experiments (§5).
 211 Furthermore, note that this transformation is meant to ease inter-objective computations, we can (and
 212 should) use the original values of y_k to perform intra-objective comparisons or decisions.



213 3.3 Incorporating preferences into the optimization

214 Now that we can effectively approximate our normalization function, we introduce a criterion function
 215 to translate DM preferences into an optimization problem (D1). To do so, we start by looking back
 216 at global criterion methods, since plugging in our transformation $\mathbf{u} = \phi(\mathbf{y})$ simplifies the problem
 217 in Eq. 3 to $\min_h \|\mathbf{u}\|_*$ as the ideal point becomes the origin, i.e., $\mathbf{u}^{\text{ideal}} = \mathbf{0}$. Then, by using the
 218 approximation described in §3.2, the problem becomes a simple finite search of the form

$$\min_{i \in \{1, 2, \dots, N\}} \|\hat{\mathbf{u}}_i\|_* \quad (10)$$

219 That is, we have reduced our problem to finding the model whose ranking vector has the smallest
 220 norm. Using this new *marginal-free global-criterion method*, mapping the DM preferences now boils
 221 down to selecting an appropriate norm for the problem in Eq. 10. To this end, we propose to use as
 222 criterion function C a norm with parameters $p \geq 1$ and $\omega \in \mathbb{R}_+^K$ defined as

²In fact, it is known to be a consistent estimator [55].

$$\|\mathbf{u}\|_{p,\omega} := \left(\sum_{k=1}^K |\omega_k \mathbf{u}_k|^p \right)^{1/p}, \quad (11)$$

where $\sum_k \omega_k = 1$. This norm can be interpreted as a regular p -norm on a space with coordinates scaled by ω . More remarkably, note that this differs from the usual weighted p -norm, as the weights are *inside* the absolute value. We justify this choice given that the values of $\mathbf{u}_k$ lie in the unit interval, and the power would often make them vanish too quickly, as we demonstrate in Fig. 10.

How can we interpret the parameters? Fortunately, the parameters of the proposed criterion function, p and ω , provide an easy and interpretable way for the DM to navigate the Pareto front (D2). Regarding ω , as we apply them in Eq. 11 *before* taking the power, we can provide a clear interpretation of ω in terms of ratio trade-offs. For example, if we had two objectives with $\omega = [0.75, 0.25]$, then we can see by equating the weighted objectives that minimizing the first objective to a value of $\mathbf{u}_1$ is worth the same as minimizing the second objective to a value of $\mathbf{u}_2 = \omega_1/\omega_2 \mathbf{u}_1 = 3\mathbf{u}_1$, i.e., $\mathbf{u}_1$ is three times more important than $\mathbf{u}_2$. If we combine this interpretation with that of $\mathbf{u}$ given in §3.1, we could say, e.g., that we value being in the top-25 % of the models for the first objective the same as being in the top-75 % for the second objective.

We can interpret p using the same intuition as in ML regularization [16]: the models selected in Eq. 10 are those first intersecting an ever-expanding p -ball centered at the origin, whose shape depends on p . Higher values of p lead to denser objective vectors, while smaller values lead instead to sparser ones. Additionally, some values of p have clear interpretations: $p = 1$ is the average rank; $p = 2$ is the Euclidean distance; and $p = \infty$ turns Eq. 10 into a min-max problem, typically used to formulate robust optimization problems [56].

Does Eq. 11 enjoy theoretical guarantees? Given the similarity with commonly-used norms, it is natural to ask whether we can leverage existing results from the MOO literature and adapt them to the proposed norm. This is indeed the case, and we can easily guarantee, e.g., that the solutions found using Eq. 11 with $1 \leq p < \infty$ are always Pareto-optimal [40, Thm. 3.4.1]. However, it might not reach all optima. Similarly, note that $p = \infty$ reduces Eq. 10 to a weighted Tchebycheff problem which reaches any Pareto-optimal solution [40, Thm. 3.4.5], but also weakly optimal ones.

In practice, using a weighted Tchebycheff problem ($p = \infty$) is a good practice when we have few objectives and a large budget for the weights ω to test. Instead, when interested in finding a particular model (i.e., solving Eq. 5 once), we suggest setting p based on the level of robustness desired (as lower values of p lead to higher tolerance to bad performance on individual objectives), and ω based on the importance of solving each objective given by the DM.

4 Related work

Our work draws connections with other scientific domains, e.g., the notion of semantically incomparability is akin to that of incommensurability in dimensional analysis [2]. Similarly, using relative rankings to make better comparisons has been previously explored in microeconomics [47], MOO [23, 31], and statistics, designing methods that avoid the normality assumption, e.g., the Friedman test [13], Wilcoxon signed-rank test [60], or Kendall’s τ coefficient [28]. Finally, as mentioned in §2, copulas exploit the probability integral transform to become marginal-distribution-free [14], and the proposed criterion functions share similarities with weighted L_p -problems in MOO [40].

In ML, the closest work to ours is Park et al. [46], which learns the joint CDF, approximated with a copula, to recover a partial order for multi-objective Bayesian optimization. In contrast, we employ marginal CDFs and provide a principled way to translate DM preferences to an optimization problem. Another line of related works are those that attempt to learn the Pareto front either for model merging [7, 32] or a posteriori MOO methods [64]. Unfortunately, these methods fail to address semantic incomparability as they use the raw objectives. ROC curves [11] provide an interesting connection, since their axes can be understood as the CDFs of the target classes [18]. In practice, many prior works proposed ad hoc approaches to normalize and aggregate objectives using, e.g., normalized RMSEs [44, 57]—we refer to §8.3 of Japkowicz and Shah [24] for other references. Notoriously, some works in multitask learning [33, 43] and domain generalization [48] use rank averages to aggregate objectives, yet the standard is to use the average of Δ_k -normalized objectives (see Eq. 6). COPA can benefit these two areas, along any others accounting for several objectives such as fair ML [39], federated learning [27], probabilistic ML [26], and multimodal learning [1].

5 COPA in action

In this section, we motivate the use of COPA by showing a range of practical scenarios which would benefit from adopting the proposed methodology. We defer additional details and results to §A.

5.1 Synthetic evaluation

To qualitative assess COPA, we consider a synthetic Pareto front of the form $y_2 = 0.25 \cos(39y_1^{0.85}) - \log(y_1) - 0.46$ where $y_1 \sim \mathcal{U}(0.02, 0.2)$. We obtain as a result a non-convex Pareto front with a flat area around $y_1 = 0.1$, and two objectives with significantly different distributions.

Does the parameter p match our intuitions?

We corroborate the insights from §3.3 by showing in Fig. 3 the distribution of solutions found taking different values of p . First, note that since the front is *strictly* increasing except in $[0.083, 0.091]$, we have that $u_1 \approx 1 - u_2$. As a result, we see that $p = 1$ almost exclusively finds solutions on the extrema. When we increase p , the distribution of solutions better spreads along the front and, as the p -balls become more square-like, we gain finer control on the solution found by tuning α . It is important to stress, however, that the finer control of $p = \infty$ comes at cost: as we increase K , finding a proper ω could prove challenging.

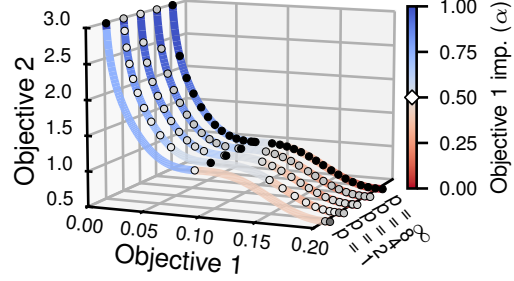


Figure 3: Distribution of solutions (circles) found for different values of p as we sweep over values of α . The darkness of the circles represents the number of times they were selected.

5.2 Case 1: Model selection

First, we explore how the norm proposed in §3.3 can help us explore the Pareto front more meaningfully, i.e., how sensibly it maps the DM preferences to Eq. 5.

1. The performance-emissions trade-off. Despite LLMs recently showing outstanding performance [42], their CO₂ footprint can be concerning and needs to be taken into account [9]. Next, we show how practitioners can leverage COPA to better navigate this crucial trade-off in the LLM space.

We gather the results of 2148 LLMs submitted to the Open LLM Leaderboard [12] and take as objectives their inference CO₂ cost and performance on 6 different datasets: IFEval [65], BBH [54], MATH [20], GPQA [49], MuSR [52], and MMLU-Pro [58]. Then, we use COPA with $p = \infty$ to select an LLM, changing ω as we vary the importance given to their CO₂ footprint, denoted by α , as $\omega := [\alpha, (1-\alpha)/6, \dots, (1-\alpha)/6]$.

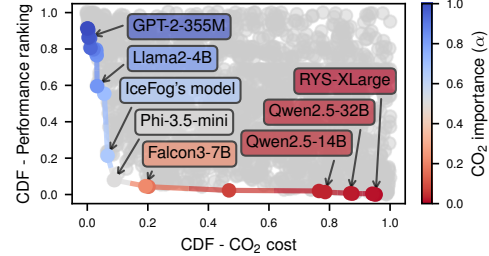


Figure 4: We can meaningfully explore the Pareto-optimal models of the Open LLM Leaderboard [12] with COPA. We use $p = \infty$ on the 7 objectives and highlight some of the selected models as we change the value of α .

We highlight the selected LLMs in Fig. 4, which groups all benchmarks into one dimension as their ∞ -norm for visualization purposes. We observe that the proposed norm enables the meaningful exploration of the Pareto front, with the values of α being uniformly spread-out across the front. Furthermore, not only can we sensibly explore the LLM space, but COPA enables interpreting these models in terms of the original objectives *and* the population they live in. For example, we can say that GPT-2 is Pareto-optimal as it consumes the least, but it only achieves a 6 % average performance score, or that Phi-3.5-mini is a top-10 % model in both aspects, consuming 0.53 kg of CO₂ vs. the 13 kg consumed by the best-performing model.

2. The fairness-accuracy trade-off. Moving to a more classic example, we consider how a DM could use COPA to choose a trade-off between accuracy and fairness in a classification problem, two objectives which are defined in completely different ways [62].

We reproduce the CelebA [34] experiment from Maheshwari and Perrot [37] using FairGrad—an algorithm whose hyperparameter ϵ upper-bounds the unfairness of the classifier—and create a population of models by sweeping through values of ϵ and five random initializations.

Fig. 5 (left) shows the Pareto front in the accuracy-fairness space, as we navigate it by changing α , clearly showing the difference between both objectives. Note that directly solving Eq. 3 leads to the solution with maximum accuracy, as in §5.1. Instead, using COPA we can uniformly navigate the Pareto front where, e.g., the robust min-max solution ($\alpha = 1/2$) lies precisely in the middle of the front. As a result, COPA offers a more reliable interpretation of its parameters than the upper-bound given by ϵ , which is clear by observing that, e.g., a value of $\epsilon = 1$ or 0.25 yields relatively similar solutions in Fig. 5.

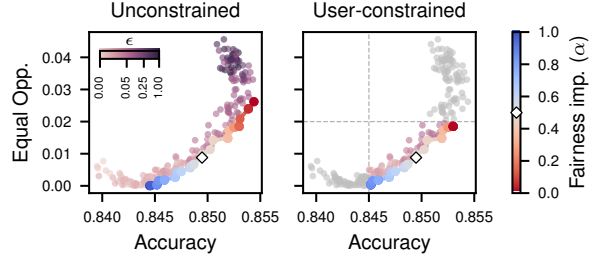


Figure 5: COPA can be used to meaningfully explore the Pareto front between accuracy and fairness (equal opportunity) in the CelebA experiment from Maheshwari and Perrot [37] in unconstrained (left) as well as user-constrained scenarios (right).

In addition, we consider a more realistic scenario where DMs bargain on acceptable values for the objectives, e.g., a regulatory body could demand equal opportunity to never exceed 0.02 [36]. Despite constraining the Pareto front to consider only valid solutions (we still use invalid ones to approximate the CDF), COPA stills provides a sensible way to navigate the space of valid models, proving that we can easily combine rules on the original and CDF-transformed objective spaces.

5.3 Case 2: Comparative model analysis

Previously, we have explored how DMs can meaningfully explore the Pareto front. Now, we focus on a related but different question: *How much could semantic incomparability alter the conclusions we draw from comparative analyses in ML research?*

1. Incomparable objectives. First, we consider a multitask learning (MTL) setting, where the heterogeneity of the tasks to solve makes it prone to face incomparable objectives. In fact, it is common to aggregate objectives with the average relative performance, Δ , as discussed in §4. To clearly showcase the issue, we look at the multi-SVHN experiment from Javaloy and Valera [25], which uses a modified version of SVHN [45] with a digit on each side of the image, and where we solve three classification tasks: **i)** left digit; **ii)** right digit; and **iii)** parity of their product; and two regression tasks: **iv)** sum of digits; and **v)** number of active pixels in the image.

Fig. 6 shows the ranking of the 14 MTL methods considered by Javaloy and Valera [25], if we were to use different criterion functions, namely: COPA with different values of p and equal weights, the average relative performance, Δ , and the regression error over the density task. The first two columns of the plot make extremely clear how much the density task dominates the average relative performance, perfectly matching its ranking. Again, this is a result of the reference method having nearly zero regression error on this task, greatly magnifying its relative performance, Δ_k .

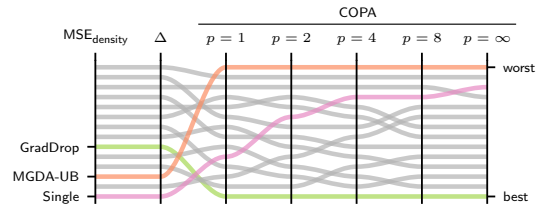


Figure 6: Ranking of MTL methods using different criteria to evaluate them. Methods whose rankings drastically change with Δ are colored.

As expected, the outlined issue has a tremendous impact on the conclusions drawn, e.g.: **i)** the *worst* method for all COPA instances, MGDA-UB [50], becomes the 3rd best method w.r.t. Δ ; or **ii)** the best one for every COPA, GradDrop [8], becomes the 6th best. Fig. 6 also shows that the reference method (Single) is among the least robust models ($p = \infty$), and slowly improves as we look less at individual performances ($p = 1$). It is worth-noting that the authors were aware of the issue and left the density task out when aggregating objectives, reporting both Δ and density MSE as a pair.

2. Seemingly comparable objectives. Sometimes, semantic incomparability can arise in unexpected scenarios. We take domain generalization as an example and, in particular, the DomainBed [17] experiment from Hemati et al. [19]. Here, the authors compare different methods by training them on some domains, and testing them on 4 unseen ones, reporting the average domain accuracy as commonly done in the literature.

Fig. 7 shows the ranking of the considered methods as we use different criterion functions, with the average accuracy in the first column. For two of the highlighted methods, RSC [22] and SagNet

[41], we observe their performance deteriorate and improve, respectively, as we consider less robust criteria, in accordance with the average accuracy. However, we see a different story with HGP [19] and Mixup [59], whose rankings are consistent for all COPA instances, but drastically change when we average accuracies. This leads to significantly different analyses concluding, e.g., that Mixup is worse than SagNet and HGP, in disagreement with every other criterion function.

In fact, accuracies present *significantly different ranges* across domains (see Tab 2) and differences in domains with less variance are less important in the average computation. If we normalize the results using norm_k (Eq. 6), we see that Mixup significantly outperforms HGP in these domains, swapping their rankings. This can also be observed in Fig. 7, where norm aligns much better with COPA.

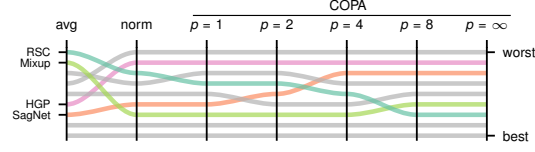


Figure 7: Ranking of domain generalization methods as we change the criterion function. Average accuracy is inconsistent with every COPA instance.

5.4 Case 3: Benchmarking

Finally, we motivate the use of COPA and CDF-normalized objectives in general benchmarking where, in contrast with the previous use cases, objectives are not necessarily aggregated into a scalar value, but plotted together. Additional plots can be found in §A.5.

We take the AutoML Benchmark (AMLB) [15] for the use-case as it “follows best practices and avoids common mistakes when comparing frameworks.” We reproduce all figures from the original work, comparing 15 AutoML methods evaluated on 104 different objectives. Since objectives are incomparable, the authors scale them using norm_k (Eq. 6) with a random forest as reference model, providing a number of analyses from these objectives. Remarkably, the authors also encourage the use of CD diagrams and Friedman tests, two methods that based on relative rankings.

A natural step is therefore to use CDF-normalized objectives. Fig. 8 shows the same AMLB boxplot using scaled and CCDF performance, i.e., $1 - F_k(y_k)$. We find that using CCDFs comes with several benefits: *i)* there are no outliers to report, unlike in the original plot (all values lie in $[0, 1]$); *ii)* there is no need for an arbitrary reference model; and *iii)* we can provide clear population-based interpretations, e.g., “on average, AutoGluon(B) [10] yields over top-10 % performance on the considered objectives.” These benefits extend to all AMLB plots, demonstrating that the proposed CDF transformation is a sensible way of normalizing objectives in general.

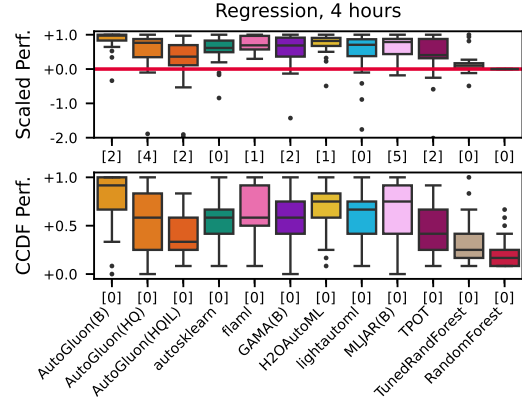


Figure 8: Comparison of AutoML methods on AMLB [15] using scaled performance, norm , with a random forest as reference method (red line); and using a CCDF-transformation (bottom). Brackets indicate the number of off-view outliers.

6 Concluding remarks

In this work, we have shown the importance of meaningfully navigating the Pareto front in multi-objective ML evaluation, allowing users to perform better-informed decisions. To this end, we have highlighted how crucial is to properly normalize all objectives and to have a criterion function that sensibly reflects DM preferences into an optimization problem. Finally, we have implemented these insights in COPA, and extensively demonstrated the impact that it can have in areas as fundamental and timely as model selection and benchmarking.

Our work opens many intriguing venues for future research. For example, we would be excited to see COPA adapted to active settings with humans-in-the-loop, criterion functions that parametrize other preference types, a formal systematization of model selection enabled by COPA, or its adoption in public portals such as the Open LLM Leaderboard [12] or the DecodingTrust benchmark [57].

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