



## 02. Picking a Direction



## Let's Second-Guess Ourselves

**However, let's not discount the prediction-focused approach yet**

In fact, it's easy to see that:

$$\begin{aligned}\mathbb{E}[\text{regret}(\hat{y}, y)] &\longrightarrow 0 \\ \mathbb{E}[L(\hat{y}, y)] &\rightarrow 0\end{aligned}$$

Intuitively::

- The more accurate we can be, the lower the regret
- Eventually, perfect predictions will result in 0 regret



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- Eventually, perfect predictions will result in 0 regret

**But then... What if we make our model bigger?**

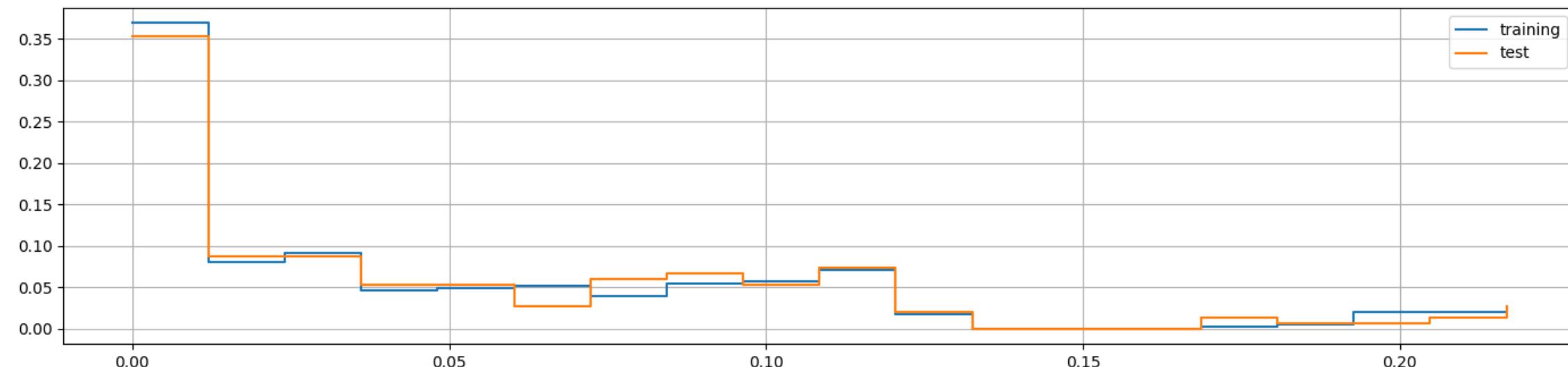
- We could get good predictions **and** good regret
- ...And training would be **much** faster



# Our Baseline

Let's check again the results for our PFL linear regressor

```
In [2]: pfl = util.build_nn_model(input_shape=1, output_shape=nitems, hidden=[], name='pfl_det', output_
history = util.train_nn_model(pfl, data_tr.index.values, data_tr.values, epochs=1000, loss='mse')
r_tr = util.compute_regret(prb, pfl, data_tr.index.values, data_tr.values)
r_ts = util.compute_regret(prb, pfl, data_ts.index.values, data_ts.values)
util.plot_histogram(r_tr, figsize=figsize, label='training', data2=r_ts, label2='test', print_m
```



Mean: 0.052 (training), 0.053 (test)



This will be our main baseline

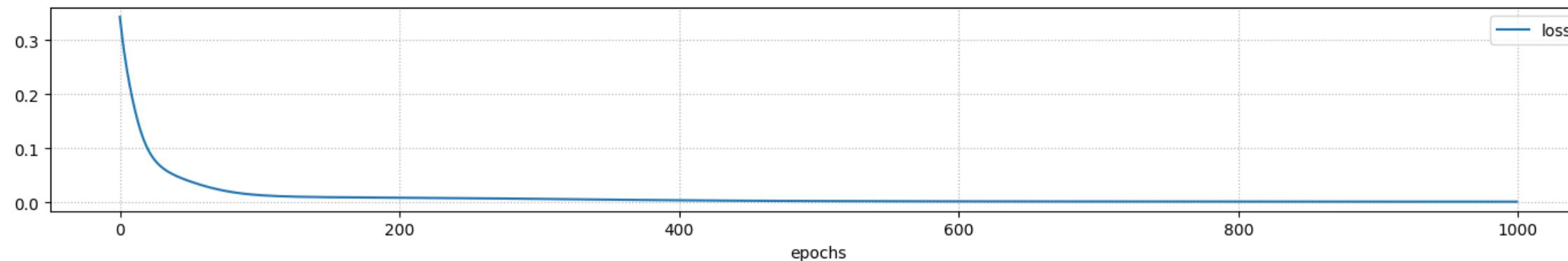
# PFL Strikes Back

Let's try to use a non-linear model

```
In [3]: pfl_acc = util.build_nn_model(input_shape=1, output_shape=nitems, hidden=[8], name='pfl_det_acc')
%time history = util.train_nn_model(pfl_acc, data_tr.index.values, data_tr.values, epochs=1000,
util.plot_training_history(history, figsize=figsize_narrow, print_final_scores=False)
util.print_ml_metrics(pfl_acc, data_tr.index.values, data_tr.values, label='training')
util.print_ml_metrics(pfl_acc, data_ts.index.values, data_ts.values, label='test')
```

CPU times: user 10.3 s, sys: 367 ms, total: 10.7 s

Wall time: 7.95 s



R2: 0.99, MAE: 0.019, RMSE: 0.03 (training)

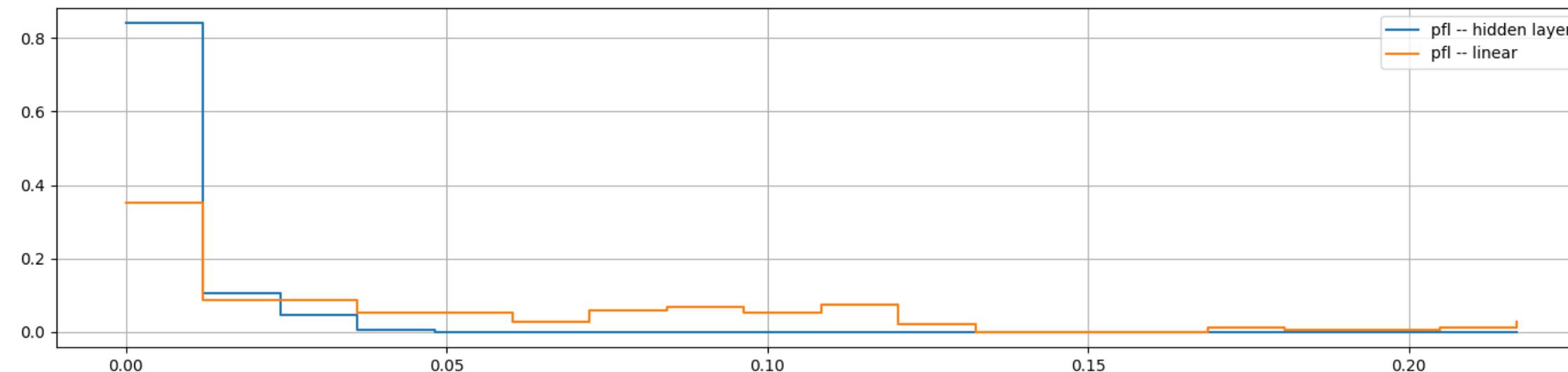
R2: 0.99, MAE: 0.019, RMSE: 0.03 (test)

More accurate, it is!

# PFL Strikes Back

...And the improvement in terms of regret is remarkable

```
In [4]: r_ts_acc = util.compute_regret(prb, pfl_acc, data_ts.index.values, data_ts.values)
util.plot_histogram(r_ts_acc, figsize=figsize, label='pfl -- hidden layer', data2=r_ts, label2='
```



Mean: 0.005 (pfl -- hidden layer), 0.053 (pfl -- linear)

DFL might do better with the same model complexity, but we the return would be diminished



## **Evening the Field**

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**Can't we do anything about it?**

- DFL predictions will always be off (more or less)
- ...But there are ways to make the approach faster



# Evening the Field

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## Can't we do anything about it?

- DFL predictions will always be off (more or less)
- ...But there are ways to make the approach faster

## For example:

- You can use a **problem relaxation**, as in [1]
- You can limit recomputation by caching past solutions, as in [2]
- You can warm start the DFL approach with the PFL weights

Let's see the last two tricks in deeper detail



# Evening the Field

## Can't we do anything about it?

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- ...But there are ways to make the approach faster

### For example:

- You can use a **problem relaxation**, as in [1]
- You can limit recomputation by caching past solutions, as in [2]
- You can warm start the DFL approach with the PFL weights

Let's see the last two tricks in deeper detail

[1] Mandi, Jayanta, and Tias Guns. "Interior point solving for  $lp$ -based prediction+ optimisation." *Advances in Neural Information Processing Systems* 33 (2020): 7272-7282.

[2] Maxime Mulamba, Jayanta Mandi, Michelangelo Diligenti, Michele Lombardi, Victor Bucarey, Tias Guns: Contrastive Losses and Solution Caching for Predict-and-Optimize. *IJCAI* 2021: 2833-2840



# Solution Cache and Warm Start

**Solution caching is applicable if the feasible space is fixed**

i.e. to problems in the form:

$$z^*(y) = \operatorname{argmin}_z \{ f(z) \mid z \in F \}$$

- During training, we maintain a solution cache  $S$
- Initially, we populate  $S$  with the true optimal solutions  $z^*(y_i)$  for all examples
- Before computing  $z^*(\hat{y})$  we flip a coin
- With probability  $p$ , we run the computation (and store any new solution in  $S$ )
- With probability  $1 - p$ , we solve instead  $\hat{z}^*(y) = \operatorname{argmin}_z \{ f(z) \mid z \in S \}$

**Warm starting simple consists in using the PFL weights to initialize  $\theta$**

Since accuracy is correlated with regret, this might accelerate convergence



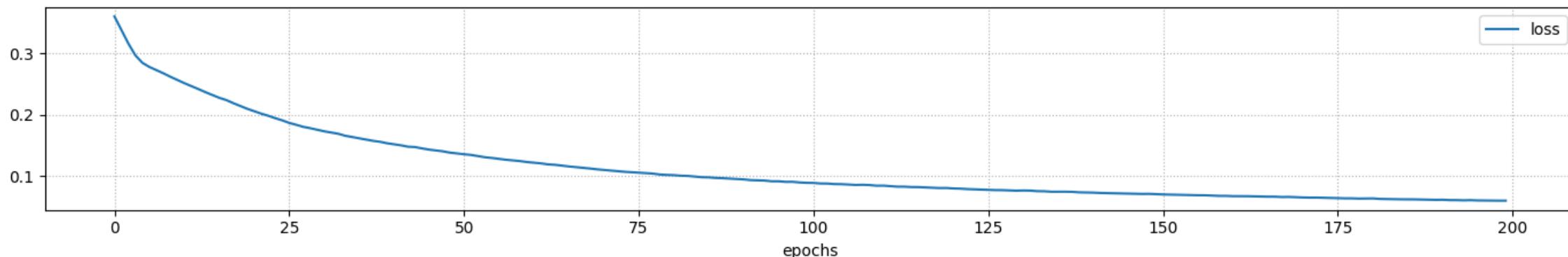
# Speeding Up DFL

Let's use DFL **with linear regression**, a warm start, and a solution cache

```
In [5]: spo = util.build_dfl_ml_model(input_size=1, output_size=nitems, problem=prb, hidden=[], name='spo')
%time history = util.train_dfl_model(spo, data_tr.index.values, data_tr.values, epochs=200, verbose=True)
util.plot_training_history(history, figsize=figsize_narrow, print_final_scores=False)
util.print_ml_metrics(spo, data_tr.index.values, data_tr.values, label='training')
util.print_ml_metrics(spo, data_ts.index.values, data_ts.values, label='test')
```

CPU times: user 50.8 s, sys: 4.91 s, total: 55.7 s

Wall time: 55.4 s



R2: 0.65, MAE: 0.12, RMSE: 0.16 (training)

R2: 0.65, MAE: 0.12, RMSE: 0.16 (test)

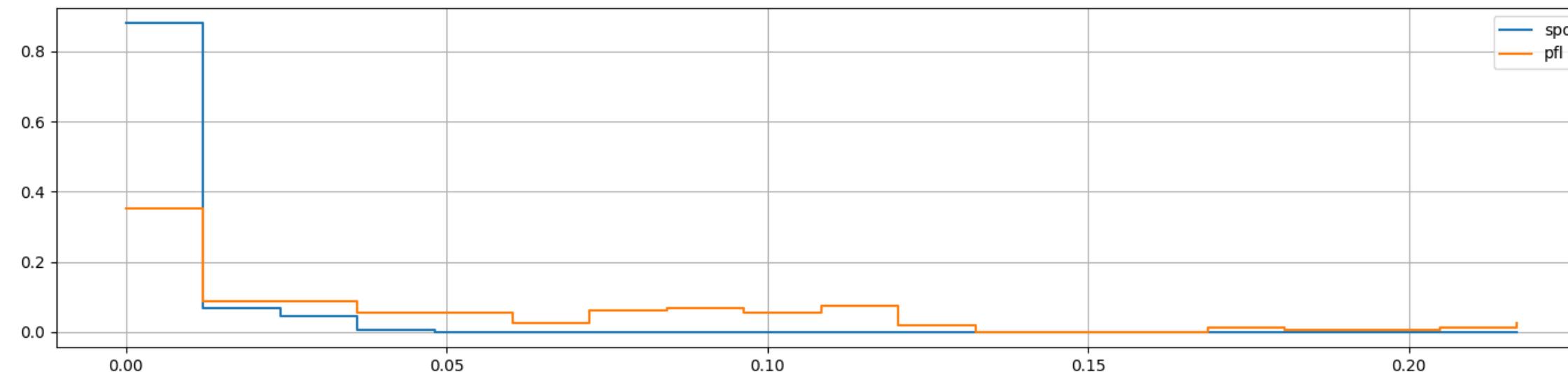


The training time is still large, but much lower than our earlier DFL attempt

# Speeding Up DFL

And the regret is even better!

```
In [6]: r_ts_spo = util.compute_regret(prb, spo, data_ts.index.values, data_ts.values)
util.plot_histogram(r_ts_spo, figsize=figsize, label='spo', data2=r_ts, label2='pfl', print_mean=True)
```



Mean: 0.004 (spo), 0.053 (pfl)

We are matching the more complex PFL model with a simple linear regressor



# Reflecting on What we Have

## Therefore, DFL gives us at least **two benefits**

First, it can lead to **lower regret** compared to a prediction-focused approach

- As the models become more complex we have diminishing returns
- ...But for some applications every little bit counts

Second, it may allow using **simpler ML models**

- Simple models are faster to evaluate
- ...But more importantly they are **easier to explain**
- E.g. we can easily perform feature importance analysis



# Reflecting on What we Have

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**Intuitively, DFL works best where PFL has estimation issues**

Can we exploit this fact to maximize our advantage?



# Maximizing Results

There's a simple case where PFL **cannot make perfect predictions**



You just need to target a stochastic problem!

- E.g. you can **usually** tell the traffic situation based on (e.g.) time and weather
- ... But there still a lot of variability

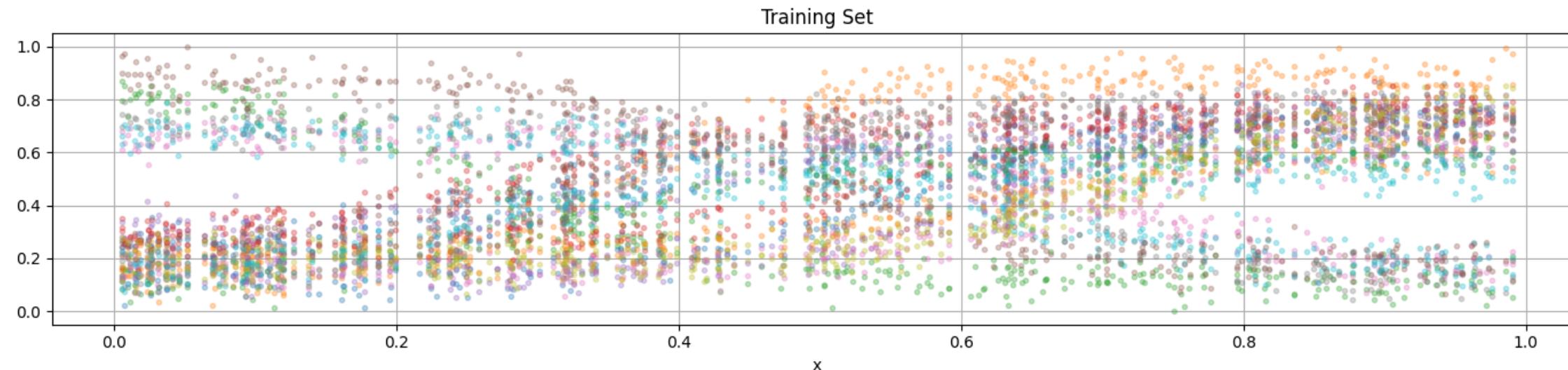


# Maximizing Results

**Formally, we need a stochastic process, i.e. a stochastic function**

We can generate for a stochastic variant of our problem

```
In [8]: data_tr = util.generate_costs(nsamples=350, nitems=nitems, seed=seed, noise_scale=.15, noise_type='uniform')
util.plot_df_cols(data_tr, figsize=figsize, title='Training Set', scatter=True)
```



We treat both  $X$  and  $Y$  as random variables, with distribution  $P(X, Y)$



# Adjusting Goals

**But with a stochastic process, what is our real objective?**

For a given  $x$ , we can formalize it like this:

$$\operatorname{argmin}_z \left\{ \mathbb{E}_{y \sim P(Y|X=x)} [y^T z] \mid z \in F \right\}$$

- Given a value for the observable  $x$
- We want to find a single decision vector  $z$
- Such that  $z$  is feasible
- ...And  $z$  minimized the **expected cost** over the distribution  $P(Y \mid X = x)$

This is called a **one-stage stochastic optimization problem**



## ...And Keeping the Setup

Let's look again at the DFL training problem

$$\theta^* = \operatorname{argmin}_{\theta} \{ \mathbb{E}_{(x,y) \sim P(X,Y)} [\text{regret}(\hat{y}, y)] \mid \hat{y} = h(x, \theta) \}$$

With:

$$\text{regret}(\hat{y}, y) = y^T z^*(\hat{y}) - y^T z^*(y)$$

Since  $y^T z^*(y)$  is independent on  $\theta$ , this is equivalent to:

$$\theta^* = \operatorname{argmin}_{\theta} \{ \mathbb{E}_{(x,y) \sim P(X,Y)} [y^T z^*(\hat{y})] \mid \hat{y} = h(x, \theta) \}$$

Which can be rewritten as:

$$\theta^* = \operatorname{argmin}_{\theta} \{ \mathbb{E}_{x \sim P(X), y \sim P(Y|X)} [y^T z^*(\hat{y})] \mid \hat{y} = h(x, \theta) \}$$



## ...And Keeping the Setup

Now, let's restrict to the case where  $x$  is fixed

$$\theta^* = \operatorname{argmin}_{\theta} \{ \mathbb{E}_{y \sim P(Y|X=x)} [y^T z^*(\hat{y})] \mid \hat{y} = h(x, \theta) \}$$

Finally, by definition of  $z^*(\cdot)$  we have:

$$\theta^* = \operatorname{argmin}_{\theta} \{ \mathbb{E}_{y \sim P(Y|X=x)} [y^T z^*(\hat{y})] \mid \hat{y} = h(x, \theta), z^*(\hat{y}) \in F \}$$

In other words:

- We are choosing  $\theta$
- So that  $z^*(\hat{y})$  minimizes  $\mathbb{E}_{y \sim P(Y|X=x)} [y^T z^*(\hat{y})]$

This is almost identical to one-stage stochastic optimization!



# DFL For One-Stage Stochastic Optimization

This means that DFL can address these problems, with one restriction and two "superpowers":

The restriction is that we control  $z$  only through  $\theta$

- Therefore, depending on the chosen ML model architecture
- ...Obtaining some solutions might be impossible
- This issue can be sidestepped with a careful model choice

**The first superpower is that we are not restricted to a single  $x$  value**

- Given a new value for  $x$ , we just need to evaluate  $h(x, \theta^*)$
- ...And then solve the usual optimization problem
- Many approaches do not deal with the estimation of the  $y$  distribution

**For the second superpower, we need to investigate a bit more**



# Classical Solution Approach

**What would be the classical solution approach?**

Starting from:

$$\operatorname{argmin}_z \left\{ \mathbb{E}_{y \sim P(Y|X=x)} [y^T z] \mid z \in F \right\}$$

We can use linearity to obtain:

$$\operatorname{argmin}_z \left\{ \mathbb{E}_{y \sim P(Y|X=x)} [y]^T z \mid z \in F \right\}$$

- So, we would first need to estimate the expected costs
- ...Then we could solve a deterministic problem



# Classical Solution Approach

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- So, we would first need to estimate the expected costs
- ...Then we could solve a deterministic problem

But isn't this what PFL is doing?



# Regression and Expectation

## (Stochastic) Regression is often presented as learning an expectation

...But it's trickier than that

- Using an MSE loss is equivalent to trying to learn  $\mathbb{E}_{y \sim P(Y|X=x)} [y]$
- ...But only assuming that  $P(Y | X = x)$  is **Normally distributed**
- ...And that it has **the same variance everywhere**

## It is possible to do the same under more general conditions

...But it is much more complex

- If we know the distribution type, we can use a neuro-probabilistic model
- Otherwise, we need a fully fledged contextual generative model

In DFL, we can address this problem with 0 added effort!



# A Simple Stress Test

We can test this idea by generating a stochastic dataset

```
In [34]: data_tr = util.generate_costs(nsamples=350, nitems=nitems, seed=seed, noise_scale=.2, noise_type='gaussian')
data_ts = util.generate_costs(nsamples=150, nitems=nitems, seed=seed, sampling_seed=seed+1, noise_type='gaussian')
util.plot_df_cols(data_tr, figsize=figsize, title='Training Set', scatter=True)
```



...And scaling the variance with  $y$  (a very common setting in practice)



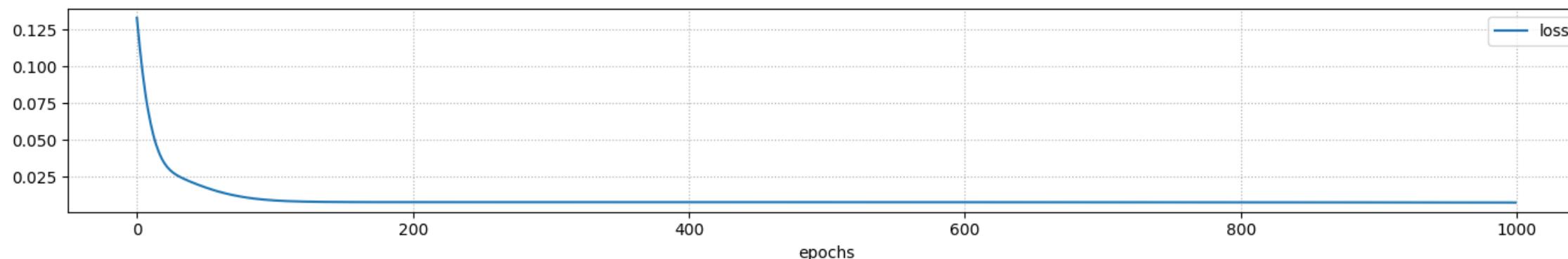
# Training a PFL Approach

We will train again a non-linear prediction focused approach

```
In [36]: pfl_1s = util.build_nn_model(input_shape=1, output_shape=nitems, hidden=[8], name='pfl_1s', output_activation='softmax')
@time history = util.train_nn_model(pfl_1s, data_tr.index.values, data_tr.values, epochs=1000, batch_size=128)
util.plot_training_history(history, figsize=figsize_narrow, print_final_scores=False)
util.print_ml_metrics(pfl_1s, data_tr.index.values, data_tr.values, label='training')
util.print_ml_metrics(pfl_1s, data_ts.index.values, data_ts.values, label='test')
```

CPU times: user 9.74 s, sys: 330 ms, total: 10.1 s

Wall time: 7.53 s



R2: 0.81, MAE: 0.068, RMSE: 0.09 (training)

R2: 0.82, MAE: 0.068, RMSE: 0.08 (test)

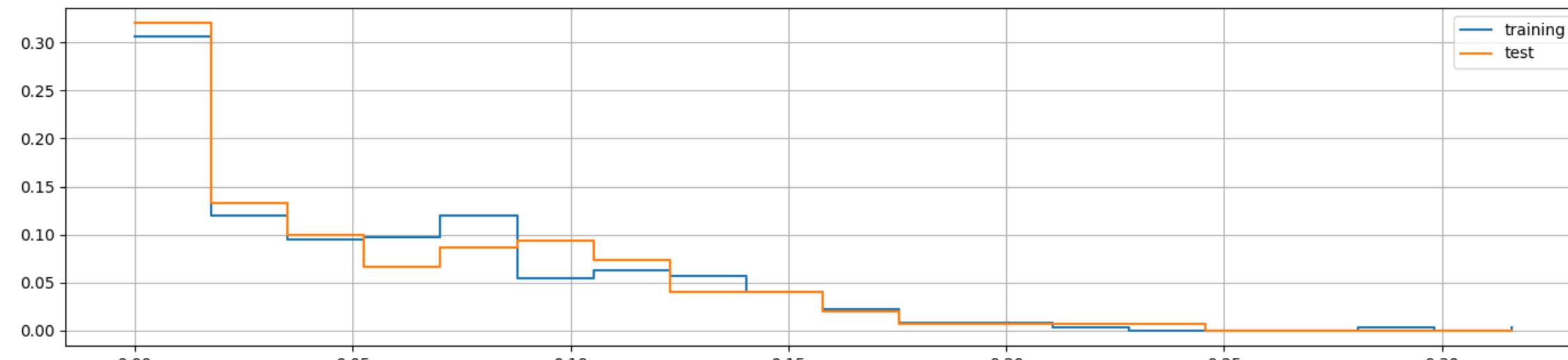


The accuracy is (inevitably) worse, but still pretty good

# PFL Regret

Let's evaluate the regret of the PFL approach

```
In [37]: r_tr_1s = util.compute_regret(prb, pfl_1s, data_tr.index.values, data_tr.values)
r_ts_1s = util.compute_regret(prb, pfl_1s, data_ts.index.values, data_ts.values)
util.plot_histogram(r_tr_1s, figsize=figsize, label='training', data2=r_ts_1s, label2='test', pr
```



Mean: 0.059 (training), 0.057 (test)

The regret has worsened, due to the effect of uncertainty



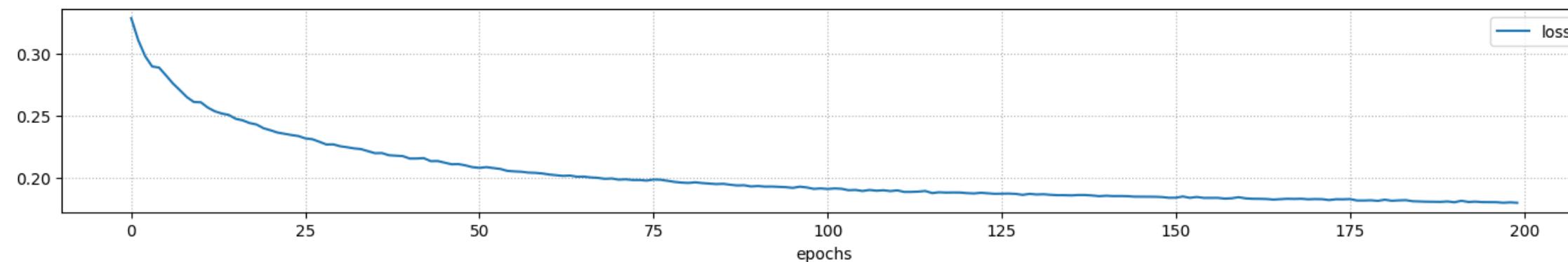
# Training a DFL Approach

We also a DFL approach with the same non-linear model

```
In [39]: spo_1s = util.build_dfl_ml_model(input_size=1, output_size=nitems, problem=prb, hidden=[8], name='spo_1s')
history = util.train_dfl_model(spo_1s, data_tr.index.values, data_tr.values, epochs=200, validation_split=0.2)
util.plot_training_history(history, figsize=figsize_narrow, print_final_scores=False)
util.print_ml_metrics(spo_1s, data_tr.index.values, data_tr.values, label='training')
util.print_ml_metrics(spo_1s, data_ts.index.values, data_ts.values, label='test')
```

CPU times: user 2min 51s, sys: 11min 19s, total: 14min 11s

Wall time: 1min 23s



R2: 0.27, MAE: 0.12, RMSE: 0.19 (training)

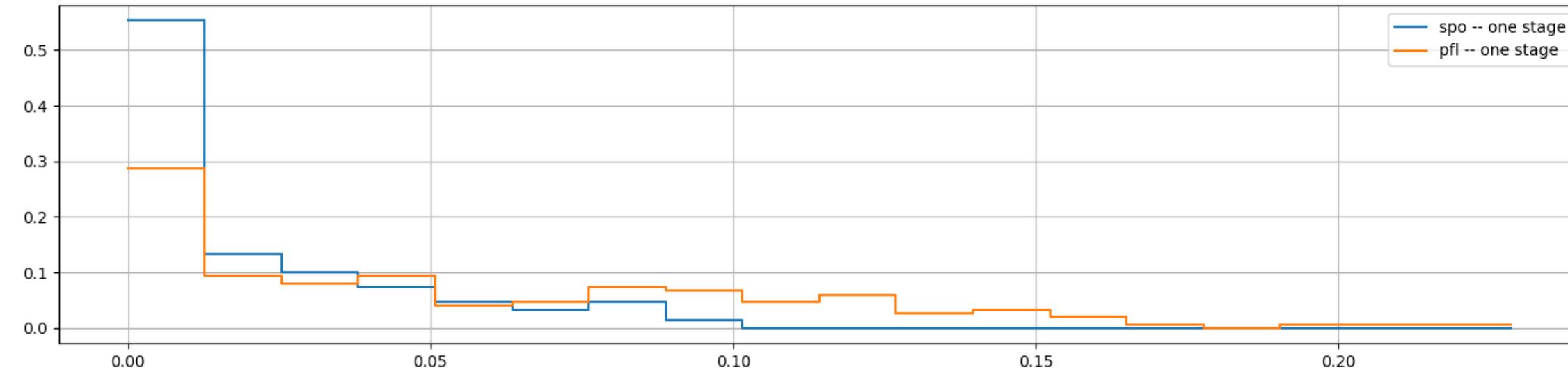
R2: 0.27, MAE: 0.12, RMSE: 0.19 (test)



# DFL Regret

Now we can compare the regret for both approaches

```
In [40]: r_ts_spo_1s = util.compute_regret(prb, spo_1s, data_ts.index.values, data_ts.values)
util.plot_histogram(r_ts_spo_1s, figsize=figsize, label='spo -- one stage', data2=r_ts_1s, label
```



Mean: 0.020 (spo -- one stage), 0.057 (pfl -- one stage)

There is a significant gap again, since the PFL approach is operating on an incorrect semantic



# Considerations

**DFL can be thought of as a one-stage stochastic optimization approach**

In this setting:

- In particular, using a more accurate PFL model might still have poor regret
- ...Unless we know a lot about the distribution
- ...or we use a very complex estimator
- Conversely, DFL has not such issues

The gap becomes wider in case of **non-linear cost functions**:

- In this case the expected cost would not be equivalent to a sum of expectations
- But a DFL approach would have no such issues
- ...Provided it could deal with non-linear functions

