Two-stage stochastic program

V. Leclère

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Presentation Outline

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A standard optimization problem

$$\begin{aligned} \min_{u_0} \quad & L(u_0) \\ s.t. \quad & g(u_0) \leq 0 \end{aligned}$$

where

- u_0 is the control, or decision.
- L is the cost or objective function.
- $g(u_0) \leq 0$ represent the constraint(s).

The (deterministic) newsboy problem

In the 50's a boy would buy a stock u of newspapers each morning at a cost c, and sell them all day long for a price p. The number of people interested in buying a paper during the day is d. We assume that $0 < c < p$.

How shall we model this ?

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How shall we model this ?

- Control $u \in \mathbb{R}^+$
- Cost $L(u) = cu - p\min(u, d)$

Leading to

$$\begin{aligned} \min_{u} \quad & cu - p\min(u, d) \\ s.t. \quad & u \geq 0 \end{aligned}$$

An optimization problem with uncertainty

Adding uncertainty ξ in the mix

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Remarks:

- ξ is unknown. Two main ways of modelling it:
  - $\xi \in \Xi$ with a known uncertainty set Ξ, and a pessimistic approach. This is the robust optimization approach (RO).
  - ξ is a random variable with known probability law. This is the Stochastic Programming approach (SP).

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- Cost is not well defined.
    - RO : $\max_{\xi \in \Xi} L(u, \xi)$.
    - SP : $\mathbb{E}\big[L(u, \boldsymbol{\xi})\big]$.

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- Constraints are not well defined.
  - RO : $g(u, \xi) \leq 0, \qquad \forall \xi \in \Xi$.
  - SP : $g(u, \boldsymbol{\xi}) \leq 0, \qquad \mathbb{P} - a.s.$.

The (stochastic) newsboy problem

Demand d is unknown at time of purchasing. We model it as a random variable $\boldsymbol{d}$ with known law. Note that

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- the cost is a random variable (depending of $\boldsymbol{d}$). We choose to minimize its expectation.

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We consider the following problem

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How can we justify the expectation ?
By law of large number: the Newsboy is going to sell newspaper again and again. Then optimizing the sum over time of its gains is closely related to optimizing the expected gains.

Solving the stochastic newsboy problem

For simplicity assume that the demand $\boldsymbol{d}$ has a continuous density f. Define $J(u)$ the expected "loss" of the newsboy if he bought u newspaper. We have

$$\begin{aligned}
J(u) &= \mathbb{E}\left[cu - p\min(u, \boldsymbol{d})\right] \\
&= (c-p)u - p\mathbb{E}\left[\min(0, \boldsymbol{d} - u)\right] \\
&= (c-p)u - p\int_{-\infty}^{u} (x-u)f(x)dx \\
&= (c-p)u - p\Big(\int_{-\infty}^{u} xf(x)dx - u\int_{-\infty}^{u} f(x)dx\Big)
\end{aligned}$$

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$$J(u) = \mathbb{E}\big[cu - p\min(u, \boldsymbol{d})\big]$$

$$= (c-p)u - p\Big(\int_{-\infty}^{u} xf(x)dx - u\int_{-\infty}^{u} f(x)dx\Big)$$

Thus,

$$J'(u) = (c-p) - p\Big(uf(u) - \int_{-\infty}^{u} f(x)dx - uf(u)\Big) = c - p + pF(u)$$

where F is the cumulative distribution function (cdf) of $\boldsymbol{d}$. F being non decreasing, the optimum control u^* is such that $J'(u^*) = 0$, which is

$$u^* \in F^{-1}\Big(\frac{p-c}{p}\Big)$$

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By monotonicity it is equivalent to

$$\begin{aligned} \min_u \quad & cu - p\min(u, \underline{d}) \\ s.t. \quad & u \geq 0 \end{aligned}$$

Alternative cost functions I

- When the cost $L(u, \xi)$ is random it might be natural to want to minimize its expectation $\mathbb{E}\big[L(u, \xi)\big]$.
- This is even justified if the same problem is solved a large number of time (Law of Large Number).
- In some cases the expectation is not really representative of your risk attitude. Lets consider two examples:
    - Are you ready to pay \$1000 to have one chance over ten to win \$10000 ?
    - You need to be at the airport in 1 hour or you miss your flight, you have the choice between two mean of transport, one of them take surely 50', the other take 40' four times out of five, and 70' one time out of five.

Alternative cost functions II

Here are some cost functions you might consider

- Probability of reaching a given level of cost : $\mathbb{P}(L(u, \boldsymbol{\xi}) \leq 0)$
- Value-at-Risk of costs $V@R_\alpha(L(u, \boldsymbol{\xi}))$, where for any real valued random variable $\boldsymbol{X}$,

$$V@R_\alpha(\boldsymbol{X}) := \inf_{t \in \mathbb{R}} \Big\{ \mathbb{P}(\boldsymbol{X} \geq t) \leq \alpha \Big\}.$$

  In other word there is only a probability of α of obtaining a cost worse than $V@R_\alpha(\boldsymbol{X})$.
- Average Value-at-Risk of costs $AV@R_\alpha(L(u, \boldsymbol{\xi}))$, which is the expected cost over the α worst outcomes.

Alternative constraints I

- The natural extension of the deterministic constraint $g(u,\xi) \leq 0$ to $g(u,\boldsymbol{\xi}) \leq 0 \; \mathbb{P} - as$ can be extremely conservative, and even often without any admissible solutions.
- For example, if u is a level of production that need to be greater than the demand. In a deterministic setting the realized demand is equal to the forecast. In a stochastic setting we add an error to the forecast. If the error is unbouded (e.g. Gaussian) no control u is admissible.

Alternative constraints II

Here are a few possible constraints

- $\mathbb{E}\big[g(u,\xi)\big] \leq 0$, for quality of service like constraint.
- $\mathbb{P}(g(u,\xi) \leq 0) \geq 1-\alpha$ for chance constraint. Chance constraint is easy to present, but might lead to misconception as nothing is said on the event where the constraint is not satisfied.
- $AV@R_\alpha(g(u,\xi)) \leq 0$

Presentation Outline

Computing expectation

- Computing an expectation $\mathbb{E}\big[L(u,\xi)\big]$ for a given u is costly.
- If ξ is a r.v. with known law admitting a density, $\mathbb{E}\big[L(u,\xi)\big]$ is a (multidimensional) integral.
- If ξ is a r.v. with known discrete law, $\mathbb{E}\big[L(u,\xi)\big]$ is a sum over all possible realizations of ξ, which can be huge.
- If ξ is a r.v. that can be simulated but with unknown law, $\mathbb{E}\big[L(u,\xi)\big]$ cannot be computed exactly.

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Solution : use Law of Large Number (LLN) and Central Limit Theorem (CLT).

- Draw $N \simeq 1000$ realization of ξ.
- Compute the sample average $\frac{1}{N}\sum_{s=1}^{N} L(u,\xi_s)$.
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This is known as the Monte-Carlo method.

Consequence : evaluating a solution is difficult

- In stochastic optimization even evaluating the value of a solution can be difficult an require approximate methods.
- The same holds true for checking admissibility of a candidate solution.
- It is even more difficult to obtain first order informations (gradient).

Standard solution : sampling and solving the sampled problem (Sample Average Approximation).

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Recall on CLT

- Let $\{C_i\}_{i\in\mathbb{N}}$ be a sequence of identically distributed random variables with finite variance.
- Then the Central Limit Theorem ensures that

$$\sqrt{N}\Big(\frac{\sum_{i=1}^N \boldsymbol{C}_i}{N} - \mathbb{E}[\boldsymbol{C}_1]\Big) \Longrightarrow G \sim \mathcal{N}(0, Var[\boldsymbol{C}_1]) ,$$

where the convergence is in law.
- In practice it is often used in the following way. Asymptotically,

$$\mathbb{P}\Big(\mathbb{E}\big[C_1\big] \in \Big[\bar{\boldsymbol{C}}_N - \frac{1.96\boldsymbol{\sigma}_N}{\sqrt{N}}, \bar{\boldsymbol{C}}_N + \frac{1.96\boldsymbol{\sigma}_N}{\sqrt{N}}\Big]\Big) \simeq 95\% ,$$

where $\bar{\boldsymbol{C}}_N = \frac{\sum_{i=1}^N \boldsymbol{C}_i}{N}$ is the empirical mean and $\boldsymbol{\sigma}_N = \sqrt{\frac{\sum_{i=1}^N (\boldsymbol{C}_i - \bar{\boldsymbol{C}}_N)^2}{N-1}}$ the empirical standard deviation.

Optimization problem and simulator

- Generally speaking stochastic optimization problem are not well posed and often need to be approximated before solving them.
- Good practice consists in defining a simulator, i.e. a representation of the "real problem" on which solution can be tested.
- Then find a candidate solution by solving an (or multiple) approximated problem.
- Finally evaluate the candidate solutions on the simulator. The comparison can be done on more than one dimension (e.g. constraints, risk...)

Conclusion

When addressing an optimization problem under uncertain one has to consider carefully

- How to model uncertainty ? (random variable or uncertainty set)
- How to represent your attitude toward risk ? (expectation, probability level,...)
- How to include constraints ?
- What is your information stucture ? (More on that later)
- Set up a simulator and evaluate your solutions.

Presentation Outline

One-Stage Problems

Assume that $\boldsymbol{\xi}$ has a discrete distribution [1] , with $\mathbb{P}(\boldsymbol{\xi} = \xi_s) = \pi^s > 0$ for $s \in [\![1, S]\!]$. Then, the one-stage problem

$$\begin{aligned} \min_{u_0} \quad & \mathbb{E}\Big[L(u_0, \boldsymbol{\xi})\Big] \\ s.t. \quad & g(u_0, \boldsymbol{\xi}) \leq 0, \qquad \mathbb{P} - a.s \end{aligned}$$

can be written

$$\begin{aligned} \min_{u_0} \quad & \sum_{s=1}^{S} \pi^s L(u_0, \xi_s) \\ s.t \quad & g(u_0, \xi_s) \leq 0, \qquad \forall s \in [\![1, S]\!]. \end{aligned}$$

[1] If the distribution is continuous we can sample and work on the sampled distribution, this is called the Sample Average Approximation approach with lots of guarantee and results

Newsvendor problem (continued)

We assume that the demand can take value $\{d^s\}_{s\in[\![1,S]\!]}$ with probabilities $\{\pi^s\}_{s\in[\![1,S]\!]}$.

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In this case the stochastic newsvendor problem reads

$$\min_u \quad \sum_{s=1}^{S} \pi^s \Big(cu - p\min(u, d^s)\Big)$$
$$s.t. \quad u \geq 0$$

Presentation Outline

Recourse Variable

In most problem we can make a correction u_1 once the uncertainty is known:

$$u_0 \rightsquigarrow \xi_1 \rightsquigarrow u_1 .$$

As the recourse control $\boldsymbol{u}_1$ is a function of $\boldsymbol{\xi}$ it is a random variable. The two-stage optimization problem then reads

$$\begin{aligned} \min_{u_0, \boldsymbol{u}_1} \quad & \mathbb{E}\Big[L(u_0, \boldsymbol{\xi}, \boldsymbol{u}_1)\Big] \\ s.t. \quad & g(u_0, \boldsymbol{\xi}, \boldsymbol{u}_1) \leq 0, \qquad \mathbb{P} - a.s \\ & \boldsymbol{u}_1 \preceq \boldsymbol{\xi} \end{aligned}$$

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Two-stage Problem

The extensive formulation of

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is

$$\begin{aligned} \min_{u_0, \{u_1^s\}_{s \in [\![1,S]\!]}} \quad & \sum_{s=1}^{S} p^s L(u_0, \xi^s, u_1^s) \\ s.t \quad & g(u_0, \xi^s, u_1^s) \leq 0, \qquad \forall s \in [\![1, S]\!]. \end{aligned}$$

It is a deterministic problem that can be solved with standard tools or specific methods.

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We can represent the newsvendor problem in a 2-stage framework.

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The problem reads

$$
\begin{aligned}
\min_{u_0,\boldsymbol{u}_1} \quad & \mathbb{E}\Big[cu_0 - p\boldsymbol{u}_1\Big] \\
s.t. \quad & u_0 \geq 0 \\
& \boldsymbol{u}_1 \leq u_0 && \mathbb{P}-as \\
& \boldsymbol{u}_1 \leq \boldsymbol{d} && \mathbb{P}-as \\
& \boldsymbol{u}_1 \preceq \boldsymbol{d}
\end{aligned}
$$

Two-stage newsvendor problem II

In extensive formulation the problem reads

$$\begin{aligned} \min_{u_0, \{u_1^s\}_{s \in [\![1,S]\!]}} \quad & \sum_{s=1}^{S} \pi^s (c u_0 - p u_1^s) \\ s.t. \quad & u_0 \geq 0 \\ & u_1^s \leq u_0 && \forall s \in [\![1,S]\!] \\ & u_1^s \leq d^s && \forall s \in [\![1,S]\!] \end{aligned}$$

Note that there are as many second-stage control u_1^s as there are possible realization of the demand $\boldsymbol{d}$, but only one first-stage control u_0.

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Presentation Outline

Time decomposition of the problem

We presented the generic two-stage problem as

$$\begin{aligned} \min_{u_0, \boldsymbol{u}_1} \quad & \mathbb{E}\Big[L(u_0, \boldsymbol{\xi}, \boldsymbol{u}_1)\Big] \\ s.t. \quad & g(u_0, \boldsymbol{\xi}, \boldsymbol{u}_1) \leq 0, \qquad \mathbb{P} - a.s \\ & \boldsymbol{u}_1 \preceq \boldsymbol{\xi} \end{aligned}$$

With $L(u_0, \xi, u_1) = L_0(u_0) + L_1(u_0, \xi, u_1)$, it can also be written as

$$\begin{aligned} \min_{u_0} \quad & L_0(u_0) + \mathbb{E}\Big[\tilde{Q}(u_0, \boldsymbol{\xi})\Big] \\ s.t. \quad & g_0(u_0) \leq 0 \end{aligned}$$

where

$$\begin{aligned} \tilde{Q}(u_0, \xi) := \min_{u_1} \quad & L_1(u_0, \xi, u_1) \\ s.t. \quad & g_1(u_0, \xi, u_1) \leq 0 \end{aligned}$$

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$$\begin{aligned} \min_{u_0} \quad & L_0(u_0) + \mathbb{E}\Big[\tilde{Q}(u_0,\boldsymbol{\xi})\Big] \qquad \text{first stage problem} \\ s.t. \quad & g_0(u_0) \leq 0 \end{aligned}$$

where

$$\begin{aligned} \tilde{Q}(u_0,\xi) := \min_{u_1} \quad & L_1(u_0,\xi,u_1) \qquad \text{second stage problem} \\ s.t. \quad & g_1(u_0,\xi,u_1) \leq 0 \end{aligned}$$

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The reformulation always exists, but is not unique

Admissible set

For a given decomposition, we set

$$U_0 := \{ u_0 \in \mathbb{R}^{n_0} \quad | \quad g_0(u_0) \leq 0 \}$$
$$\widetilde{U}_1(u_0, \xi) := \{ u_1 \in \mathbb{R}^{n_1} \quad | \quad g_1(u_0, \xi, u_1) \leq 0 \}$$

Note that

- $\widetilde{U}_1(u_0, \xi)$ is the set of admissible solutions of the second stage problem
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- $\widetilde{U}_1(u_0, \xi)$ is the set of admissible solutions of the second stage problem
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- We say that we are in a complete recourse framework, if for all $u_0 \in U_0$, and almost-all possible outcome $\boldsymbol{\xi}$, every control $\boldsymbol{u}_1$ is admissible, i.e.,

$$\mathbb{P}\big(\widetilde{U}_1(u_0, \boldsymbol{\xi}) = \mathbb{R}^{n_1}\big) = 1, \quad \forall u_0 \in U_0.$$

- We say that we are in a relatively complete recourse framework, if for all $u_0 \in U_0$, and almost-all possible outcome ξ, there exists a control $\boldsymbol{u}_1$ that is admissible, i.e.,

$$\mathbb{P}\big(\widetilde{U}_1(u_0, \boldsymbol{\xi}) \neq \emptyset\big) = 1, \quad \forall u_0 \in U_0.$$

- We say that we are in an extended relatively complete recourse framework, if there exists $\varepsilon > 0$ such that, for all $u_0 \in U_0 + \varepsilon B$, and almost-all possible outcome ξ, there exists a control $\boldsymbol{u}_1$ that is admissible, i.e.,

$$\mathbb{P}\big(\widetilde{U}_1(u_0, \boldsymbol{\xi}) \neq \emptyset\big) = 1, \quad \forall u_0 \in U_0 + \varepsilon B.$$

Obtaining relatively complete recourse

Assume that the two-stage program is given by

$$\min_{u_0 \in U_0} \Big\{ L_0(u_0) + \mathbb{E}\big[\tilde{Q}(u_0,\boldsymbol{\xi})\big] \Big\} \qquad \text{and} \qquad \tilde{Q}(u_0,\boldsymbol{\xi}) := \min_{u_1 \in \widetilde{U}_1(u_0,\xi)} L_1(u_0,\xi,u_1)$$

with finite value, but not necessarily relatively complete recourse.

Then the program is equivalent to

$$\min_{u_0 \in U_0 \cap U_0^{ind}} \Big\{ L_0(u_0) + \mathbb{E}\big[\tilde{Q}(u_0,\boldsymbol{\xi})\big] \Big\} \qquad \text{and} \qquad \tilde{Q}(u_0,\boldsymbol{\xi}) := \min_{u_1 \in \widetilde{U}_1(u_0,\xi)} L_1(u_0,\xi,u_1)$$

where U_0^{ind} is the set of induced constraints given by

$$U_0^{ind} = \Big\{ u_0 \in \mathbb{R}^{n_0} \quad \big| \quad \mathbb{P}\big(\widetilde{U}_1(u_0,\boldsymbol{\xi}) \neq \emptyset\big) = 1 \Big\},$$

and with this formulation we are in a relatively complete recourse framework.

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$$\min_{u_0\in U_0} \Big\{ L_0(u_0) + \mathbb{E}\big[\tilde{Q}(u_0,\boldsymbol{\xi})\big]\Big\} \qquad \text{and} \qquad \tilde{Q}(u_0,\boldsymbol{\xi}) := \min_{u_1\in \widetilde{U}_1(u_0,\xi)} L_1(u_0,\xi,u_1)$$

with finite value, but not necessarily relatively complete recourse.
Then the program is equivalent to

$$\min_{u_0\in U_0\cap U_0^{ind}} \Big\{ L_0(u_0) + \mathbb{E}\big[\tilde{Q}(u_0,\boldsymbol{\xi})\big]\Big\} \qquad \text{and} \qquad \tilde{Q}(u_0,\boldsymbol{\xi}) := \min_{u_1\in \widetilde{U}_1(u_0,\xi)} L_1(u_0,\xi,u_1)$$

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Presentation Outline

Two-stage framework : three information models

Consider the problem

$$\min_{\boldsymbol{u}_0, \boldsymbol{u}_1} \mathbb{E}\big[L(\boldsymbol{u}_0, \boldsymbol{\xi}, \boldsymbol{u}_1)\big]$$

- Open-Loop case : $\boldsymbol{u}_0$ and $\boldsymbol{u}_1$ are deterministic. In this case both controls are choosen without any knowledge of the alea $\boldsymbol{\xi}$. The set of control is small, and an optimal control can be found through specific method (e.g. Stochastic Gradient).
- Two-Stage case : $\boldsymbol{u}_0$ is deterministic and $\boldsymbol{u}_1$ is measurable with respect to $\boldsymbol{\xi}$. This is the problem tackled by the Stochastic Programming case.
- Anticipative case : $\boldsymbol{u}_0$ and $\boldsymbol{u}_1$ are measurable with respect to $\boldsymbol{\xi}$. This case consists in solving one deterministic problem per possible outcome of the alea, and taking the expectation of the value of this problems.

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Splitted formulation

The extended formulation (in a compact way)

$$\begin{aligned} \min_{u_0, \{u_1^s\}_{s\in[\![1,S]\!]}} \quad & \sum_{s=1}^{S} \pi^s L(u_0, \xi^s, u_1^s) \\ s.t \quad & g(u_0, \xi^s, u_1^s) \leq 0, \qquad \forall s \in [\![1, S]\!]. \end{aligned}$$

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Information models for the Newsvendor I

Open-loop :

$$\begin{aligned}
\min_{u_0, u_1} \quad & \sum_{s=1}^{S} \pi^s (cu_0 - pu_1) \\
s.t. \quad & u_0 \geq 0 \\
& u_1 \leq u_0 \\
& u_1 \leq d^s & \forall s \in [\![1, S]\!]
\end{aligned}$$

Information models for the Newsvendor II

Two-stage :

$$
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& u_1^s \leq d_s && \forall s \in [\![1, S]\!]
\end{aligned}
$$

Information models for the Newsvendor III

Anticipative :

$$\begin{aligned} \min_{\{u_0^s, u_1^s\}_{s\in[\![1,S]\!]}} \quad & \sum_{s=1}^{S} \pi^s \big(c u_0^s - p u_1^s\big) \\ s.t. \quad & u_0^s \geq 0 && \forall s \in [\![1, S]\!] \\ & u_1^s \leq u_0 && \forall s \in [\![1, S]\!] \\ & u_1^s \leq d^s && \forall s \in [\![1, S]\!] \end{aligned}$$

Comparing the information models

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Hence, by simple comparison of constraints we have

$$V^{anticipative} \leq V^{2-stage} \leq V^{OL}.$$

Value of information

- The Expected Value of Perfect Information (EVPI) is defined as

$$EVPI = v^{2-stage} - v^{anticipative} \geq 0.$$

- Its the maximum amount of money you can gain by getting more information (e.g. incorporating better statistical model in your problem)
- The Value of Stochastic Solution is defined as

$$VSS = v^{OL} - v^{2-stage} \geq 0.$$

- The expected value problem is the value of the deterministic problem where the randomness is replaced by its expectation

$$v^{EV} = \min_{u_0, u_1} L(u_0, \mathbb{E}[\xi], u_1).$$

- If (u_0^{EV}, u_1^{EV}) is the solution of the EV problem, then $\mathbb{E}\Big[L(u_0^{EV}, \xi, u_1^{EV})\Big]$, is known as Expected Value of Expected Value problem v^{EEV}.

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Comparison and convexity

- Without assumption we have

$$v^{EEV} \geq v^{OL} \geq v^{2-stage} \geq v^{anticipative}$$

- If additionally L is jointly convex we have

$$\begin{aligned} v^{anticipative} &= \mathbb{E}\Big[L(u_0^\xi, \xi, u_1^\xi)\Big] \\ &\geq L(\mathbb{E}\big[u_0^\xi\big], \mathbb{E}\big[\xi\big], \mathbb{E}\big[u_1^\xi\big]) \\ &\geq L(u_0^{EV}, \mathbb{E}\big[\xi\big], u_1^{EV}) = v^{EV} \end{aligned}$$

- Hence, under convexity we have,

$$v^{EEV} \geq v^{OL} \geq v^{2-stage} \geq v^{anticipative} \geq v^{EV}$$

Solving the problems

- The solution of v^{EEV} is easy to find (one deterministic problem), and its value is obtained by Monte-Carlo.
- v^{OL} can be approximated through specific methods (e.g. SG).
- $v^{2-stage}$ is obtained through Stochastic Programming specific methods. There are two main approaches:
  - Lagrangian decomposition methods (like Progressive-Hedging algorithm).
  - Benders decomposition methods (like L-shaped or nested-decomposition methods).
- $v^{anticipative}$ is difficult to compute exactly but can be estimated through Monte-Carlo approach by drawing a reasonable number of realizations of ξ, solving the deterministic problem for each realization ξ_i and taking the means of the value of the deterministic problem.
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Presentation Outline

How to deal with continuous distributions ?

Recall that if ξ as finite support we rewrite the 2-stage problem

$$\begin{aligned} \min_{u_0, \boldsymbol{u}_1} \quad & \mathbb{E}\Big[L(u_0, \boldsymbol{\xi}, \boldsymbol{u}_1)\Big] \\ s.t. \quad & g(u_0, \boldsymbol{\xi}, \boldsymbol{u}_1) \leq 0, \qquad \mathbb{P} - a.s \end{aligned}$$

as

$$\begin{aligned} \min_{u_0, \{u_1^s\}_{s \in [\![1,S]\!]}} \quad & \sum_{s=1}^{S} \pi^s L(u_0, \xi^s, u_1^s) \\ s.t \quad & g(u_0, \xi^s, u_1^s) \leq 0, \qquad \forall s \in [\![1, S]\!]. \end{aligned}$$

If we consider a continuous distribution (e.g. a Gaussian), we would need an infinite number of recourse variables to obtain an extensive formulation.

Simplest idea: sample $\boldsymbol{\xi}$

First consider the one-stage problem

$$\min_{u \in U} \mathbb{E}\big[L(u, \boldsymbol{\xi})\big] \qquad (\mathcal{P})$$

- Draw a sample $(\xi^1, \dots, \xi^N)$ (in a i.i.d setting with law $\boldsymbol{\xi}$).
- Consider the empirical probability $\hat{\mathbb{P}}_N = \frac{1}{N}\sum_{i=1}^N \delta_{\xi^i}$.
- Replace $\mathbb{P}$ by $\hat{\mathbb{P}}_N$ to obtain a finite-dimensional problem that can be solved.
- This means solving

$$\min_{u \in U} \frac{1}{N}\sum_{i=1}^N L(u, \xi^i) \qquad (\mathcal{P}_N)$$

- We denote by $\hat{\boldsymbol{v}}_N$ (resp. v^*) the value of $(\mathcal{P}_N)$ (resp. $(\mathcal{P})$), and $\boldsymbol{S}_n$ the set of optimal solutions (resp. S^*).

Biased estimator

Generically speaking the estimators of the minimum are biased

$$\mathbb{E}\big[\hat{\boldsymbol{v}}_N\big] \leq \mathbb{E}\big[\hat{\boldsymbol{v}}_{N+1}\big] \leq v^*$$

proof :

- Let $(\xi_i)_{i\in\mathbb{N}}$ be a sequence of iid copies of ξ
- Set $J(u) := \mathbb{E}\big[L(u,\xi)\big]$, $\boldsymbol{J}_N(u) := \frac{1}{N}\sum_{i=1}^N L(u,\xi_i)$
- We have, for every $u' \in U$, $\boldsymbol{J}_N(u') \geq \inf_{u\in U} \boldsymbol{J}_N(u)$.
- Taking the expectation yields,

$$J(u') = \mathbb{E}\Big[\boldsymbol{J}_N(u')\Big] \geq \mathbb{E}\Big[\inf_{u\in U} \boldsymbol{J}_N(u)\Big] = \mathbb{E}\big[\hat{\boldsymbol{v}}_N\big].$$

- We now take the infimum over $u' \in U$, to obtain

$$v^* = \inf_{u'\in U} J(u') \geq \mathbb{E}\big[\hat{\boldsymbol{v}}_N\big].$$

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Decreasing bias

We now show that the bias is monotonically decreasing. Notice that

$$\boldsymbol{J}_{N+1}(u) = \frac{1}{N+1}\sum_{i=1}^{N+1}\Big[\frac{1}{N}\sum_{j\neq i} L(u,\boldsymbol{\xi}_j)\Big].$$

Hence,

$$\begin{aligned}
\mathbb{E}\big[\hat{\boldsymbol{v}}_{N+1}\big] &= \mathbb{E}\Big[\inf_{u\in U}\boldsymbol{J}_{N+1}(u)\Big] = \mathbb{E}\Big[\inf_{u\in U}\frac{1}{N+1}\sum_{i=1}^{N+1}\Big[\frac{1}{N}\sum_{j\neq i} L(u,\boldsymbol{\xi}_j)\Big]\Big] \\
&\geq \mathbb{E}\Big[\frac{1}{N+1}\sum_{i=1}^{N+1}\inf_{u_i\in U}\Big[\frac{1}{N}\sum_{j\neq i} L(u_i,\boldsymbol{\xi}_j)\Big]\Big] \\
&= \frac{1}{N+1}\sum_{i=1}^{N+1}\mathbb{E}\Big[\inf_{u_i\in U}\Big[\frac{1}{N}\sum_{j\neq i} L(u_i,\boldsymbol{\xi}_j)\Big]\Big] \\
&= \frac{1}{N+1}\sum_{i=1}^{N+1}\mathbb{E}\big[\hat{\boldsymbol{v}}_N\big] = \mathbb{E}\big[\hat{\boldsymbol{v}}_N\big]
\end{aligned}$$

Consistency of estimator

Definition

Let $\{\boldsymbol{f}_N\}_{N\in\mathbb{N}}$ be a sequence of random functions mapping X into $\mathbb{R}$. We say that $\boldsymbol{f}_N$ converges almost surely toward $f : X \mapsto \mathbb{R}$ uniformly on X, if

$$\forall \varepsilon > 0, \quad \exists N \in \mathbb{N}, \quad \forall n \geq N, \qquad \mathbb{P}\Big(\sup_{x\in X} |\boldsymbol{f}_n(x) - f(x)| \leq \varepsilon\Big) = 1.$$

Theorem (Consistency of SAA)

If $\boldsymbol{J}_{N+1}$ converges almost surely toward J uniformly on U, then $\hat{v}_N$ converges almost surely toward $v^\sharp$.

Theorem (Convergence in the compact case)

Assume that

1. U *is compact non empty,*
2. $\boldsymbol{J}_N$ *converges uniformly on* U *toward* J*,*
3. $\boldsymbol{U}_N^\sharp$ *in non-empty,*
4. J *is continuous on* U*.*

Then,

- $\boldsymbol{v}_N^\sharp \to v^\sharp \quad \mathbb{P}^N$*-a.s.,*
- $\mathbb{D}\big(\boldsymbol{U}_n^\sharp, U^\sharp\big) \to 0 \quad \mathbb{P}^N$*-a.s.*

1. can be relaxed in a compact set containing optimal solution
2. usually comes from the uniform law of large number
3. can be obtained if J_N is lower semi-continuous with some non-empty but uniformly bounded level set
4. often rely on a domination theorem.

Theorem (Convergence in the convex case)

Assume that

1. j *is a.s. convex l.s.c.*
2. U *is closed convex*
3. J *is l.s.c, and there exists* $u \in U$ *such that a neighboorhood of* u *is contained in* $\mathrm{dom}(J)$
4. $S \neq \emptyset$ *is bounded*
5. *the LLN holds*

Then,

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Theorem (Convergence speed)

Assume that,

- $\mathbb{E}\left[j(u,\boldsymbol{\xi})^2\right] < \infty$,
- $u \mapsto j(u,\xi)$ *is Lipschitz-continuous with constant* $L(\xi)$ *with* $\mathbb{E}\left[L(\boldsymbol{\xi})^2\right] < \infty$,
- U *is compact,* $U^\sharp = \left\{u^\sharp\right\}$.

Then,

- $\boldsymbol{v}_N^\sharp = \boldsymbol{J}_N(u^\sharp) + o(\frac{1}{\sqrt{N}})$,
- $\sqrt{N}(\boldsymbol{v}_N^\sharp - v^\sharp) \Rightarrow \mathcal{N}(0, \sigma^2(u^\sharp))$,

where $\sigma^2(u) := \mathbb{E}\Big[\big(j(u,\boldsymbol{\xi}) - \mathbb{E}\left[j(u,\boldsymbol{\xi})\right]\big)^2\Big]$.

The unicity of solution assumption can be relaxed.
Good reference for precise results : Lectures on Stochastic Programming (Dentcheva, Ruszczynski, Shapiro) chap. 5.

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